Davie, Mark C. (2011) *Mountain bike suspension systems and their effect on rider performance quantified through mechanical, psychological and physiological responses.* PhD thesis.

# MOUNTAIN BIKE SUSPENSION SYSTEMS AND THEIR EFFECT ON RIDER PERFORMANCE QUANTIFIED THROUGH MECHANICAL, PSYCHOLOGICAL AND PHYSIOLOGICAL RESPONSES.

Mark C. Davie

A thesis submitted for the degree of Doctor of Philosophy in Engineering

Department of Mechanical Engineering

University of Glasgow

November 2010

## Acknowledgements

The author would like to express his wholehearted thanks to his supervisor Dr Arthur Whittaker without his help and supervision this thesis would not have been possible. Further thanks goes to Dr Fairlie-Clarke and Dr Stan Grant for their supervision on the design and physiology guidance throughout the project. I must also thank everyone from the various departments and faculties that have helped me. Particular thanks to the technical and administrative staff in the Department of Mechanical Engineering and the Department of Physiology; especially Ian Watt for his help during the physiological tests. Thanks to John White bikes that sponsored the project and provided the test bicycles for the project.

Thanks to my family for their continued support throughout the thesis.

Finally and most importantly thanks to Gillian Henry for all of her help and support without your encouragement this would not have been possible.

# Abstract

Mountain bike suspension systems have been designed to improve riding performance and comfort for the cyclist. Additionally, a suspension system may reduce fatigue, energy expenditure, and enhance time trial performance. It has also been proposed, however, that using a rear suspension system on a mountain bike may be detrimental to the cyclist, causing the cyclist's energy to be dissipated via the rear suspension system.

Prior to undertaking the current research, a survey into mountain bike suspension systems was conducted to establish rider preferences, as well as their perceptions of suspension systems and riding styles. The resulting responses - that the majority of cross-country cyclists chose to ride a bike with front suspension only (a hardtail bike), despite the significant advantages that a fully suspended system has to offer – aided in the decision to address the unanswered questions that remain in this area of research.

This thesis presents an investigation into mountain bike suspension systems and their effect on rider performance, quantifying the dynamic loads exerted on the bike frame and rider. Both the psychological and physiological effects of using a rear suspension system on cross-country cycling are additional considerations of this study.

An initial laboratory experiment was completed to investigate the effects of rear wheel dynamics on a rough track with a high impact frequency and the consequent impact this terrain has on rider performance, comparing a full suspension and hardtail bike. Further testing was conducted on a rolling road rig, specifically designed for the purpose of the current research, which more closely represented the conditions encountered by a cyclist on a cross-country track. Testing was conducted on the rolling road rig on both a flat road and rough track, examining the interaction forces between the bike and rider. Greater resistance was experienced by cyclists when cycling on the rolling road rig compared to the roller rig which equated to the resistance encountered when cycling uphill or into a headwind. The mechanical results from both rigs were compared to dynamic simulations as a means of validating and comparing the mechanical results.

An additional series of tests was carried out on an indoor track which had a similar terrain to that of the rolling road rig. This set of tests placed fewer restrictions on the cyclist as only physiological data was collected using unobtrusive portable measurement devices, and provided further results to illuminate correlations or discrepancies between the roller rig and rolling road rig experiments.

The experimental rolling road rig results indicated that, when cycling on a smooth surface, the hardtail bike offered no significant physiological advantage to the cyclist; however, more power was required by the rider to pedal the fully suspended bike. This was also advocated by the simulation results. Conversely, it was highlighted that the fully suspended bike provided a significant advantage to the rider compared to the hardtail bike when cycling on extremely rough terrain on the roller rig. This was the case across the simulation results, mechanical measurements, physiological measurements and psychological measurements. Similarly, the indoor track tests indicated that cycling on a fully suspended bike provided significant advantages to a cyclist in terms of rider performance. On the contrary, the experimental rolling road rig results on a rough surface demonstrated that no significant difference was apparent between cycling on either the hardtail or fully suspended bike. This result suggests that, when a rider encounters added resistance to cycling, as is the case when cycling uphill, there is less of an advantage for a fully suspended bike even on rough terrain.

# i. Table of Contents

## ii. List of Figures

# iii. List of Tables

# i. List of Equations

## ii. Nomenclature

These symbols are used within the body of the text, figures and tables of this document:

| | |
|---|---|
| A | Area |
| a | Acceleration |
| C | Circumference |
| Cd | Coefficient of drag |
| d | Diameter |
| E | Energy |
| Hz | Hertz |
| J | Joules |
| kHz | Kilohertz |
| k | Kinetic Energy |
| Ep | Potential Energy |
| F | Force |
| f | Frequency |
| g | Gravity |
| I | Inertia |
| IC | Integrated Circuit |
| M | Mass |
| m | Mean |
| MHz | Megahertz |
| N | Newtons |
| Ω | Ohms |
| P | Power |
| psi | Pounds per square inch |
| r | radius |
| t | Time |
| v | Velocity |
| V | Voltage |

$x$..........Denotes undefined variable

W……………Watts

$w$..........Width

$\omega$..........Rotational Velocity

## iii. Abbreviations

These symbols are used within the body of the text, figures and tables of this document:

| | |
|---|---|
| ADAMS | Mechanical Simulation Software |
| A to D Converter | Analogue to digital Converter |
| ANOVA | The Analysis Of Variance |
| AUTOLEV | Online dynamics |
| Avg | Average |
| $CO_2$ | Carbon dioxide |
| CK | Creatine Kinase |
| DADS | Dynamic Analysis and Design System |
| DC | Direct Current |
| HR | Heart rate |
| HT | Mountain bike with front suspension only |
| LT | Lactate Threshold |
| Lab View | Data recording display |
| LifeMod | Plug in for ADAMS to represent a model of a human |
| Max | Maximum |
| Min | Minimum |
| $O_2$ | Oxygen consumption |
| p | (Probability) Statistical confidence level |
| PCB | Printed Circuit Board |
| PTFE | Polytetrafluoroethylene |
| RPE | Rating of perceived exertion |
| s | Standard deviation |
| SMD | Surface Mount Device |
| SRM | Schoberer Rad Messtechnik |
| SU | Mountain bike with front and rear suspension |
| $VCO_2$ | Volume of carbon dioxide uptake |
| $VO_2$ | Volume of oxygen uptake |

$VO_{2max}$..........................................................……......Volume of maximal oxygen uptake

# iv. Terms Glossary

**Accelerometer**

An accelerometer is a device that measures proper acceleration, the acceleration experienced relative to freefall.

**Aerobic**

Having oxygen present, describes the metabolic process utilising oxygen.

**ADAMS**

A Mechanical System Simulation Software.

**Anaerobic**

Inadequate oxygen present, describes the metabolic process that does not use oxygen.

**Bobbing**

Oscillation of the bike due to the suspension

**Brake jack**

The rear suspension of a bike extending and stiffening when the rear break is applied.

**Breath-by-breath**

The expression of a particular physiological value averaged over on respiratory cycle.

**Bottom bracket**

The bottom bracket on a bicycle connects the crankset to the bicycle and allows the crankset to rotate freely.

**Chainstay**

This is the section of a bicycle frame which connects the bottom bracket with the rear wheel connection.

**Crank**

The crank is an arm attached at right angles to a rotating shaft.

**Crankset**

This is the component of a bicycle drivetrain that converts the motion of the rider's legs into rotational motion used to drive the chain, which in turn drives the rear wheel.

**Frequency**

The amount of times an event occurs per second.

**Four-bar linkage**

Consists of four rigid bodies, attached by single joints or pivots to form a closed loop.

**Fully Suspended**

A bike with front and rear suspension.

**Hardtail**

A bike with front suspension only.

**Heart rate**

The rate at which the heart beats per minute

**Incremental exercise test**

An exercise test designed to provide a gradational work rate to the subject.

**Lactate**

The form in which lactic acid is measured.

**Lactate threshold**

The exercise $VO_2$ above which lactic acid concentration increases the blood.

**LifeMOD**

Is a human simulation tool.

**Matlab**

(MATrix LABoratory) is a numerical computing environment programming language.

**Optical encoder**

Is a device that converts motion into a sequence of digital pulses.

**Pedal feedback**

This is when the distance between the axle and cranks increases as the suspension compresses.

**Power**

The rate at which work is performed.

**Preload**

The amount a suspension system compresses from the weight of the rider alone.

**Ridged bike**

A bike with no suspension.

**Shock absorber**

A shock absorber is a mechanical device (one kind of dashpot) designed to smooth out or damp shock impulse, and dissipate kinetic energy.

**Servo-hydraulic testing actuators**

Are used in materials and component testing to reproduce precise, pre-determined forces and travel.

**Single Swing Arm or Single pivot**

Is a rear suspension system that consists of a pivot near the bottom bracket and a single swingarm to the rear axle.

**Spring Preload**

The compression the spring of the suspension is under to compensate for a riders weight.

**Steady State**

A characteristic of a physiological system in which the functional demands are being met such that its output per unit of time become constant.

**Transducer**

A transducer is a device that converts one type of energy to another.

**$VO_2$**

The amount of oxygen extracted from the inspired gas in a given time period.

**$VO_{2max}$**

The maximum oxygen uptake that a subject can achieve.

**$VO_{2peak}$**

The highest oxygen uptake achieved during exercise.

**Work**

A physical quantification of the force operating on a mass that causes it to change its location.

# 1. Introduction

The main research question is to establish the effect on rider performance when cycling a fully suspended mountain bike compared to a hardtail mountain bike. Nielens and Lejeune (2004) reviewed the most relevant studies conducted to measure the energy efficiency of rear suspensions and concluded that there is not enough evidence to make a decision about the use of hardtail or full suspension bikes: the type and degree of suspension and its effect on rider performance are topics of much debate yet (González et al., 2008). This thesis will address this gap in research by investigating the effects that cycling on a full suspension and front suspension only mountain bike has on rider performance. Rig experiments; indoor track tests; dynamic simulations and the resulting analysis of physiological, psychological, and mechanical data, aided in meeting the objectives of the research.

Mountain biking, or off-road cycling, was initially developed in the 1970s when heavyweight bikes were modified to freewheel down mountain tracks and enable riders to cope with bumpy terrain. The first official mountain bike championships were held in 1990, and mountain biking became an Olympic sport in 1996 (Union Cycliste Internationale (UCI) Official Website, 2009). Since its accreditation, mountain biking has developed into a popularly acclaimed sport.

There are three types of mountain bike: a rigid frame mountain bike with no suspension; a hardtail mountain bike with front suspension only; and a fully suspended mountain bike which has both front and rear suspension. The first mountain bikes were manufactured with a rigid frame and fork (rigid frame mountain bikes), and it was not until the early 1990s that the first mountain bikes with suspension forks were introduced. This made cycling on rough terrain easier and less physically stressful. Riding over rough terrain presents numerous problems for cyclists: the rougher the terrain, the more vibrations felt by a rider which consequently results in discomfort and an increase in physical stress on muscles, thus cycling on rough terrain can impair a cyclist's ability to perform. Needle & Hull (1997) assert that vibrational discomfort associated with riding a bike over rough terrain has been known to contribute to rider fatigue and affect rider performance. Levy & Smith (2005) suggest that a reduction of vibration in cycling has the potential for improved performance and comfort.

Front suspension systems were incorporated into the design of mountain bikes to aid in absorbing bump impact energy, shielding both the frame and rider from jolts (Leventon, 1993). In addition to absorbing bump impact, Olsen (1996) identifies basic goals that should be satisfied by a mountain bike suspension design: (i) to isolate the rider from the roughness of the road; (ii) to absorb energy and shock that comes from hitting large obstacles; (iii) to keep the wheels on the ground to provide useful functions such as driving, braking and steering; and (iv) to avoid adding undesirable characteristics to the bike. Undesirable characteristics include chain-suspension pedalling interactions (Good & McPhee, 1999) and the bobbing effect of the suspension, felt as the cyclist pedals.

Front suspensions have become standard equipment on mountain bikes (Leventon, 1993) and are widely used in off-road bikes since they have no disadvantages except for a slight weight penalty in the fork (González et al., 2008). Conversely, rear suspension systems are not broadly accepted by off-road cyclists (González et al., 2008). In support of this view, the analysis of the questionnaire respondants (Chapter 3) found that the majority of cyclists chose to ride hardtail bikes over bikes fitted with a full suspension system: only 95 out of the 260 respondents rode a fully suspended mountain bike. Reasons cited for this were that full suspension mountain bikes used up excess energy through effects such as bobbing, pedal feedback, and brake jack.

The majority of front and rear suspension systems are comprised of an elastic (spring) and viscous (damper) component mounted in parallel between the wheel and frame of the bike, as illustrated in Figure 1-1. The elastic component is made of a steel spring which can be pre-constrained at different levels or an air chamber that can be pre-inflated at varied pressures according to the nature of the terrain and cyclist’s preference. The viscous component generally comprises of a piston and cylinder chamber filled with oil - the oil travels through orifices made in the piston (Nielens & Lejeune, 2004). Most front suspensions are comprised of telescopic forks with elastic and viscous components in each arm of the fork. Rear suspension designs, however, are numerous. The most frequently manufactured rear suspension designs are: single swing arm; four bar linkage; four bar horst link; virtual pivot point; unified rear triangle; and suspension seat posts.

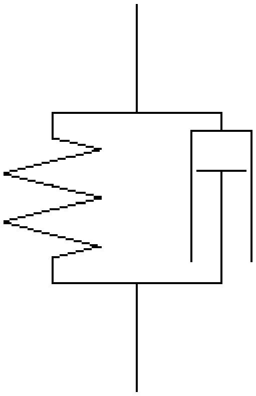


*Figure 1-1: Components of a suspension system*

The hardtail mountain bike used for the experiments in the current study was fitted with a font suspension telescopic fork. The fully suspended mountain bike comprised of a front telescopic fork suspension system, and a single swing arm rear suspension design; a mountain bike with this type of rear suspension design was chosen as it is one of the most widely used rear suspension systems. This is supported by the findings from the cyclists’ questionnaire responses (Chapter 3) which highlight that out of the 95 cyclists who rode fully suspended bikes, the majority (33 %) cycled on bikes comprising of a single swing arm rear suspension design. The single swing arm suspension design consists of a pivot near the bottom bracket and a single swing arm to the rear axle (Figure 1-2). The rear axle will always rotate in a part-circle around the pivot point.

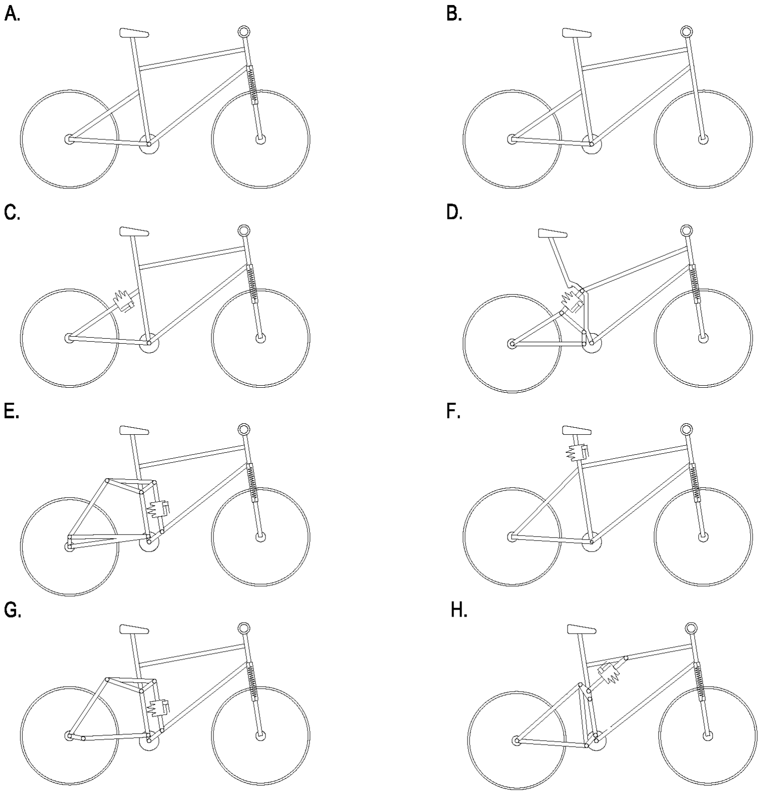


*Figure 1-2: Most common bicycle suspension designs: (A) Hardtail bike with front suspension only: (B); Ridged bike with no suspension (C) Single swing arm; (D) Unified rear triangle; (E) 4-bar linkage; (F) Suspension seat post; (G) Horst link; (H) Virtual pivot point.*

There have been many attempts to develop improved suspension systems with much attention being devoted by the off-road bike industry in developing designs that either minimise or eliminate the coupling between the pedalling actions of the rider and the motion of the suspension (bobbing effect) (Ishii et al., 2003). However, the benefits and drawbacks of a rear suspension mountain bike design are still subject to much debate.

The review of literature pertaining to the three types of mountain bike and their corresponding suspension systems (Chapter 2) and the analysis of cyclists' questionnaire responses (Chapter 3) demonstrate that anomalies exist between experiments, time trails, race results and simulations. The gaps in research aided in deciding which objectives the current research should explore. As the research pertaining to mountain bike suspension systems and their effects on rider performance is limited (MacRae et al., 2000; Nielens & Lejeune, 2001; Seifert et al., 1997), the focal objective of the study is to investigate the effects of cycling on a hardtail and fully suspended bike on a smooth and rough surface to explore if either suspension system presents an advantage to the cyclist in terms of rider performance. This was carried out by analysing the physiological, psychological and mechanical aspects of cycling on both the hardtail and fully suspended mountain bike. Previous research (Berry et al., 1993 & 2000; Ishii et al., 2003; MacRae et al., 2000; Nielens & Lejeune, 2001; Seifert et al., 1997; Titlestad et al., 2006) investigated the effects of suspension systems on a rider's physiology and psychology. Similarly, tests have been undertaken which investigate mountain bike suspension systems and their mechanical design - Champoux et al., 2004; Karchin & Hull, 2002; Levy & Smith, 2005; Needle & Hull, 1997. However, no previous study (with the exception of Titlestad et al., 2006) has combined these two aspects.

In order to investigate the effects that cycling on either a hardtail or fully suspended mountain bike has on rider performance, the energy efficiency of cyclists was studied. Wang & Hull (1996) maintain that it seems reasonable that energy efficiency can be used as one measure of performance. One method of recording energy efficiency is through measuring the rate of oxygen uptake during exercise ($VO_2$). $VO_2$ is related linearly to power for able bodied subjects up to (and beyond) the lactate threshold; $VO_{2max}$ is defined as the $VO_2$ at which performance of increasing levels of work rate exercise failed to increase $VO_2$, despite an increase in work rate (Wasserman et al., 1994). The $VO_2$ response

during exercise can be divided into two parts: aerobic and anaerobic exercise. Aerobic simply means in the presence of oxygen (Powers & Howley, 1990). The muscles use the oxygen to burn the fuel - adenosine triphosphate (ATP). During exercise, when the required oxygen ($O_2$) amount is not met, the subjects enter an anaerobic state - 'without oxygen'. This state is when the fuel is burned without oxygen; a by-product of which is an increase in expired $CO_2$. The subject is said to reach the lactate threshold at the transition between the aerobic and anaerobic phases; consequently, lactic acid is an end product of this anaerobic state, produced when there is inadequate oxygen supply to the muscles. The lactic threshold can be identified by either blood sampling or from gas exchange data. When testing subjects, it is more beneficial to test in an aerobic state in order to control the $VO_2$ to a level below the lactate threshold: sub-maximal testing. For this reason sub-maximal testing, where subjects are in an aerobic state, was chosen for the tests undertaken in the current study.
Additionally, subjects' heart rates were recorded during testing as these results can be used to measure energy efficiency. There is a linear relationship between heart rate and $VO_2$, however heart rate is variable and can be easily affected by environmental conditions (body temperature, stress and anxiety). Even with controlled environmental conditions and removal of stimulus, subjects can still become easily distracted. In this respect, it was important to allow for these variations and to record other physiological and psychological measurements in addition to heart rate, in order to present further results from which to draw conclusions.

Each subject's psychological response for comfort rating and rating of perceived exertion (RPE) was also recorded during testing. These responses were included in the research to investigate correlations between physiological elements and rider opinions and responses. Literature pertaining to psychological testing, where subjects' comfort rating levels are recorded, is limited (Seifert et al., 1997; Titlestad et al., 2006). It was therefore decided that further testing in this area would be advantageous.

Literature concerned with physiological testing (Berry et al., 1993 & 2000; Ishii et al., 2003; MacRae et al., 2000; Nielens & Lejeune, 2001; Seifert et al., 1997; Titlestad et al., 2006) identified research which measured subjects' heart rate; $VO_2$; comfort rating; and RPE levels. It was decided that by recording these measurements in the current research, comparisons and inconsistencies could be highlighted between the current and previous research which would aid in meeting the objectives of the study. As all testing in the current research was to be sub-maximal, subjects' blood lactate levels were not recorded, as they were in MacRae et al's (2000) maximal testing study.

Literature pertaining to mechanical testing (Champoux et al., 2004; Karchin & Hull, 2002; Levy & Smith, 2005; Needle & Hull, 1997) recorded the forces exerted on the front and rear axles, handlebars, saddle and pedals; acceleration of the front and rear axles and handlebars; displacement of the suspensions; and angle of the crank. It was deemed that some of these measurements were relevant to the current study, yet additional mechanical measurements were required to fully investigate the differences between cycling on a hardtail and fully suspended bike, and the resulting effect this has on the cyclist. The mechanical measurements recorded during the experiments of the current research comprised of: the forces exerted on the handlebars, saddle and crank; acceleration of the handlebars and saddle; velocity of the handlebars, saddle, crank and road surface; and displacement of the handlebars and saddle.

The research study comprised of tests on a roller rig, rolling road rig, indoor track and dynamic simulations. The initial roller rig was developed to investigate the effects of rear wheel dynamics on a rough track and the consequent effects on rider performance. It was considered that although the obtained results from the roller rig were relevant, the rig itself was deemed too restrictive and did not present a close representation of true outdoor riding conditions. With this in mind, the rolling road rig was designed to present a closer representation of true outdoor riding conditions. The rolling road rig was designed to investigate both front and rear wheel dynamics, and additional measurements (to those obtained during the roller rig experiments) were recorded which considered the interaction between the bike and rider. Further experimentation was carried out on the indoor track in an attempt to further create a testing environment which closely matched that of riding outdoors. Furthermore, the findings from the indoor track test provided additional results to highlight correlations or discrepancies between the roller rig and rolling road rig test results.

Dynamic simulations were carried out to assist in meeting the objectives of the current research. Simulations aided in the design of the rolling road rig, yet they were also used to compare the mechanical results from the rig tests to the simulation results. Findings from the comparison of results could be used to establish if simulations are a valid means of measuring the mechanical difference between cycling on a fully suspended bike compared to a hardtail bike.
The outline of the thesis is as follows: Chapter 2 presents a review of the most relevant and valuable research carried out in relation to mountain bike suspension systems. This is divided into three sections: suspension systems and their effects on a rider's physiology and psychology; the mechanical testing of suspension systems; and the dynamic simulations of mountain bikes and their suspension systems. These three aspects were also investigated in the current research.

Chapter 3 analyses and discusses the cyclists' responses to the questionnaire (Appendix A). 260 cyclists, ranging from amateur to professional level, were questioned on their preference of mountain bike suspension system and riding style. The results from the questionnaire aided in identifying which area of study the current research would investigate.

Chapters 4, 5 and 6 present the methodologies and findings obtained from the roller rig, rolling road rig and indoor track tests respectively. Chapter 4 presents details of the previously designed roller rig; the experiments undertaken on the rig; and the findings obtained from the tests. The rolling road rig test objectives, rig design, experiment methodology and test results are outlined in Chapter 5, and similarly, the indoor track test design, methodology and test results are detailed in Chapter 6.

Following on from this, Chapter 7 details the dynamic simulations carried out to compare the mechanical results obtained from the roller rig and rolling road rig to the simulation results. The simulation methodology and results are both presented in this chapter.

A discussion of the results obtained from the roller rig, rolling road rig, indoor track tests, and the simulations are presented in Chapter 8. The results from the three experimental tests are compared to one another, and to previous literature, and similarities and disparities are identified. Overall conclusions from all of the experimental tests and the simulations are brought together in Chapter 9, together with suggestions for future work.

# 2. Literature Review

## 2.1. Introduction

Mountain bike suspension systems are one of the most discussed subjects in off-road cycling (Karchin & Hull, 2002; MacRae et al., 2000; Nielens & Lejeune, 2001; Seifert et al., 1997). However, despite significant advances in mountain bike suspension systems, little is known about the effects of these systems on rider performance (Holden et al., 1999; MacRae et al., 2000; Nielens & Lejeune, 2001; Seifert et al., 1997). Levy & Smith (2005) stipulate that the appropriate choice of rear suspension is often based on subjective statements, with few testing results available. The aim of this literature review is to provide a synopsis of the most relevant and valuable research carried out in relation to mountain bike suspension systems and to provide directions for future research. Identifying unanswered questions in the literature aided in deciding which direction the current thesis should undertake.

Researchers (Berry et al., 1993; Burke, 1996; De Lorenzo et al., 1994; Good & McPhee, 1999; Karchin & Hull, 2002; MacRae et al., 2000; Needle & Hull, 1997; Nielens & Lejeune, 2004; Olsen, 1996; Seifert et al., 1997) have published literature highlighting some of the benefits that rear suspension systems provide for a cyclist. Nielens & Lejeune (2004) stipulate that rear suspension systems may significantly reduce physical stress; De Lorenzo et al. (1994) that suspensions isolate the cyclists from vibrations; Olsen (1996) and MacRae et al. (2000) that they improve comfort and bicycle handling and Needle & Hull (1997) that they improve braking, cornering, line holding and higher downhill speeds.

Conversely, researchers (Burke, 1996; Ishii et al., 2003; Karchin & Hull, 2002; Kukoda, 1992; Olsen 1996; and Wang & Hull, 1997) have stated that there are some drawbacks to using a rear suspension system. Kukoda (1992) believes that the benefits provided by suspension systems have come at a cost: higher weight, increased frame flexibility and a bobbing of the suspension under pedalling loads. This bobbing effect is thought to be disadvantageous as energy is lost in overcoming the dissipative forces in suspension systems, and also because the pedalling motion of the cyclists may be affected (Karchin & Hull, 2002).

For the purpose of this literature review the research is divided into three sections in order for topics to be identified and evaluated concisely. These three sections are: literature relating to suspension systems and their effects on a rider's physiology; literature surrounding the mechanical testing of suspension systems; and the dynamic simulations of mountain bikes and their suspension systems.

## 2.2. Physiological Testing

Physiological testing can be used to measure the energy expenditure of a rider which can be determined by heart rate, oxygen consumption ($VO_2$), and in some cases by measuring blood lactate levels. Such tests are carried out under two main conditions: in a laboratory setting using treadmills, ergometers or specifically designed rigs; and under field conditions including outside time trials, track tests and racing competitions.

Physiological factors play a fundamental role in an off-road cyclist's performance; an opinion held by Wang & Hull (1996) who proclaim that it seems reasonable that energy efficiency can be used as one measure of performance. Ample research has been carried out in respect to the physiological factors involved in road cycling. Despite this however, few studies have investigated these physiological aspects in relation to mountain biking and even fewer relating specifically to mountain bike suspension systems (Impellizzeri et al., 2002).

Demchak & Linderman (1999) and Seifert et al. (1997) agree, highlighting that the effects of suspension systems on rider performance have, to their knowledge, only received limited investigation.

The most significant and influential literature available on suspension systems and their effects on a rider's physiology was studied to establish correlations and contradictions. The relevant literature falls into two distinct categories: tests that have been carried out in a controlled environment inside a laboratory (Berry et al., 1993; Berry et al., 2000; Ishii et al., 2003; MacRae et al., 2000; Nielens & Lejeune, 2001; Titlestad et al., 2006), and tests that have been carried out under field conditions (Ishii et al., 2003; MacRae et al., 2000; Seifert et al., 1997).

Berry et al. (1993) were amongst the first researchers to consider investigating the physiological aspects involved in cycling mountain bikes with suspension systems. The study was undertaken to determine if total rider energy expenditure would decrease depending on the type of suspension system used, and to investigate both rider-induced and terrain-induced energy losses. Terrain-induced energy losses are those that arise due to surface irregularities, while rider induced losses are those due to the energy dissipated in the suspension system as a result of the rider's muscular action (Wang & Hull, 1996).

Berry et al. (1993) initially attempted to carry out this research in an outdoor environment, however, due to encountering various problems including tearing of balloons for gas collection; and difficultly in having the subjects maintain the same speed over the same course when riding the suspended and non-suspended bikes, it was decided to undertake the experiment in a laboratory controlled environment. It can be argued that laboratory controlled research does reduce some of the variables involved in outdoor mountain biking as there are many (such as weather conditions, terrain, velocity) that affect mountain biking performance (Needle & Hull, 1997).

Berry et al's (1993) study used a modified treadmill with a 1.5" bump in the form of a 2" x 4" board which was attached to the belt of the treadmill using duct tape. The treadmill ran at 2.9 m/s with a four percent grade. One advantage to using a treadmill as a form of testing for mountain bikes is that cycling a bicycle on a treadmill with a constant velocity is dynamically equivalent to riding a bicycle on flat level ground at a constant speed (Kooijman & Schwab, 2009). However, although this finding has been demonstrated for a treadmill simulating cycling on flat level ground, there is no evidence to suggest that this is true for cycling uphill on a treadmill simulating a smooth or bumpy track.

The mountain bike used for testing in Berry et al's (1993) study was a fully suspended off-road Proflex 862 (Ocean State International) with a single swing arm suspension design and urethane bumpers; the same bicycle was adapted and used for the non-suspended trials. A factor involved in using only one type of suspension design for testing is that the results can only be established for this specific type of design. Further studies (under the same set of test conditions) using different suspension designs, may have been beneficial and would have presented a broader range of results from which to compare and contrast.

Additional issues and concerns which may emerge from using a treadmill as a means of testing in a laboratory environment include: dangers that can arise from cycling a bike on equipment that is not specifically designed for a mountain bike; the time it can take for a subject to become familiar riding under these test conditions; and the reality that cycling in this controlled environment may feel unnatural to the subject. As Kooijman and Schwab (2009) maintain, a significant problem with cycling on a treadmill is the conflicting information which the rider receives. Although the rider is cycling with respect to the moving belt, he remains stationary with respect to the surrounding world. Berry et al. (1993) also highlighted that impending bumps on the treadmill may pose additional problems for subjects as they struggle to remain balanced on the mountain bike, and that these bumps may move on impact with the wheel as they are only secured to the belt of the treadmill by duct tape.

Berry et al’s (1993) methodology of study involved using six subjects: five males and one female. All of the selected subjects were keen cyclists and most had ridden mountain bikes previously. This could be deemed as a drawback as it suggests that some of the cyclists had not ridden a mountain bike previous to the study. This factor could potentially affect the results as the riding style of a road cyclist differs from that of a mountain biker; thus possibly affecting the amount of energy expended. Additionally, in light of this statement, it could be argued that some of the cyclists had never previously ridden on a bike with any form of suspension system; thus once again affecting riding style and possibly the energy expenditure of the subjects.

Berry et al’s (1993) subjects visited the laboratory on three separate occasions, completing two 6 min trials in each visit. On the initial visit, subjects cycled on both a fully suspended and rigid frame bike on a treadmill with no bumps; on the second visit subjects again cycled on both a fully suspended and rigid frame bike, but this time on a treadmill with one bump attached to it. On the third and final visit, subjects cycled on a bike with rear suspension only and on a hardtail bike; again on a treadmill which had one bump attached to it. The subjects however, were not tested riding on a hardtail bike or on a bike with rear suspension only, on the treadmill with no bumps. Further testing investigating either one of these scenarios may have presented the researchers with a broader range of results for comparison.

Three of the subjects performed these tests as outlined above in the order stipulated - the other three subjects performed the tests in reverse order. It is highly likely that the reason for this was to prevent bias of one system over another. Conversely, it could be argued that in order to further eliminate bias each subject should perform the test sequence in a different order. Further studies (Berry at al., 2000; Nielens & Lejeune, 2001) which have investigated energy expenditure in relation to mountain bike suspension systems support this view. Berry at al's (2000) study consisted of subjects carrying out tests in a randomised order and Nielens & Lejeune's (2001) research comprised of six different possibilities for the order of their three tests: two subjects were randomly assigned to each one of the six possible orders so as to eliminate any possible order effect.

Prior to testing, Berry et al. (1993) allowed the research subjects to practice on the treadmill until they became comfortable riding in the test environment; this usually involved between four and eight visits. An issue which may have emerged from this is that, prior to testing, a subject could familiarise themselves on any of the three types of systems, thus possibly affecting the results by giving a bias of one or more systems over the other.

Throughout each test the treadmill was run at 2.9 m/s; a speed significantly lower than those reached when riding in a competitive race. The justification for this lower speed was that at higher speeds, most of the riders had difficulty in controlling the bike on the treadmill. In order to compensate for the lower speeds involved in the testing, a four percent grade was added to the treadmill to increase the metabolic rate of the subject. The decision to use a grade of only four percent was to ensure that a subject's work level was sub-maximal; that is at a level below that to prevent lactate production. In supporting this view McArdle et al. (2001) stipulate that, in order for…calculations (on energy expenditure) to be valid, it is important that subjects not have excessive amounts of lactate acid in their blood (i.e., anaerobiosis). This causes an increase in carbon dioxide production, and thus prevents a correct evaluation of 'fuel mix'.

The physiological measurements recorded throughout Berry et al's (1993) test were: heart rate; ratings of perceived exertion (RPE) - how hard a person feels they are exercising on a subjective scale from between 6 and 20 (McArdle et al., 2001); the respiratory exchange ratio - the ratio of carbon dioxide production to oxygen consumption (McArdle et al., 2001); and oxygen uptake ($VO_2$). The average respiratory exchange ratio and the average $VO_2$ were used to estimate energy expenditure in kcal/min.

Once all testing had been completed and all physiological measurements recorded and evaluated, Berry et al's (1993) research found that there was no significant difference between riding uphill on a fully suspended mountain bike on a smooth treadmill, compared to a rigid frame mountain bike. The measurements of $VO_2$, heart rate, RPE and average respiratory exchange ratio showed no significant difference in results when comparing the two mountain bikes. In support of these findings Berry et al. (1993) carried out a visual inspection of the mountain bike suspension systems during the tests and found that no significant oscillation was present due to pedalling. This is an unexpected result as the questionnaire for this current study (Appendix A) found that seventy-six percent of mountain bikers felt that a fully suspended bike expended more of their energy when riding uphill. One possible explanation for this is that although a visual inspection is a useful method of highlighting movement in the suspension systems, a more accurate method of recording these movements may provide additional data to support or disprove Berry et al's (1993) findings.

In contrast to Berry et al's (1993) results, Wang & Hull (1996) found that the use of a rear suspension system results in 1.3% of the rider's power being dissipated by the rear suspension system. Wang & Hull's (1996) dynamic model simulated a fully suspended mountain bike cycling up a smooth track with a six percent grade at a velocity of 6.5 m/s. Although Berry et al's (1993) and Wang & Hull's (1996) experiments were carried out using different road grades, González et al. (2008) maintain that this should not affect the amount of power dissipated in the rear suspension; that is to say that power dissipation does not depend on road grade.

Another significant difference between Berry et al's (1993) and Wang & Hull's (1996) experiments, which may go some way to explaining the discrepancies in results, is the speed at which both the treadmill and simulation were run. As Berry et al's (1993) and Wang & Hull's (1996) tests were operated at significantly different speeds; 2.9 m/s and 6.5 m/s respectively, this consequently resulted in a difference in crank torque between the two tests. González et al. (2008) maintain that the crank torque generated by a cyclist heavily increases the power dissipated by the rear suspension system. González et al's (2008) statement presents one reason for the discrepancy between Berry et al's (1993) and Wang & Hull's (1996) results. Another reason to account for the fact that Berry et al. (1993) found that no energy was dissipated at the rear suspension when cycling uphill on a smooth treadmill may be that the small measurement of 1.3 % of rider's power dissipated by the rear suspension system found by Wang & Hull (1996), is less than the average measurement error expected when measuring oxygen consumption in an experimental test (Howley et al., 1995).

Further results from Berry et al's (1993) study found that the fully suspended mountain bike, compared to the rigid frame and hardtail mountain bike, can decrease a rider's energy expenditure when cycling uphill on a rough track, thus improving rider performance. The results illustrated that the $VO_2$, RPE and average respiratory exchange ratio of a subject were lower when cycling on a fully suspended bike uphill on a rough track. The results for heart rate under these same conditions however, contradict the other physiological results; a higher heart rate was recorded for subjects when cycling the fully suspended bike compared to cycling the bike with front suspension only. Berry et al. (1993) gave an explanation for this anomaly, stating that in the study all the subjects expressed some degree of concern about riding the bike on the treadmill with the bump attached, and most remained apprehensive even after practice. Lowered anxiety after successfully completing visit two might explain lessened heart rate in visit three. This supports what was previously discussed in relation to this type of experiment; that a subject may be apprehensive when cycling on the treadmill due to the unfamiliar riding conditions.

Berry et al. (1993) also observed that, when cycling on a rigid frame bike uphill on a rough track, subjects would briefly rise 1 or 2 inches off the saddle prior to hitting the bump, thus allowing their legs to absorb the impact. This was not the case for either the fully suspended, hardtail or rear suspension only mountain bikes. For these types of mountain bikes, used in Berry et al's (1993) tests, it is the suspension systems, and not the cyclists' legs, which absorb the impact of the bumps; thus supporting the view that suspension systems decrease energy expenditure.

Berry et al. (1993 & 2000) is the only researcher to have investigated the effects of cycling on a treadmill with bumps attached. Titlestad et al's (2006) study is perhaps the closest representation of Berry et al's (1993) research as this study also compared cycling on a rough track under a controlled environment using a fully suspended bike, comparing it to a hardtail mountain bike. Titlestad et al's (2006) results concur with those found by Berry et al. (1993), Titlestad et al. (2006) also found that a fully suspended mountain bike, compared to a hardtail bike, can improve a rider's performance whilst cycling on a rough track. Olsen (1996) maintains that a suspended bike would improve rider performance because of the shock absorption properties which improve the tyre to ground contact time. This statement supports the findings of Berry et al. (1993) and Titlestad et al. (2006).

A further finding of Berry et al's (1993) study showed that the use of a mountain bike with rear suspension only, when cycling uphill on a treadmill with bumps, gave similar results, in terms of energy expenditure, to that of riding a fully suspended bike. This suggests that mountain bikes with a rear suspension system have an advantage, in terms of energy expenditure, over hardtail bikes when cycling uphill on a rough track; the $VO_2$, heart rate and RPE measurements all coincide with this finding. It could be argued however, that this is not as significant a finding as the previous two discussed as all off-road mountain bikes now have front suspension and to encounter a bike with rear suspension only is rare. Later studies in this field (MacRae et al., 2000; Ishii et al., 2003; Nielens & Lejeune, 2001; Seifert et al., 1997; Titlestad et al., 2006) have eliminated this issue by excluding the rear suspension only system from studies and have focussed solely on testing rigid frame, hardtail and fully suspended bikes.

Berry et al. (2000) decided to develop their previous research (Berry et al., 1993) by studying the influence of velocity, grade and mass on mountain biking - again focussing on terrain and rider-induced energy expenditure. One of the main differences between Berry et al’s (1993) and Berry et al’s (2000) study was that in the latter study only a fully suspended mountain bike was used during testing. Berry et al’s (1993) research demonstrated that the use of a well designed suspension system would decrease the energy cost during simulated off road cycling. However, a potential problem with the use of suspension systems is the additional mass to the bike that they add; thus potentially increasing the force required to overcome the increased rolling resistance and the increased resistance due to gravity. In light of this, Berry et al’s (2000) research focuses on the effect that the mass of a bike has on a rider’s energy expenditure in relation to differing velocities and road grades. The subjects’ energy expenditure was measured by recording and analysing oxygen consumption; heart rate and RPE were also measured.

For testing, Berry et al. (2000) used a fully suspended, Trek Y-22 with a single swing arm pivot suspension design consisting of a spring and oil damper. The subjects used for this study consisted of eight males and one female, yet in contrast to Berry et al’s (1993) study, all of the subjects in Berry et al’s (2000) study were avid off-road cyclists. This is beneficial to this form of testing as all subjects would be familiar with mountain bikes and the different techniques involved in mountain biking, thus helping to reduce any potential bias in results.

In contrast to Berry et al's (1993) research, Berry et al's (2000) study used a sub-maximal test - that is when a subject's performance is incrementally increased until fatigue. The tests were conducted on a treadmill with one 44.5 cm by 3.8 cm by 8.9 cm long wooden bump and, as in the previous study, were attached to the belt using duct tape. This form of treadmill testing will once again however, present the same set of issues and concerns as discussed in relation to Berry et al's (1993) study. On the initial visit subjects were instructed to cycle at 3.1 m/s (7 mph) and at a grade of zero percent; the speed then increased incrementally by 1 mph each minute thereafter until the subjects reached a speed of 5.8 m/s (13 mph). The grade was then increased by 1 % each minute thereafter until volitional fatigue was reached.

On subsequent visits, subjects completed a maximum of nine experimental trials encompassing three bike masses (11.6 kg; 12.6 kg; 13.6 kg), three speeds (2.7 m/s; 3.6 m/s; 4.5 m/s) and three grades (0 %; 2.5 %; 5 %). These tests were carried out in a randomised order; an aspect of testing which differed from Berry et al's (1993) study, where testing was carried out in only two orders. Berry et al. (2000) opted for a randomised sequence of testing in their later study in order to reduce bias from their results. Similar to Berry et al's (1993) study, the subjects were asked to cycle on the treadmill until they felt comfortable riding under these conditions. Again, this presents the same concerns as Berry et al's (1993) previous study as some subjects may have had more time to familiarise themselves with this form of testing, thus generating possible bias in results.

As expected, Berry et al's (2000) results found that a subject's energy expenditure, heart rate and RPE increased significantly with each increase in velocity and grade. However, the most significant finding of the results was that on examining the effect of bike mass on energy expenditure, heart rate and RPE, no significant differences were found between the three different bike masses. This result is surprising as an increase in weight should present a rider with an increased disadvantage when riding uphill due to increased rolling resistance and forces due to gravity. In supporting this view, Howe (1995) states that the reduction in the mass of a bicycle should significantly improve uphill cycling performance. One possible explanation for this unexpected finding of Berry at al. (2000) is that testing on a treadmill is unnatural and unfamiliar to the majority of subjects and may consequently affect results. Another possible reason for this result, which Berry et al. (2000) stipulate, is that the expected difference between the different bike masses is smaller than the average measurement area expected when measuring oxygen consumption (Howley et al., 1995). Berry at al. (2000) highlighted that the apparatus used for testing was not sensitive enough to measure the differences between bike masses; one solution would be to take additional measurements, such as the amount of power transmitted through the pedals and the time taken to complete a set distance, in order to establish if a difference between the bike masses can be found using these measurements.

Similar to Berry et al. (1993 & 2000), Nielens & Lejeune (2001) also investigated rider-induced energy expenditure under laboratory controlled conditions. One significant difference between the two studies however, was Nielens & Lejeune's (2001) use of an electromagnetically braked cycle ergometer (Tacx®, model Cycleforce Excel) as a means of testing. As bumps can not be attached to an ergometer, as they can on a treadmill, the terrain-induced energy expenditure for the subjects in Nielens & Lejeune's (2001) study could not be ascertained.

Nielens & Lejeune (2001) used only one mountain bike during testing: an FRM® Be Active fully suspended mountain bike with a four-bar linkage system. Both the front and rear suspension systems had oil/air shock absorbers. This study compared a fully suspended mountain bike to both a hardtail and rigid bike; the suspension system of the FRM® Be Active mountain bike was replaced with custom made rigid elements to create each type of suspension system. By using only one model of bike this ensured that bike weight was not a factor taken into account throughout testing and that only the difference between the types of suspension system were evaluated.

The use of ergometers as a form of testing mountain bikes has both benefits and drawbacks. In comparison to cycling on a treadmill, ergometers are a safer mode of testing as the bike is held rigid at the rear wheel hub ensuring that the bike remains stable. The use of an ergometer ensures that a rider's upper body movement is kept to a minimal and that the rider does not have to balance the bike; thus isolating the pedalling movement, ensuring that this is the only factor measured during testing. Kooijman et al. (2009) observed that during normal cycling riders do not lean their upper body to balance the bike; this is done using steering control. Another distinct advantage to this mode of testing is that subjects may be familiar with ergometers as they are often used for training purposes, consequently, as was the case with Nielens & Lejeune's (2001) subjects, no familiarisation of cycling on the ergometer was required prior to testing.

Although treadmills have, as highlighted by Berry et al. (1993 & 2000), several drawbacks when used as a form of testing mountain bikes, in comparison to ergometers, they give a truer representation of the conditions encountered when riding on an outdoor trail. Ricci & Leger (1983) support this view, stating that bicycle ergometer tests might not be specific enough to evaluate the ability of trained cyclists performing an endurance or aerobic task as they appear to achieve higher $VO_2$ on the bicycle ergometer compared to the treadmill; the dynamics of which, as previously outlined by Kooijman & Schwab (2009), match that of riding outside on flat level ground.

An additional drawback of using Nielens & Lejeune's (2001) ergometer as a mode of testing mountain bikes is that as it does not allow the use of the front wheel during cycling, it does not give a true representation of mountain biking. Additionally, as no bumps or grade can be applied to the ergometer, only riding on a smooth, flat road can be represented; this limits the results which can be obtained as no comparisons can be made to cycling uphill or cycling on a rough track. A further aspect to consider is that the use of ergometers makes standing on the pedals whilst riding impossible; however, Nielens & Lejeune (2001) justify this, maintaining that during mountain biking, riders rarely stand on the pedals because of the loss of traction of the rear wheel in that position, thus giving a justification for the rider remaining in a seated position for the duration of the tests.

Nielens & Lejeune's (2001) study comprised of 12 competitive racers who were asked to undergo a maximal test of three 15 min exercise tests of increasing workloads; this workload increased in 3 min stages starting at fifty Watts and increasing by fifty Watt increments until a level of 250 W was reached (Nielens & Lejeune, 2001). As with Berry et al's (2000) study, the subjects were randomly assigned the order in which they rode the bikes, thus ensuring that any bias with results was eliminated. During testing the subjects' maximal oxygen uptake ($VO_2$) and carbon dioxide production ($VCO_2$) was measured and from both these measurements the respiratory gas exchange ratio (RER) was obtained. The subjects' heart rates were also recorded throughout the test. In contrast to Berry et al's (1993 & 2000) research, Nielens & Lejeune's (2001) did not measure the subjects' RPE; something which may have been valuable to the research as RPE results could be compared to the other obtained results. McArdle et al. (2001) assert that RPE is an indication as to how hard a person feels they are exercising; this is important as it reveals rider opinion.

The results of Nielens & Lejeune's (2001) test concur with those found by Berry et al. (1993) and Wang and Hull (1996): All found that there was no significant difference between suspension systems in regards to the amount of $VO_2$ and heart rate measured when cycling on a flat surface. One noticeable difference to these latter tests however, was that Nielens & Lejeune's (2001) study was a maximal test. The power output from Berry et al's (1993) test was approximately

100 W, whereas that of Nielens & Lejeune's (2001) was increased incrementally until a power of 250 W was reached. The reason given for having a limit of 250 W was to ensure that $VO_2$ uptake would reliably reflect the energy expended by the subject even in the last stage of the test, and also to minimise the effects of fatigue as each subject had to undergo three tests during the same session. Despite this justification, Nielens & Lejeune (2001) highlight that having a limit on the power output may present a limitation to the study as some riders may, in a real-life race situation, exceed a power of 250 W.

Interestingly, despite Nielens & Lejeune's (2001) decision to use a higher power output for their tests, both Berry et al's (1993) and Nielens & Lejeune's (2001) experiments obtained similar results; therefore, both results indicate that there is no difference between riding on a flat surface using either a fully suspended, a hardtail or a rigid frame mountain bike. As discussed previously, this finding may have arisen as a result of the equipment used being unable to detect the small variation between results. In order to address this issue, the power the rider exerts on the pedals could additionally be measured and compared to the physiological findings; this may highlight slight differences between the three types of suspension systems which the measurements of $VO_2$ uptake and heart rate were unable to detect. In order to further support or disprove Nielens & Lejeune's (2001) findings, it would be beneficial to record any movement that occurred in the suspension systems whilst the subjects were cycling. This would highlight any bobbing motion that occurred and establish if any power was lost to via the suspension system. Berry et al. (1993) observed suspension motion by visual inspection with the use of a video camera, capturing any possible movements at the rear suspension. The use of a video camera presents limitations as small displacements in the rear suspension cannot be detected. One way of addressing this is through the use of accelerometers which accurately measure any slight movements at the point which they are placed on a bike.

Titlestad et al. (2006) carried out a similar study to Nielens & Lejeune (2001). The aim of Titlestad et al's (2006) study was to compare the physiology and psychological responses of cyclists riding on a hardtail and fully suspended bike on level surfaces, with and without bumps. Similar to Berry et al's (1993 & 2000) and Nielens & Lejeune's (2001) studies, Titlestad et al. (2006) carried out tests in a laboratory setting. A laboratory-based test was chosen so that the actions of the rider (such as standing up out of the saddle) could be controlled, while the dynamics of the bicycle-suspension-rider system could be simulated as closely as possible and physiological, psychological and dynamic measurements could all be recorded. As this research carried out tests on both a flat surface and on a surface with bumps on a specifically designed rig, both the terrain and rider induced losses were investigated.

Titlestad et al. (2006) were the first researchers to adopt the use of a rig as a form of testing mountain bikes. The test rig was designed to isolate the rear wheel dynamics of the mountain bike, thus no front wheel was incorporated into the design; instead front forks were held in position by a front bracket. The rig was designed so that the rear wheel of the mountain bike would drive a heavy roller. In order to recreate a rough riding surface two bumps, each 30 mm high and 70 mm long, were added to the roller. During the flat surface tests a weighted friction belt was wrapped over the roller to provide an equivalent resistance to that of the bumps. This roller was designed to match the inertia of a cyclist when riding outside; a design feature which ensures that the force required to decrease the bikes velocity is equivalent to that of riding outside. Fregly et al. (2000) highlight the importance of this maintaining that where crank kinematic variations are important, (as in the investigation of mountain bike suspension systems) inertial effects may influence test results.

Titlestad et al. (2006) advocate the advantage of using such a rig over treadmill testing, stating that trials on a standard powered treadmill have limitations because the inertia effects are not accurately simulated and the rider must exert considerable control simply to keep the bike on the treadmill. This innovative approach to testing also has the added advantage of reducing the safety risks to subjects. Cycling on a treadmill with a mountain bike can often be a stressful task and potential affect the physiological results (Titlestad et al., 2006).

Two mountain bikes were used for the study: the fully suspended Marin Mount Vision with single-swing arm rear suspension design and oil damped coil spring rear and front suspension system; and the hardtail Marin Rocky Ridge mountain bike with the same front suspension as the Marin Mount Vision. Using two different types of mountain bike presents the problem of weight being an additional factor that must be taken into account, however if what Berry et al. (2000) concluded is accurate - that weight does not affect energy expenditure - then this should not have affected Titlestad et al's (2006) results.

Similar to Berry et al's (1993) study, Titlestad et al's (2006) tests were also set at a sub-maximal level where the physiological variables could be shown to have stabilised. The subjects were asked to cycle at a speed of between 10 km/h and 15 km/h that could be maintained comfortably for ten minutes; this speed was maintained for all subsequent tests. 20 male participants undertook two different series of tests. The first test series consisted of each of the 8 participants cycling on both the fully suspended and hardtail mountain bike on both the smooth surface and on the surface with bumps attached. The second test series consisted of six subjects cycling on both the fully suspended and hardtail mountain bike, but only on the surface with bumps attached. Additionally, in the second series of tests, six subjects were tested repeatedly on the same bike on the surface with bumps attached to discover if there was a familiarisation effect to riding on the rig. As with Berry et al's (2000) and Nielens & Lejeune's (2001) studies, the subjects of Titlestad et al's (2006) test were randomly assigned the order in which they rode the bikes in order to eliminate any bias in results.
Each participant of the experiment undertook one familiarisation session prior to testing in order to become accustomed to cycling under the test conditions. In

this respect, the use of a rig provides an advantage over the treadmill as a means of testing as fewer practice sessions are required prior to testing.

As with Berry et al's (1993) & (2000) and Nielens & Lejeune's (2001) tests, all of the participants of Titlestad et al's (2006) tests were to remain seated for the duration of the test. This was to ensure that the rider's movement was minimal and would not affect the test results. Ryschon & Stray-Gundersen (1991) found, in their study on the effect of body position on the energy cost of cycling, that there is a notably higher oxygen uptake in standing compared to seated cycling, concluding that seated cycling is metabolically more efficient than standing cycling.

The physiological and psychological factors measured in Titlestad et al's (2006) test were $VO_2$, heart rate, RPE and comfort rating of the rider. This study has a distinct advantage over Berry et al's (1993) & (2000) and Nielens & Lejeune's (2001) studies in that the additional psychological measurement of rider comfort was assessed; this provides valuable information which can be compared and contrasted to the other results.

The results of Titlestad et al's (2006) study found that the amount of $VO_2$ measured was slightly lower for subjects cycling on the hardtail mountain bike compared to the fully suspended bike on the roller with no bumps; thus illustrating that this type of fully suspended bike expends more of a cyclist's energy than this type of hardtail bike. There was also a trend for the RPE and the heart rate of a rider to be higher, and the comfort rating to be lower, when riding on the fully suspended bike on the surface with no bumps. These results conflict with the studies carried out by Berry et al. (1993) and Nielens & Lejeune (2001), whose results both showed that there was no significant difference between riding a fully suspended or a hardtail bike whilst cycling on a flat surface with no bumps. A possible explanation for the differences in results could be a result of the type of rear suspension that was chosen for the studies. Nielens &

Lejeune (2001) used a four-bar linkage rear suspension design for their study, whereas Titlestad et al. (2006) used a single swing arm rear suspension design. Despite this, Berry et al. (1993) also used a single swing arm rear suspension design and found similar results, in relation to the energy expended whilst cycling on a flat surface with no bumps, to those of Nielens & Lejeune (2001), thus suggesting that the type of rear suspension design used does not significantly influence results.

Another possibility for the conflicting results of Titlestad et al. (2006) and those of Berry et al. (1993) and Nielens & Lejeune (2001) may be a direct result of the form of testing used. The numerous drawbacks that have been highlighted and discussed previously regarding the use of treadmills and ergometers as a mode of testing mountain bikes may be one reason that Berry et al. (1993) and Nielens & Lejeune (2001) found no difference, in terms of energy expenditure, between cycling on the fully suspended mountain bike compared to the hardtail and rigid frame bike on a flat surface with no bumps. As Titlestad et al's (2006) rig was specifically designed for testing mountain bikes this could explain why differences between the suspension systems were recorded.

Titlestad et al's (2006) decision to use two different types of mountain bike presents a further possible reason for their finding that when cycling on a hardtail bike, compared to a fully suspended bike, a lower $VO_2$ ratings were recorded. This result could relate to the issue of bike weight and its effect on rider performance. The hardtail mountain bike used in Titlestad et al's (2006) study was 2.2 kg lighter than the fully suspended mountain bike which may account for the difference in the amount of $VO_2$ measured when cycling on the two different types of bike. Kyle (1990) noted that during competitive road cycling the addition of as little as 1 kg to the mass of a bike on flat terrain could decrease bike speed due to an increase in rolling resistance. Although Kyle (1990) found this for road cycling if the same is true for off-road cycling, in order to maintain the same speed that was required for Titlestad et al's (2006) test, a subject would have to use more energy whilst cycling on the fully suspended bike compared to the hardtail bike. Conversely, Berry et al's (2000) study found that weight had no effect on rider energy expenditure which would disprove the theory that Titlestad et al's (2006) findings were influenced by bike mass.

Through analysis of Titlestad et al's (2006) results of the tests carried out on the surface with bumps, it was found that the measurements of $VO_{2,}$ heart rate and RPE for all subjects (with the exception of one value for RPE) riding the hardtail bike were higher than when riding the full suspension bike. Comfort levels were recorded to be either the same on both bikes or better whilst cycling on the full suspension bike. These results indicate that the fully suspended bike gives an advantage to a rider, when cycling on a bumpy track, as less energy is expended and comfort is rated higher. Despite the fact that Berry et al. (1993) conducted tests on an uphill bumpy track, their findings, that a fully suspended bike can decrease energy expenditure over rough terrain, concur with those of Titlestad et al. (2006).

Titlestad et al. (2006) recognised a limitation of their research, stipulating that the roller with bumps simulating a rough track was unrealistic as the bumps and their frequency were particularly high. Such a track is unlikely to be encountered by a mountain biker as it is highly likely that such bumps would either be avoided or the rider would rise out of the saddle to alleviate their impact.

Although Berry et al. (1993 & 2000), Nielens & Lejeune (2001) and Titlestad et al. (2006) found some significant results based on their indoor laboratory tests, further outdoor field testing would be beneficial to either validate or challenge findings. One such researcher who adopted this form of field testing was Seifert et al. (1997), who were one of the first researchers to consider the effects of mountain bike suspension systems on energy expenditure in a field test environment. Seifert et al. (1997) looked at both terrain and rider-induced energy losses, carrying out two tests on a flat looped course. The course was built on a hard, level ground on which forty-five bumps, of a height and width of 5 x 10 cm, were placed. The test participants were instructed to cycle at velocity of 16.1 km/h for a time period of 63 min for phases 1 and 2. 3 bikes were tested and compared during the study: a rigid frame and hardtail bike, both of unspecified make and model; and a Specialized Stumpjumper fully suspended bike. Both the hardtail and fully suspended bike had an air/oil front suspension system. The rear suspension system comprised of a spring/oil suspension system with a four-bar linkage design.

Their research was divided into three phases - the first of which was completed by twenty subjects who were randomly assigned to ride around the track on one of the three bike types. In contrast to the previous studies of Berry et al. (1993 & 2000), Nielens & Lejeune (2001) and Titlestad et al. (2006) - all of whom tested each subject on all of the different types of suspension systems to compare similarities and differences between them - Seifert et al's (1997) first phase test allowed the subject to ride on only one of the three types of bike. Although the subjects were matched by riding ability and body weight, due to the differing physiologies of each individual, a correlation between results would be difficult to establish. The only measurement taken during phase one was the 24 h change in creatine kinase (CK), measured by assessing the muscular stress of each subject. Intense or repeated muscular contractions have been shown to increase the amount of trauma/damage to the myofibrils thereby increasing CK release (Clarkson et al., 1985). Obtaining additional physiological measurements would have been beneficial during Seifert et al's (1997) tests as it would have allowed comparisons, with the results found from the change in CK, to be made.

Only twelve of the twenty subjects who completed Seifert et al's (1997) first phase test also completed the second phase test. The cycling protocol for the second phase test exactly matched that of the first, except for one distinct difference; during the second phase test all subjects rode on all three of the different bikes. During the second phase test, the physiological factors $VO_2$ and heart rate were measured in addition to the psychological factors of RPE and comfort rating.

For the final phase of the study, seven riders completed three separate time trails for each of the suspension systems. The protocol for this final set of tests differed from the first and second phase tests. The final phase consisted of a climbing time trial (0.76 km); a descending time trial (0.76 km); and a cross country time trial (10.44 km). The uphill and downhill time trials were performed on the same single track course which had a vertical rise of 61 m. After a rest period of 45 min, the riders then completed four laps of the cross country time trial which consisted of a 2.61 km loop.

The results for Seifert et al's (1997) phase one test showed that the mean change in CK was statistically greater for the rigid frame bike and no statistical difference was observed between the full suspension and hardtail bike (Seifert et al., 1997). As expected, these findings illustrate that greater muscle trauma, and consequently an increase in heart rate, results from cycling on a rigid frame bike, indicating that the full suspension and hardtail bike have a distinct advantage to a rider whilst cycling over rough terrain.

The phase two test results are more comparable to those of Berry et al. (1993) and Titlestad et al. (2006) as similar physiological parameters were collected. Seifert et al's (1997) measurements of heart rate for the phase two tests coincide with those from the first phase test: the riders' heart rates were considerably higher when cycling the rigid frame bike compared to the fully suspended and hardtail bike. There was however, no difference recorded between the heart rates for cyclists riding on the hardtail and fully suspended bike on rough terrain.

To some degree, Seifert et al's (1997) phase one and two results coincide with those found by Berry et al. (1993), who also found that mountain bikes with a suspension system have an advantage over rigid frame bikes when used on bumpy terrain. However, in contrast to Seifert et al's (1997) results, Berry et al. (1993) and Titlestad et al. (2006) both established that there was a significant gain, in terms of energy expenditure, to a rider using a fully suspended bike over a hardtail bike.

Unexpectedly, no statistical differences were observed in Seifert et al's (1997) phase two test for measurements of $VO_2$ between any of the three bike types. These results conflict with those of Berry et al. (1993) and Titlestad et al. (2006), whose results both found that the amount of $VO_2$ measured was lower for subjects riding on the fully suspended bike compared to the other suspension types, when riding over rough terrain. Berry et al. (1993) also found that a subject's $VO_2$ was lower when riding on a hardtail bike compared to a rigid frame bike.

Similar to Seifert et al's (1997) findings for $VO_{2,}$ the results for RPE showed that, although the fully suspended bike had a slightly lower RPE rating than the hardtail, no statistical difference was measured; the results for RPE for the rigid frame bike are however, significantly higher than both the other bike types. These RPE results also conflict with the findings of Berry et al. (1997) and Titlestad et al. (2006), who both found that RPE was significantly higher for a hardtail bike over a fully suspended bike. Despite the fact that all three tests were carried out on a bumpy course, one possible explanation for the variation in Seifert et al's (1997) results is that this experiment was conducted on an outdoor track. Prins et al. (2007) support this theory, asserting that no significant relationship could be found between their experiment on outdoor performance with the laboratory tests.

The final measurement taken during Seifert et al's (1997) phase two test was the comfort level of each cyclist. This comfort scale was identical to the one used by Titlestad et al. (2006) and similar results were obtained: the fully suspended bike was perceived to be the bike that offered the most comfort, followed by the hardtail bike and finally the rigid frame bike - which cyclists perceived to be the least comfortable bike to ride. These results are to be expected as suspension systems are designed to dissipate terrain induced energy and improve comfort for the rider (Olsen, 1996).

The phase three results showed that no differences were observed for heart rate whether ascending, descending or riding on a cross-country course. Cyclists riding the hardtail bike completed the cross-country course in a faster time compared to those who rode the rigid frame or fully suspended bike, which may account for why many mountain bikers still use bikes with front suspension only. Nielens & Lejeune (2004) support this, maintaining that in cross-country racing, most competitors still ride front-suspended bikes claiming that rear suspensions generate too much energy loss on most racecourses.

It could be maintained that Seifert et al's (1997) study is the closest representation of true race conditions as testing was conducted on both a bumpy track and a cross-country course. However, the results of the study differ significantly from the results obtained from the tests carried out by Berry et al. (1993) and Titlestad et al. (2006) - both of whom conducted tests on bumpy courses under laboratory conditions. In order to investigate and evaluate any possible reasons for these differences in results, it is advantageous to investigate similar outdoor studies so that comparisons and contradictions can be made; MacRae et al. (2000) also conducted outdoor field tests, comparing results in order to establish if riding either a hardtail or fully suspended bike had an effect on the physiological responses of a cyclist.

Initially, MacRae et al. (2000) carried out a laboratory test with six male, sub-elite mountain bikers with the aid of an ergometer. This was simply to establish the peak anaerobic power and $VO_2$ of each cyclist so that these could be compared to the experimental trial results. The same six subjects then undertook outdoor tests cycling on both a hardtail and fully suspended bike. The hardtail and fully suspended bikes used in the tests were manufactured by Specialized with Rock Shox Indy front forks (models not stated). The rear suspension system on the fully suspended mountain bike had a four-bar linkage system with a Rock Shox Deluxe rear-shock absorber.

Similar to Titlestad et al. (2006), MacRae et al. (2000) did not study the effect of energy losses on cyclists riding on rigid frame bikes, specifying that the majority of mountain bikes produced at present are manufactured with a front suspension system. This statement is even more apparent in the mountain biking industry today as all cross-country mountain bikes are equipped with a front suspension system; this would present as a valid reason for omitting tests using rigid frame bikes.

MacRae et al. (2000) carried out two tests: the first phase test consisting of cycling uphill on a flat, 1.62 km, asphalt course (14.2 % grade) and the second consisting of cycling uphill on an off-road, 1.38 km long course (11.3 % grade). The subjects were instructed to cycle as fast as possible at an intensity similar to that encountered in typical race conditions. All six cyclists rode on both the hardtail and fully suspended bike during each phase and in order to prevent any bias in results all cyclists completed the tests in a randomised order.

Issues and concerns which arise from MacRae et al's (2000) form of testing relate to when the experiments took place; track conditions; the speed maintained by cyclists; and riding style. Phase two of the experiment was carried out exactly one week after phase one, during which time weather conditions could have affected the course and consequently the cyclists' performance, thus making it increasingly more difficult to compare results. Kooijman et al. (2009) highlight this in their literature, specifying that when riding a bike outside, the bicycle-rider system encounters numerous external disturbances such as wind and road unevenness. This may account for researchers (Berry et al., 1993; Berry et al., 2000; Nielens & Lejeune, 2000; Titlestad et al., 2006) preferring to test under laboratory conditions. Exact conditions of testing are also difficult for each of MacRae et al's (2000) subjects to recreate as some subjects will ultimately choose different routes on the courses than others. Additionally, it would be difficult to ensure that cyclists maintain a constant speed on both the hardtail and fully suspended bike in order for comparisons to be made. The riding style adopted by each cyclist also raises concerns as these may vary according to whether the cyclist stands or remains seated during the ascent; Harnish et al. (2007) maintain that seated cycling is more economical than standing when cycling uphill.

During both phases of the experiment, MacRae et al. (2000) measured the $VO_2$, heart rate and blood lactate of each subject on both the hardtail and fully suspended bikes. Unlike the previous studies (Berry et al., 1993; Berry et al., 2000; Nielens & Lejeune, 2000), MacRae et al. (2000) also measured the amount of power transmitted through the pedals, in addition to pedal cadence, with the aid of an SRM Training System (Schoberer Rad Messtechnik, Welldorf, Germany). Although Titlestad et al. (2006) also measured pedal cadence and the power transmitted through the pedals, the device used for the measurements in Titlestad et al's (2006) experiment was custom built for this specific purpose.

The results obtained from MacRae et al's (2000) tests on a flat, uphill course coincide with Berry et al's (1993) and Seifert et al's (1997) tests, also conducted on an uphill, flat course. All three researchers found that no significant physiological difference was measured for cyclists whether riding on a hardtail or fully suspended bike when cycling uphill on a flat course. These results are surprising due to the fact that, as aforementioned, researchers (Kukoda, 1992; Wang & Hull, 1994) have stated that a bobbing effect is apparent when riding a fully suspended bike uphill which may consequently contribute to a rider's loss of energy. Additionally, cyclists who completed the questionnaire (Appendix A) agree with this: seventy-six percent of respondents stated that they felt a bobbing effect when cycling uphill on a fully suspended bike. A reason for the results obtained by Berry et al. (1993), Seifert et al. (1997) and MacRae et al. (2000) cannot be attributed to the type of suspension system used as Berry et al. (1993) used a single-swing arm suspension design and both Seifert et al. (1997) and MacRae et al. (2000) used a suspension with a four-bar linkage design. The test conditions however, could contribute to the fact that no physiological differences were measured by Berry et al. (1993); Seifert et al. (1997) and MacRae et al. (2000) for cyclists riding either the hardtail or fully suspended bike uphill on a flat course - as previously discussed, the use of a treadmill or an outdoor cycling track can raise concerns when used as a form of testing mountain bikes.

MacRae et al's (2000) results for riding uphill on an off-road course correspond with the results obtained by Seifert et al. (1997), who also found that there was no significant difference between riding a fully suspended or hardtail bike on a bumpy course. However, both these findings differ from those obtained by Berry et al. (1993), who found that the cyclists' measurements of heart rate, $VO_2$ and RPE were lower whilst riding on the fully suspended bike, compared to the hardtail bike, on a bumpy track. One explanation for these differences in results is that Seifert et al. (1997) and MacRae et al. (2000) do not state how rough their uphill tracks are. This is an important factor to consider as the benefits of a fully suspended bike may not become apparent until a certain level of track roughness is reached. Berry et al. (1993) may have found that the fully suspended bike presented a physiological advantage to a cyclist riding uphill on a rough track as the bumps encountered were frequent and of a significant height to highlight differences between the hardtail and fully suspended bike.

MacRae et al's (2000) results for pedal cadence and velocity also found that there was no difference between the fully suspended and hardtail bike when riding uphill on either of the two surfaces. Conversely, the results obtained for power output conflict with the results obtained for the measurements of $VO_2$, heart rate and blood lactate. The power output results showed that a cyclist riding on a hardtail mountain bike used less power than on a fully suspended mountain bike when cycling uphill on both the asphalt and on the off-road course. MacRae et al. (2000) give an explanation for this stating that, although a cyclist had to generate a higher power output to cycle uphill on a dual suspension bike, that power was likely conserved by the rear suspension spring and, during rebound of the spring after compression, contributed to the forward momentum of the bike. This explanation is perhaps surprising as rear suspension systems are designed to absorb bump impact and not to propel a bike forward. Olsen (1996) identifies that a suspension system should absorb energy and shock from riding over rough terrain.

Similar to MacRae et al. (2000) and Seifert et al. (1997), Ishii et al. (2003) also carried out an outdoor trial test. However, Ishii et al's (2003) study extends the previous studies as laboratory tests on a treadmill were also completed and compared to the outdoor trail test. Ishii et al. (2003) was the first researcher to publish data comparing and contrasting these two forms of testing in relation to mountain bike suspension systems. This form of comparative testing is advantageous as it can highlight comparisons and differences through different forms of testing.

Ishii et al's (2003) laboratory test was carried out to establish if the energy losses due to the suspension system are rider induced. Treadmill tests were undertaken by five, well trained cross-country cyclists who raced at an intermediate level. The same fully suspended, single swing arm bike was used throughout all tests; a Y-33 Trek with a Strashock-Pro Stratos rear suspension system - which could be locked to replicate a hardtail mountain bike- and a Gravier-DH, SHOWA front suspension system. Both suspension systems consisted of a swing arm design with an air spring and an oil damper. By exchanging the front suspension system for a rigid fork and locking the rear suspension, the rigid frame bike was formed. Ishii et al's (2003) decision to use a rigid frame bike is perhaps surprising as previous researchers, namely McRae et al. (2000), did not use a rigid frame bike during testing as few mountain bikes today are manufactured without some form of front suspension system.

Each of the participants of the study cycled on all three of the different types of suspension systems in both a seated and standing position. Participants were instructed to cycle on the treadmill with no grade for three minutes at a speed of 250 m/min; all tests were carried out in a randomised order. Interestingly, Ishii et al. (2003) is the only researcher in this field who instructed subjects to ride on each type of suspension system in both a seated and standing position. This again contradicts the views of Nielens & Lejeune (2001), who stipulate that competitive cyclists do not stand when cycling, and who consequently chose not to include tests with subjects riding in the standing position in their studies.

Ishii et al. (2003) measured each subject's heart rate, $VO_2$ and RPE and data was collected from the last 30 s of the test. The results illustrated - coinciding with Berry et al. (1993); Nielens & Lejeune (2001); Titlestad et al. (2006) - that no significance difference was found between the three different types of suspension systems, whether cycling on the treadmill in either the seated or standing position. These results disprove the theory that rear suspension systems use up a rider's energy through rider-induced motion. Subsequent findings of the treadmill tests showed a significantly higher set of results for cycling whilst standing compared to cycling when seated. These results support Nielens & Lejeune's (2001) statement that riders do not stand whilst cycling.

For the second set of outdoor trial tests, Ishii et al. (2003) again used the same three types of suspension systems and make of bike as his initial set of tests. As this outdoor course consisted of a rough riding surface, both terrain and rider induced energy losses were measured. The rough course included both ascending and descending sections and cyclists were asked to complete it in as fast a time as possible; once again in a randomised order, riding on all three types of suspension systems on the same day. The drawbacks of this form of outdoor testing have been brought to light previously in this chapter.

During the outdoor tests, Ishii et al. (2003) measured each cyclist's heart rate, $VO_2$, blood lactate and time taken to complete each of the tests. One significant finding from the outdoor trial tests was that $VO_2$ was significantly higher for subject riding on the fully suspended bike compared to the hardtail and rigid frame bikes. These results conflict with those obtained by MacRae et al. (2000) and Seifert et al. (1997), both of whom found that there was no significant difference between the physiology of cyclists riding on either a hardtail or fully suspended system. The results of the outdoor trial tests also highlighted that the changes of blood lactate concentration were significantly higher for the subject cycling on the hardtail mountain bike compared to the rigid and fully suspended mountain bike. One possible explanation for the increased levels of blood lactate found when riding a hardtail bike is that the cyclists must work to support themselves using their arms and legs to absorb the bump impacts when riding over rough terrain (Burke, 1996). Ishii et al. (2003) suggests that a lower blood lactate accumulation is a better condition for cross-country race events, even though the fully suspended mountain bike requires greater energy consumption than the hardtail bike.

## 2.3. Mechanical Testing

In contrast to physiological testing, mechanical testing relates specifically to mountain bikes and their design. It involves measuring the structural loads and forces that act upon a bike, with an attempt to design bikes for optimal performance. At several points on the bike, force input is received from external sources. These points include: the front and rear axles, handlebar, saddle, front and rear brakes and pedals (Champoux et al., 2004). Additionally, internal forces act upon a mountain bike; these include chain forces; crank torque; suspension forces; inertial forces and forces acting on the frame. For the purpose of this current study, only literature relating to the forces acting on the bike due to suspension systems will be studied. Literature on the mechanical testing of mountain bikes was found to be limited; and that specifically relating to suspension systems was even more so.

An optimal suspension system should ultimately improve a cyclist's performance, yet it is apparent that there are no set criteria on how to maximise the benefits of a suspension system for cyclists (Hrovat, 1988; Hrovat & Hubbard, 1981; Karnopp & Margolis, 1984; Karnopp & Trikha, 1960; Pennestri & Strozzieri, 1988; van Vliet & Sankar, 1983). The mechanical literature reviewed in this research - Champoux et al., 2004; Karchin & Hull, 2002; Levy & Smith, 2005; Needle & Hull, 1997 - as with the literature on physiology, used two forms of testing: laboratory and field trials.

Needle & Hull (1997) carried out the mechanical testing of a mountain bike under laboratory conditions and, similarly to Berry et al. (1993 & 2000), used a treadmill as a form of testing. The aim of the research was to design and construct a dual suspension mountain bike with the same geometry as a Specialized M2 frame, with adjustable suspension characteristics. This enabled the optimal pivot point for this rear suspension design to be obtained in order to improve rider performance. As Wang and Hull (1996) demonstrated; pivot point height of a single swing arm rear suspension system can affect rider efficiency. Needle & Hull (1997) used a four-bar linkage design for testing, yet this is still considered a single swing arm design as the wheel is rigidly connected to the pivoting linkage (chainstay).

Needle & Hull (1997) studied rider induced energy losses and the effect this has on the rear suspension system only. Rigid links (instead of shock absorbers) were used in the front forks to isolate the effects of the rear suspension. The pivot point was located from the bottom bracket to 22 cm above the bottom bracket; the clamping mechanism used allowed the pivot point to be locked in 0.42 cm increments. Only one subject, who rode in a seated position on a smooth, inclined treadmill (six percent grade) at 23.3 km/h, was used for testing. Data was collected through the use of a linear motion potentiometer and a variable reluctance transducer and was analysed for an eight second period. This data consisted of magnitude and phase information collected from the crankset and the shock absorber; the amount of travel of the shock absorber; crank angle; and the shock displacement amplitudes. The results concluded that the optimal pivot point height was 8.4 cm above the bottom bracket, this gave the minimum energy loss from the rear shock absorber (Needle & Hull, 1997).

As discussed previously in the chapter, there are several issues and concerns which arise through using a treadmill specifically for the testing of mountain bikes and similarly, there are issues and concerns with the test procedure adopted. As only one subject was used during testing, no comparisons could be made to other cyclists and their riding styles. As riders are of different physical builds and adopt different riding styles, it is fair to stipulate that the optimal pivot point may differ for each one. Needle & Hull’s (1997) decision to use only one subject for testing differs greatly from researchers carrying out physiology testing where more than one subject was tested for comparison of results (Berry et al., 1993; MacRae et al., 2000; Nielens & Lejeune, 2004; Seifert et al., 1997).

Other aspects to consider in Needle & Hull’s (1997) study relate to the bike design and suspension system: the bike used for testing was constructed to replicate a Specialized M2 model, yet throughout the study no comparison was made to an actual Specialized M2 model. Comparisons would have been beneficial to validate both the bike design, and the results obtained through testing. Additionally, the dynamics of the bike were altered by removing the oil from the rear damper in order to lessen the damping effect and the front suspension system was locked out throughout the testing in order to isolate the rear suspension which, in turn, altered the mountain bike such that it did not truly replicate the dynamics of an actual Specialized M2 model rode by cyclists. Consequently, the results obtained only refer to a bike with rear suspension and no comparisons were made to a bike with a full suspension system. Berry et al. (1993) studied the effects of riding a mountain bike with rear suspension only, yet this study compared the results to those obtained from riding on a rigid frame, hardtail and fully suspended bike.

A further aspect to consider when evaluating Needle & Hull's (1997) findings is the result obtained for the optimal pivot point. This was concluded to be 8.4 cm above the bottom bracket on the seat tube of the mountain bike, yet as stipulated by Wang & Hull (1997); it is likely that the true optimum pivot point location does not lie directly on the seat tube. The form of testing undertaken by Needle & Hull (1997) is therefore limited in this respect, as an optimal pivot point cannot be obtained unless a different bike frame design is used.

The time period where data was collected highlights an additional aspect of testing that could be revised in Needle & Hull's (1997) study. Data was collected for a short period of 8 s only and it would have been advantageous to the study to conduct testing for a longer time period in order to gain average values to compare and contrast.

Karchin & Hull (2002), whose study is a variation of the research carried out by Needle & Hull (1997), additionally carried out mechanical testing. As with Needle & Hull's (1997) tests, controlled experiments were carried out under laboratory conditions with the use of a smooth treadmill (six percent grade), using the same bike designed and used by Needle & Hull (1997) in their experiment. The only notable difference was that the front suspension system was replaced with a RockShox Judy SL design which could also be locked. The aim of Karchin & Hull's (2002) study was to test two hypothesis: the first that interaction between the front and rear suspensions does not affect the action of the rear suspension, and hence determination of the optimal pivot point height; and the second that the optimal pivot point height is insensitive to pedalling mechanics in one posture (either standing or seated).

In contrast to Needle & Hull’s (1997) research, Karchin & Hull (2002) used eleven experienced subjects during the experimentation. Each subject carried out a total of seventy-two trials under four conditions, testing a total of eighteen pivot point heights from 5.04 to 12.18 cm above the bottom bracket. These four conditions consisted of cycling in a seated position with a locked out front suspension system; cycling in seated position with an active front suspension; cycling whilst standing with a locked out front suspension system; and cycling whilst standing with an active front suspension. Each subject cycled for a period of 30 s until a speed of 24.8 km/h was reached; this speed was maintained for a further 20 s and data collected for 14 s. As was the case in Needle & Hull’s (1997) study, data was collected using several transducers, linear potentiometers and an optical encoder.

The data was obtained by measuring the displacement of the front and rear suspension systems and the crank angle. On analysis of the data, Karchin & Hull (2002) found that the power loss, through the displacement of the front and rear suspension systems, was significantly lower when cycling in a seated position. Further results found that there was no interaction between the front and rear suspension systems and that the optimal pivot point height above the bottom bracket was 9.8 cm for a cyclist in a seated position. This result is interesting as it differs from that obtained by Needle & Hull (1997), who found the optimal pivot point to be 8.4 cm above the bottom bracket. It could be maintained that Karchin & Hull’s (2002) result holds more validity as eleven subjects were used for testing, enabling an average value to be calculated.

Karchin & Hull’s (2002) final test result showed that the optimal pivot point for a cyclist in a standing position was lower than that of a cyclist in a seated position; a value of 5.9 cm was obtained as optimal pivot point height for a cyclist riding in a standing position. A possible reason for the different values obtained for optimal pivot point height between a seated or standing cyclist could be explained by the increase in crank torque when standing during cycling (Stone & Hull, 1993). This could also be explained by the different inertia loads encountered by cyclists in either two of the riding scenarios. As a significant difference was found between the optimal pivot point heights during cycling whilst either sitting or standing, a decision on which height would be most beneficial to a rider must be reached. As Tinaka et al. (1996) maintain that the majority of uphill cycling is carried out by cyclists riding in a seated position (due to the energy expenditure of the cyclist being lower under this riding condition) it is logical that the optimal pivot point height for this position would be chosen for a rear suspension design.

As Karchin & Hull's (2002) study was a continuation of Needle & Hull's (1997), the same issues and concerns remained apparent for the former experiment. Karchin & Hull (2002) did, however, address some of these issues and concerns in their research to provide more comparable data. One significant difference was the decision to use eleven subjects for testing as opposed to Needle & Hull's (1997) use of only one subject. Additionally, Karchin & Hull's (2002) tests were carried out for a slightly longer time period and data collected for 14 s. Although this 6 s increase on Needle & Hull's (1997) duration for data collection enabled more data to be compared, it could be argued that it would be advantageous to increase this further so as to establish if changes occur over a greater time scale.

As with the studies relating to the physiology aspects of mountain biking, mechanical testing can also be undertaken outdoors under field conditions. By comparing results between both laboratory and field tests, differences and similarities can be highlighted and discussed. Levy & Smith (2005) are two such researchers who conducted their experiments in an outdoor environment. The aim of their research was to describe the damping effectiveness patterns associated with various suspension forks over different surface conditions. Five different suspension system combinations were used during the experimentation and were compared to results obtained from a rigid frame bike. Three different types of front suspension were tested: an air-oil, elastomer and a linkage design. Further testing was then carried out using an air-spring rear suspension system along with the air-oil and linkage front suspension system. No indication was given as to why no further testing was carried out with the elastomer front suspension system and the air-spring rear suspension system. The make and model of bike used during the testing also remained unspecified.

As with Needle & Hull's (1997) mechanical research, Levy & Smith (2005) opted to use only one subject for testing; an issue which, as aforementioned, may present areas of concern for the validity of results. The test consisted of the subject riding under two outdoor conditions: one on coarse gravel and the other on hard-pack dirt. Both courses were flat and had a ten centimetre bump placed at the end of the tracks. Testing involved cycling on each track at a speed of 6.5 to 7 m/s and the sequence of the five suspension system combinations and one rigid frame test was randomised for each of the two surface conditions. The subject was instructed to ride passively over the trail or gravel slightly elevated out of the saddle. This instruction appears to be ambiguous as riding in a passive manner suggests cycling whilst in a seated position. Consequently, as there would be no means by which to control the distance the rider stands from the saddle in each of the tests, this would present an uncontrollable variable in the experiment and thus results may be affected.

Levy & Smith (2005) used accelerometers placed at the front wheel hub and the top of the head tube to measure the vibrations at the wheel and on the frame of the bike. The results from the accelerometers found that the gravel track produced higher frequency accelerations than the dirt track. This result is to be expected as a gravel track normally consists of a higher frequency of smaller bumps compared to a dirt track made up of bigger, smoother bumps.

Further results gained from the accelerometers demonstrated that the air/oil suspension system, both with and without the rear suspension, was more effective at reducing vibration than the other suspension designs. However, as this study only investigate vibrations occurring at the front wheel and at the head tube, it is unknown which system is most effective for reducing vibration at the rear of the bike. Further studies, which could be carried out by placing accelerometers at the rear hub and seat of the bike, would provide useful data to establish which system is most effective at reducing vibrations at the rear of the bike.

Similar to Levy & Smith's (2005) research, De Lorenzo & Hull (1999) also carried out mechanical research on mountain bikes using outdoor field trials as a mode of testing. De Lorenzo & Hull's (1999) methodology of study involved quantifying the terrain-induced loads acting on a bike caused by surface irregularities. As the test trials were carried out with subjects maintaining a standing position with the crank arms of the bike in a horizontal position, rider-induced loads due to pedalling were not investigated in the study. This is in contrast to other researchers in this field: Berry et al. (1993); Berry et al. (2000); Karchin & Hull (2002); Levy & Smith (2005); MacRae et al. (2000); Needle & Hull (1997); Nielens & Lejeune (2001); Seifert et al. (1997); Titlestad et al. (2006) - all of whom undertook tests where subjects were required to pedal.

In contrast to Needle & Hull's (1997) and Levy & Smith's (2005) studies, De Lorenzo & Hull (1999) used more than one subject for experimentation. Seven experienced cyclists were requested to undertake two trials on a rough, downhill track with an 8% slope at speeds of 22 km/h to 32 km/h: one on a fully suspended mountain bike and one on a hardtail mountain bike. The bike used during the experimentation was a fully-suspended, FSR Specialized mountain bike with a four-bar linkage rear suspension design which could be locked to form a hardtail mountain bike. Each of the 7 subjects were allowed one practice on the course prior to testing in order to familiarise themselves with the track.

Each subject was instructed to ride both mountain bikes in a randomised order, during which time mechanical measurements were taken. These included the pedal force - measured using a dynamometric pedal; forces at the front and rear hub - measured using dynamometric hubs; brake forces - measured using strain gauges; bicycle speed - measured using transducers; rotation speed of the rear wheel - measured using an infrared emitter and detector; and handlebar forces. The total time for sampling for each rider was 60 s, which consisted of two thirty second trials (De Lorenzo & Hull, 1999). This is a relatively short time scale in which to collect data, however it is a longer duration than that used by Needle & Hull (1997) and Karchin & Hull (2002), who collected data for 8 s and 14 s respectively.

De Lorenzo & Hull's (1999) decision to use more than one subject for testing was similar to Karchin & Hull's (2002). Karchin & Hull (2002) used eleven subjects for testing, thus allowing an average value for the optimal pivot point of a single swing arm rear suspension system to be obtained. Karchin & Hull's (2002) optimal pivot point value however, differed from that one obtained by Needle & Hull (1999) who undertook the same test as Karchin & Hull (2002) but used only one subject. As previously discussed, it could be asserted that Karchin & Hull's (2002) findings have greater validity as more subjects were used during testing. If this is the case, it could, therefore, also be concluded that De Lorenzo & Hull's (1999) results will also hold more value as more than one subject was used and averages were recorded.

In contrast to Needle & Hull (1997), Karchin & Hull (2002) and Levy & Smith (2005) - the former two having carried out cycling tests uphill and the latter having carried out tests on level ground - De Lorenzo & Hull (1999) investigated the effects of suspension systems whilst cycling downhill. De Lorenzo & Hull (1999) are one of the only researchers to compare the mechanical effects of a fully suspended and hardtail mountain bike whilst riding downhill. A possible reason for the limited number of studies that are carried out comparing these two types of suspension system whilst cycling downhill is perhaps due to the fact that it is undisputed that cycling downhill on a fully suspended mountain bike, compared to a hardtail bike, provides more benefits to a rider. This is highlighted by Nielens & Lejeune (2004) who state that the numerous advantages of a fully suspended bike (improved comfort, bike handling, improved cornering, braking capacity, bike control and traction) explain why all downhill mountain bike racers use front and rear suspension systems that allow much higher downhill speeds. If this is the case then it can be assumed that De Lorenzo & Hull (1999) will also find that the fully suspended bike is more effective when cycling downhill. De Lorenzo & Hull's (1999) study is however, still important in order to highlight the load differences between the two types of suspension system.

The most significant results obtained from De Lorenzo & Hull's (1999) study indicated that the use of the rear suspension led to significant reductions in the dynamic loading at the rear tyre. This was also evident in other components of the bike where loads were measured; all of the loads in the horizontal plane for the fully suspended bike - with the exception of the front wheel load - showed a reduction in dynamic loading. As previously discussed these results were expected - a point certified by De Lorenzo & Hull (1999) in their literature. Issues and concerns which arise from De Lorenzo & Hull's (1999) test protocol include their decision to instruct subjects to coast downhill without the use of pedals. This is an unrealistic representation of true race conditions as it would be uncommon for a cyclist to ride for the full duration of a downhill track without using pedals. Adversely, conducting tests under these conditions allowed terrain-induced loads to be investigated independent of the rider-induced loads which affect the dynamics of a suspension system. Although the results from the tests were expected, the research is interesting as they are one of the only researchers to have studied the mechanical effects of terrain-induced loads only on a fully suspended and hardtail bike.

De Lorenzo & Hull's (1999) methodology imposed yet another restriction on subjects - the cyclists were to remain in a standing position for the duration of the tests. This does not truly represent race conditions as cyclists on a fully suspended bike may choose to remain seated for part of their descent. In order to validate results and provide data from which to compare and contrast, De Lorenzo & Hull (1999) may have benefited from conducting further tests with subjects being allowed to either remain seated or to cycle whilst standing. .

## 2.4. Simulation Testing

Wang & Hull (1994) state that the experimental approach (discussed in the physiological and mechanical sections of the literature review) is adequate if a suspension system design has already been developed and the amount of dissipated energy is to be established. However, to establish the affect that adjusting parameters - such as the stiffness of the spring or moving the pivot point to a different location - has on bobbing, then the experimental approach becomes cumbersome as re-testing of subjects is required. Additionally, when considering the experimental approach as a form of testing, a new bike may have to be built specifically for experimentation as was the case in Krachin & Hull's (2002) and Needle & Hull's (1997) studies.

A method widely used to counteract the cumbersome affects of the experimental approach is to investigate suspension systems and their affect on rider performance through the use of computer simulated models. These computer simulations are dynamic models of bikes and riders which are developed using dynamic simulation software - examples of this type of software are DADS, AUTOLEV, Matlab, ADAMS and LifeMOD. Simulations can be beneficial for research on suspension systems as, unlike the experimental approach to testing, once a dynamic model of a bike and rider has been developed using the specific software, parameters can be adjusted promptly, and without difficulty, to conduct different tests to compare suspension configurations. González et al. (2008) support these benefits maintaining that through the development of a dynamic simulation model it becomes easier to recognise the forces interacting between the bike and rider on the various system parameters (bike geometry, suspension design, rider's anthropometric data and terrain profile), all of which can be easily modified and the corresponding energy efficiency evaluated in a few seconds. Additionally, simulation models can aid in determining rider and terrain induced energy losses. Although it is possible to determine rider induced energy losses experimentally, it is easier and less time consuming to determine such energy losses on the various system parameters through the use of dynamic computer simulations (Wang & Hull, 1996).

The research pertaining to dynamic computer simulations included in this literature review falls into three categories: investigating the optimisation of suspension systems; investigating rider-induced energy losses; and investigating terrain-induced energy losses. These three categories are often interrelated and it is not uncommon for researchers (Good & McPhee, 1999 & 2000 and Wang & Hull, 1994, 1996 & 1997) to initially develop a simulation model which investigates either the rider or terrain-induced energy losses and to then use the models to optimise frame or rear suspension design. Studies relating to the development of simulation models (Bu et al., 2009; Wang & Hull, 1994 & 1996; Wilczynski & Hull, 1994) also incorporate mechanical testing. Simulation and mechanical testing are combined for two distinct reasons: to establish input parameters for the computer model; and to validate results. Fregly et al. (2000) advocate the benefit of this, stating that a dynamic model of a bike is desirable to assess how well various experimental situations mimic the dynamics of outdoor riding.

Wilczynski & Hull (1994) are pioneers in the field of developing and optimising mountain bikes through the use of dynamic simulations. They were the first researchers to use simulations to investigate mountain bike optimisation through investigating the loads on a bike frame when cycling over rough terrain. The fundamental aim of Wilczynski & Hull's (1994) study was to develop a simulation model that would enable mountain bike designers to optimise frame designs. A previous study by Wong & Hull (1983) also investigated surface-induced frame loads of a bike; however, the study investigated this in relation to on-road cycling only.

Wilczynski & Hull's (1994) study, in addition to developing a dynamic simulation model for testing, used mechanical testing to obtain results which were then compared and contrasted to those obtained from the simulations; a factor beneficial in validating results. The mechanical tests involved measuring the horizontal and vertical loads at the rider's contact points - the seat, handlebars and the pedals – through the use of strain gauges. In order to emulate the simulation model 1 subject coasted over a short, 6.5 metre track with 6 square obstacles attached (3.8 cm side-length) at an initial velocity of approximately 3.5 m/s on a hardtail mountain bike. The subject was instructed to complete the trial in both a standing and seated position and for both trials the crank arms remained in a horizontal position. This form of mechanical testing is similar to the tests carried out by Levy & Smith (2005), whose subjects were also instructed to coast over a track with a bump. However, this protocol of allowing the subject to coast over the track presents the same issues and concerns as outlined in the discussion of Levy & Smith's (2005) study. As with Levy & Smith's (2005) and De Lorenzo & Hull's (1999) research, Wilczynski & Hull (1994) also used only 1 subject for testing. As previously discussed in relation to Krachin & Hull's (2002) findings, results differ when more than one subject is used for testing.

A matter that became apparent when studying Wilczynski & Hull's (1994) mechanical test protocol was that few measurements were recorded (with the exception of the loads at the rider's contact points). It would perhaps have been beneficial to additionally measure the bike velocity, acceleration and displacement in order to establish how the bike was affected by contact with the bumps and to compare these to the simulation results.

Wilczynski & Hull's (1994) dynamic simulation model was developed using Dynamic Analysis and Design Software (DADS) (CADSI Corp., Oakdale, IA) and was modelled on the hardtail mountain bike used for their mechanical testing. The input parameters for the model were either estimated or taken from previous studies (Chandler et al., 1979; Greene et al., 1979; Wong & Hull, 1981; Wong & Hull, 1983). The simulation model was created using two rigid bodies - the frame and front fork of which were connected through the use of a spring. The wheels were modelled by two linear springs and the pedals were represented by a spring connected to the bottom bracket. As Wilczynski & Hull (1994) were the first researchers to use simulation models as a mode of testing mountain bikes and their optimisation, it can be maintained that they laid the foundations for future simulation model development. However, as is to be expected with the first model of its type, it became apparent where improvements could be made to ensure a more realistic model is created to represent truer riding conditions. Perhaps the two most apparent aspects relate to the decision to use springs to represent the wheels and pedals of the mountain bike. The research may have benefited from using a simulation model which incorporated a more realistic tyre and pedal design to give a more accurate representation of an outdoor mountain bike.

Wilczynski & Hull's (1994) simulation experiment was carried out in two phases, both of which replicated the mechanical testing which was undertaken prior to the simulations. Both simulation phases - as with the mechanical tests - were completed with the rider cycling in both a seated and standing position. For the first phase simulation, the rider coasted over a smooth surface with no pedalling action, thus representing the approach period of the subject prior to hitting the bump as carried out in Wilczynski & Hull's (1994) mechanical testing. This initial first phase was used to adjust the simulation's input parameters until the output matched that of the mechanical testing. The second phase of the simulation represented the period following the rider's initial contact with the bump as carried out in the mechanical test.

Although the simulation was designed to emulate the mechanical test, slight differences were observed: only 1 bump was used in the simulation, in contrast to the six obstacles that the subject encountered during the mechanical test. The length of the track and the velocity of the cyclist are not stipulated for the simulation model, thus making any comparisons between the simulation and mechanical tests difficult as the parameters are not identical for both.

Wilczynski & Hull's (1994) simulation model, as with the mechanical tests, measured the horizontal and vertical loads on the mountain bike at the handlebars, pedals and saddle in both a standing and seated position. The initial results obtained from the simulation tests were significantly different from the experimental results. However, once the input parameters were adjusted, simulated loads for the final parameter values were not significantly different from those measured experimentally (Wilczynski & Hull, 1994). The results found that - similar to the static forces - the dynamic loads were greatest in the horizontal direction for the seated position. The results also yielded that of the ten loads measured, only the horizontal handlebar force in the standing position and the vertical seat force in the seated position did not exceed the static load magnitude. Wilczynski & Hull's (1994) results indicate that a computer simulation can represent similar frame loads to that of an actual mountain bike, thus indicating that simulations can assist in optimising bike and suspension design.

Developing an optimal suspension design can be challenging, as advocated by researchers in the field of mountain biking and suspension systems (Berry et al., 1993; Burke, 1996; De Lorenzo et al., 1994; Good & McPhee,1999; Karchin & Hull, 2002; MacRae et al., 2000; Needle & Hull, 1997; Nielens & Lejeune, 2004; Olsen, 1996; Seifert et al., 1997). However, as Wilczynski & Hull's (1994) research indicated, computer simulations can assist in optimising mountain bike design. Wang & Hull (1994 & 1996) recognised this and carried out studies, using a dynamic simulation model, which investigated the effects of energy losses due to bobbing. Mechanical testing was employed after the initial simulations as a means of validating results. The simulation model used for Wang & Hull's (1994 & 1996) experiment was created using Kane's (1985) method of dynamic analysis using the computer programme AUTOLEV (OnLine Dynamics, 1990). A two-dimensional model was created to emulate a dual suspension mountain bike with a single swing-arm rear suspension design. This model allowed for five degrees of freedom and comprised of six rigid bodies. The tyres were represented by compression springs and both the front and rear suspensions were constructed using a spring and damper configuration. The frame loads on the rider's contact points used for the simulation were taken from previous literature (Stone, 1990) and the stiffness and damping characteristics of the suspension systems were established using a servo-hydraulic load frame.

Wang & Hull's (1994 & 1996) methodology involved simulating a seated rider pedalling up a smooth surface with a grade of six percent at a constant velocity of 6.2 m/s. As this simulation involved cycling up a smooth surface, only the rider induced energy losses due to bobbing were considered. As is the case for Wilczynski & Hull's (1994 & 1996) simulation model, Wang & Hull's (1994 & 1996) model presents similar drawbacks as a means of testing: the decision to use springs to represent tyres does not create a true representation of tyre dynamics. Similarly, as with Wilczynski & Hull's (1994) simulation model, Wang & Hull (1994 & 1996) chose not to incorporate the crank and pedals into their simulation model, thus consequently altering the dynamic and inertia characteristics of true riding conditions. In addition to these limitations of the study, the stability of the simulation presented a further area of concern. If the simulations were allowed to continue for long periods of time then the tyres would leave the ground and the bicycle would eventually flip over backwards (Wang &

Hull, 1996). This limitation highlights the unrealistic characteristics of simulating mountain bikes using dynamic computer models.

In order to lend validity to the simulation results, Wang & Hull (1996) conducted mechanical experiments to verify their simulation model. The displacements of the fork and rear suspension were measured and compared to the displacements predicted by the simulation model. The protocol for the mechanical tests was taken from Stone (1990); this consisted of a subject riding a fully suspended mountain bike on an indoor treadmill with a six percent grade at 7.2 m/s. This is a similar form of testing to Berry et al. (1993 & 2000), who also used treadmills as a mode of testing. In this respect, similar concerns arise through using treadmills as a means of testing mountain bikes, as outlined in the physiological section of this literature review.

During Wang & Hull's (1994 & 1996) mechanical tests, the displacement of the front and rear suspension systems were measured using linear transducers attached to the suspension systems. The crank angle data was also measured using an optical encoder, and all sets of results compared to the simulation model. This is in contrast to Wilczynski & Hull (1994), whose approach involved measuring the loads at the contact points between the bike and rider. The results of Wang & Hull's (1994 & 1996) simulation and mechanical displacement analysis concur with Berry et al's (1993) treadmill test results, which similarly demonstrated that no front fork compression is observed when cycling uphill on a smooth surface. This result has therefore been proven using a mechanical test; a simulation (Wang & Hull, 1994 & 1996); and physiological tests (Berry et al., 1993) - indicating that no energy is dissipated whilst cycling (remaining seated) uphill on a smooth surface on a bike with a front suspension system. This finding, however, is true only of cyclists riding in a seated position. Kyle's (1990) calculations proved that for a cyclist climbing out of the saddle, the front suspension would consume 1% to 2% of the total energy whilst riding uphill on a smooth surface. It is however important to highlight that most extended climbing is done in the seated posture because of increased energy expenditure in the standing posture for equivalent average power output (Tanaka et al., 1996). This may attribute to Berry et al's (1993); MacRae et al's (2000); and Wang & Hull's (1994 & 1996) decision to conduct all tests with subjects riding in a seated position.

A further result obtained from Wang & Hull's (1994 & 1996) mechanical tests showed that the rear suspension had a mean displacement of 6.6 mm ± 2.7 mm. The simulation displacement results showed that the mean displacement of the rear suspension differed from those obtained during the mechanical tests by 0.7 mm and that the amplitude differed by 0.3 mm. Furthermore, the simulation displacement results for the rear suspension, in relation to the crank angle, are shown to occur twenty-nine degrees behind those of the mechanical test crank angle results. Wang & Hull (1994 & 1996) suggest that the reason for these differences could be due to load data being taken from previous literature. The data used for the simulation analysis was acquired from Stone (1990) whose subject's biomechanics may have differed from the subject used for Wang & Hull's (1994 & 1996) mechanical experiment, thus making the mechanical and simulation results difficult to compare. In order to increase accuracy of results it may have been beneficial - as in Wilczynski & Hull's (1994) study - to measure the interaction loads between the bike and the rider completing the mechanical tests to ensure that the subject was identical for both the simulation and mechanical tests.

Wang & Hull (1994 & 1996) stipulate that no spring preload was used for the test analysis, presenting this as one possible reason for the large displacement results found from both the mechanical and simulation tests. Spring preload is normally set to compensate for a rider's static weight, thus the results presented are, in a sense, for a worst case scenario. This theory was recognised and tested by doubling the stiffness of the spring in the rear suspension system which consequently decreased the mean displacement by fifty percent. Although Wang

& Hull (1994) illustrated that the use of a stiffer spring can reduce displacement of the rear suspension system, this may also have the adverse effect of the suspension system being unable to react to small bumps.

Wang & Hull’s (1994 & 1996) mechanical and simulation displacement results illustrated that on average, the rear suspension dissipated 6.9 W out of the 531 W input by the rider (1.3 % of the total input power from the rider). Although 1.3 % may not appear to be a large amount, in competitive cycling being 1.3 % slower can be a significant disadvantage (Wang & Hull, 1994 & 1996). This finding of Wang & Hull (1994 & 1996) differs from the physiological results found by Berry et al. (1993) and MacRae et al. (2000); both of whom carried out similar tests with the use of a treadmill. Both Berry et al. (1993) and MacRae et al. (2000) found that there was no significant difference in a subject’s energy expenditure whilst cycling uphill on a smooth surface in the seated position on either a hardtail or fully suspended bike. However, MacRae et al’s (2000) results relating to the mechanical aspects of testing, namely the power output of a cyclist measured through the pedals, concur with those found by Wang & Hull (1994 & 1996). MacRae et al. (2000) also found that a cyclist riding on a hardtail mountain bike used less power than on a fully suspended mountain bike when cycling uphill on a smooth surface.

A possible reason for some of the discrepancies between the results of Berry et al. (1993), MacRae et al. (2000) and Wang & Hull (1994 & 1996) may relate to the type of rear suspension and the location of the pivot point used during each of the three experiments. Wang & Hull (1994 & 1996) chose to use a single swing arm rear suspension design with the pivot point located 20 cm above the bottom bracket. Berry et al. (1993) also used a single swing arm rear suspension design, but with the pivot point located 10 cm above the bottom bracket. Conversely, MacRae et al. (2000) used a four bar linkage rear suspension system during testing. For a high pivot point design, the chain force causes the rear suspension to extend (Wang & Hull, 1994) - this may aid in explaining the large displacement results found in Wang & Hull's (1994) tests. One possible means of validating these discrepancies found between the results would be to combine and compare the physiological results (as obtained in Berry et al's (1993) and MacRae et al's (2000) research) with both the mechanical results of displacement and power through the pedals (as obtained in Wang & Hull's (1994) and MacRae et al's (2000) studies). This would also aid the development of a more realistic simulation model that could be validated from the mechanical results.

Wang & Hull's (1994 & 1996) research investigated rider induced energy losses, concluding that power was dissipated by the rear suspension while cycling uphill on a smooth surface. As a result of their previous work, they deemed a study on how to minimise these energy losses as a natural progression to their previous studies, maintaining that it is desirable to optimise the bicycle design to minimise the rider induced energy losses. Wang & Hull's (1997) optimisation study sought to determine the relationship between the power dissipated through the rear suspension and pivot point location by systematically varying the location of the pivot point. The model used for the study was the previously developed dynamic computer simulation model as used in Wang & Hull's (1994 & 1996) earlier studies. The model used during testing was a single swing arm rear suspension design, thus only two design parameters could be altered in order to investigate the optimisation of the rear suspension: pivot point location and the spring/damper parameter values. As the results pertaining to altering the spring or damper would result in the conclusion that having no suspension or damping would minimise energy loss, it would be ineffective to investigate this as suspension is required on a mountain bike in order to minimise vibrations felt by the rider. Samuelson et al. (1989) reported that cycling performance decreased under the influence of vibrations. It is a view held by researchers (Levy & Smith, 2005 and Seifert et al., 1997) that in order to counteract this vibration effect, a suspension system is required. Seifert et al. (1997) maintain that suspension systems enhance absorption of shock and vibration, allowing the rider to maintain a constant velocity. Levy & Smith (2005) agree with this, stating that suspensions are effective at dampening vibrations at the bike frame. In considering this, Wang & Hull's (1997) research investigated the optimisation of the pivot point location.

Wang & Hull's (1997) methodology involved locating the optimal pivot point located on the seat tube by incrementally increasing the pivot point height by 0.5 cm and measuring the displacement of the rear suspension system each time. The model used for the research was identical to that used in Wang & Hull's (1994 & 1996) tests. Subsequently, once the optimal pivot point on the seat tube had been established, the dependence of the optimal pivot point on pedalling mechanics; spring and damper parameter values; and the chain line (gear combination) were evaluated. The optimal location due to pedalling mechanics was found using data from three other subjects (taken from Stone, 1990) which was inserted into the computer simulation. Spring and damping parameters were varied both independently and simultaneously and the optimal pivot point was then determined. The effect of the chain line on the optimal pivot point was determined by altering the chain line using four front chain ring sizes and ensuring that the gear ratio remained constant.

The results of Wang & Hull's (1997) study indicated that the optimal pivot point on the seat tube is 11 cm above the bottom bracket of the bike frame. This optimal pivot point location is 9 cm lower than the pivot point location used in Wang & Hull's (1994 &1996) previous studies. By moving the pivot point from the initial 20 cm above the bottom bracket, as used in Wang & Hull's (1994 & 1996) tests, to the optimal location of 11 cm, the power losses were reduced by 83 % from 6.9 W to 1.2 W. This finding may explain the reason why less bobbing was experienced by the subject in Berry et al's (1993) test compared to the subject in Wang & Hull's (1994 & 1996) tests. Berry et al. (1993) found that no significant oscillation due to pedalling was observed; the pivot location used for this study was 10 cm above the bottom bracket - only 1 cm below that of the optimal location of 11 cm found by Wang & Hull (1997).

Needle & Hull (1997) and Karchin & Hull (2002) carried out similar tests to Wang & Hull's (1997) optimisation test - also conducting experiments to establish the optimal pivot point of a rear suspension system. Needle & Hull's (1997) results however, found the optimal pivot point to be 8.4 cm above the bottom bracket and Karchin & Hull (2002) found it to be 9.77 cm above the bottom bracket. A possible reason for the differing optimal pivot point values obtained may be due to the different modes of testing that each research undertook: Needle & Hull (1997) and Karchin & Hull (2002) carried out mechanical tests and Wang & Hull (1997) used computer simulations.

Once the optimal pivot point was found by Wang & Hull (1997), the effect of the subject's pedalling mechanics on the eleven centimetre optimal pivot point was investigated. Through testing four subjects it was found that the optimal pivot point varied for each rider by a value of up to 2 cm, suggesting that the optimal pivot point is dependent on the rider. The decision to use four subjects to investigate this highlights the value of using more than one subject for testing in order to gain an average result. Additionally, Wang & Hull (1997) found that the optimal pivot point location changed by a small amount of up to 1 cm when the stiffness of the spring was altered. Altering the damping parameters however, did not have any effect on the optimal pivot point location. Although the optimal pivot location is rider and spring rate dependent, these dependencies are weak. As a result, a bicycle suspension system optimised for a particular cyclist and spring rate will be nearly optimal for a wide variety of cyclists and spring rates (Wang & Hull, 1997).

One parameter that does have a significant effect on the optimal pivot point location is the effect of the gear combination (chain line). The optimal pivot point location depends upon the gear combination used and was shown by Wang &

Hull (1997) to range from 7 cm to 16 cm. Thus, it is not possible to achieve optimal performance for all gear combinations using a single swing arm rear suspension design. This may not be ideal as competitive cyclists often use a range of different gear combinations to optimise riding performance. Good & McPhee's (1999) research investigated these chain-suspension interactions, yet in contrast to Wang & Hull's (1997) and Wilczynski & Hull's (1994) simulation studies, Good & McPhee (1999) chose to create a simplified simulation model combining the rider, frame and crank into one single rigid body where the interaction loads between the bike and rider were not taken into account. By including the body of the rider in the system model, the need to include rider-bike interface load is eliminated (González et al., 2008). Good & McPhee's (1999) research focused specifically on the chain-suspension pedalling interactions - Wang & Hull (1997) highlighted this as one of the undesirable characteristics of a rear suspension. The chain-suspension pedalling interactions occur when the pedalling of the rider causes unwanted motion (compression or extension) of the rear suspension (Good & McPhee, 1999).

Good & McPhee's (1999) simulation used a four body dynamic model of a bicycle with a single swing arm rear suspension design. The geometry and mass properties of the bike were the same as those used by Wang & Hull (1996). No front suspension was included in the model as previous studies by Wang & Hull (1994 & 1996) demonstrated that no displacement occurred in the front suspension when cycling uphill on a smooth surface. The four bodies of the simulation consisted of the front wheel; rear wheel; rear triangle; and a final body consisting of the main frame and the fork of the bike and rider. The dynamics programme used for the simulations was developed by Good & McPhee (1999) and simulated a seated rider cycling up a smooth surface with a six degree grade at a velocity of 7.2 m/s. The input data used to simulate the pedalling of the rider was modelled by a simple harmonic function taken from Wang & Hull (1996). Although Good and McPhee's (1999) simulation study is an important contribution to the study of seated cyclists riding suspended bikes, it does not consider the rider's movement on the bike. According to González et al. (2008), the motion of the rider's body on a bike is one of the main causes of the bobbing effect experienced by riders.

In order to increase validity, the results of Good & McPhee's (1999) simulation study were compared to the simulation results from Wang & Hull's (1996) dynamic model. Both Good & McPhee's (1999) and Wang & Hull's (1996) displacement results for the rear suspension system were similar - only Good & McPhee's (1999) model gave a displacement of 1 mm less than that of Wang & Hull's (1996). The similar displacement results indicate that the interaction loads between the bike and rider do not affect results as Good & McPhee (1999) did not take these into account during testing. These interaction loads are considered highly rider dependent, complex and numerous, and have to be determined experimentally for each rider, terrain and grade scenario prior to running the simulation. If Good & McPhee's (1999) results are accurate and the interaction loads do not account for any differences in results, then excluding this cumbersome process from simulation testing can be justified. Good & McPhee (1999) advocate this, stating that the use of a computer simulation can be used to investigate the effects of different bike designs on the response of the rider, without the expense of building and testing a prototype for each design.

Good & McPhee's (1999) simulation study is beneficial as it can (as with Wang & Hull's (1997) study) be used as a design tool to optimise mountain bike design. Good & McPhee's (2000) study used the previously designed simulation model to optimise the rear suspension design to minimise chain-suspension interactions felt by the rider. In contrast to Needle & Hull (1997) and Wang & Hull (1997), whose tests attempted to minimise the energy lost through the spring-damper in the rear suspension system, Good & McPhee (2000) adopted a different approach by choosing to minimise the pitching motion of the rider and bike frame. Good & McPhee (2000) stipulate that reducing the pitching motion consequently reduces the movement of the bike frame and rider.

Good & McPhee's (2000) research used the same model as that of Good & McPhee's (1999) previously designed simulation model. The study sought to locate the optimal pivot point (that which gives the minimum pitching motion) of the simulation model through the use of a genetic algorithm. The resulting optimal pivot point was found to be at a point located 11.6 cm above the bottom bracket and 2.7 cm behind the seat tube. The findings for the optimal pivot point value coincide with the optimal pivot point value found by Wang & Hull (1997), who recorded a value of between 10.5 -12.5 cm above the bottom bracket.

Wang & Hull (1994 & 1996) and Good & McPhee (1999) both used simulations to investigate the energy dissipated through a rear suspension design, subsequently using the models to investigate the optimisation of a single swing arm rear suspension design. Similarly, González et al. (2008) investigated the effect of a rider's body movement on energy dissipation in order to optimise the design of a rear suspension, yet a key difference was González et al's (2008) decision to investigate this using a four-bar linkage rear suspension design.

González et al. (2008) used Matlab computer software to develop a simulation model similar to that of Wang & Hull (1996) and Good & McPhee (1999); that of a seated rider cycling up a smooth surface with a six percent grade at a velocity of 6.5 m/s. However, in contrast to Good & McPhee's (1999) model, González et al. (2008) produced a simulation model where the exact direction of the chain tension was evaluated during the simulation and where only the upper part of the body was fixed to the frame, thus allowing leg motion. The decision to incorporate the cyclist's legs and pedalling movement into the simulation model is a truer representation of riding conditions as this produces similar inertia effects to cycling outside. Karchin & Hull (2002) support this view, stipulating that the inertial loading due to the pedalling action of the rider's legs would cause suspension motion.

As a means of validating the model, González et al. (2008) initially ran the simulation, neglecting the effect of the rider's body movement and measuring the rear suspension displacement as a function of the crank angle. The obtained results were then compared to those of Wang & Hull (1996) and Good & McPhee (1999) and showed that, compared to the experimental results found by Wang & Hull (1996), a difference of only 1% was recorded for González et al's (2008) mean displacement results. A difference of thirty-seven percent was however, recorded for the amplitude of the displacement between Wang & Hull's (1996) experimental tests and González et al's (2008) simulation test. This difference of thirty-seven percent is significantly large, and surprising, as González et al's (2008) model used the same input parameters as those from Wang & Hull's (1996) and Good & McPhee's (1999) simulations, whose results for displacement amplitude showed a difference of nine percent and ten percent respectively which was comparable to Wang & Hull's (1996) experimental results. A probable reason for the significant difference in displacement results compared to Wang & Hull (1996) and Good & McPhee (1999), may be due to González et al's (2008) use of a four-bar linkage rear suspension design for testing rather than a single swing arm design. Yet interestingly, González et al. (2008) highlight that the single swing arm rear suspension design has been superseded by modern designs such as the four-bar linkage and is one of the most used rear suspension designs in off-road cycling.

González et al. (2008) ran the simulation with the cyclist's legs in a fixed position and compared this to the simulation where the cyclist's legs were in motion. The results showed that the mean displacement increased when the cyclist's leg movements were incorporated into the simulation. The amplitude of the displacement however, decreased, and consequently the power dissipated in the rear suspension was reduced. The results from the study also found that the gradient of a slope does not affect energy use. González et al. (2008) stipulate that this finding goes against common belief - a remark validated by Good & McPhee's (1999) assertion that cycling uphill increases the effect of bobbing.

Furthermore, González et al's (2008) study found that lower cadence and higher crank torque result in more power being dissipated through the rear suspension. Wang & Hull (1996) stipulate that the power loss due to bobbing is 1.3 % of the total rider input for a rear suspension system, indicating that a rider's input power is directly proportional to the power dissipated by the rear suspension system. In this respect, González et al's (2008) finding, that higher crank torque results in higher power dissipation at the rear suspension, is unsurprising, as is the finding that lower cadence attributes to more power being dissipated through the rear suspension since a higher cadence results in a more even pedal stroke. González et al. (2008) used the simulation model to establish whether the moving legs of a rider, compared to a model where the rider is a rigid body, would impact on the results obtained for the amount of power dissipated in the rear suspension. It was found that the inclusion of a rider's body motion during testing had produced a twenty percent reduction in power. This indicates that the inclusion of a rider's body movement is an important aspect to consider when designing a mountain bike simulation.

González et al. (2008) subsequently used the simulation model to optimise the rear suspension geometry. The results showed that the power dissipation could be reduced from 8 W to 0.8 W through optimising the rear geometry of the four-bar linkage rear suspension. Wang & Hull's (1997) optimisation test concluded that the rider induced power loss could be reduced to 1.2 W through use of the optimal pivot point. This is 0.4 W higher than González et al's (2008) result, which indicates that the four-bar linkage system, according to these tests results, has the capability to reduce the power dissipated in the rear suspension system to a greater degree than a single swing arm design.

Similar to González et al's (2008) research, Bu et al. (2009) also designed a simulation model to replicate a mountain bike with a four-bar linkage rear suspension design which was subsequently used to optimise the rear suspension geometry. The aim of Bu et al's (2009) study was to reduce the vibration effects transmitted to the rider due to terrain irregularities. This is a different approach to the one adopted by González et al. (2008); Good & McPhee (1999); Wang & Hull (1994 & 1996) and Wilczynski & Hull (1994), all of whom investigated the rider induced affects on the energy dissipated via the rear suspension system.

Bu et al. (2009) created a dynamic model using ADAMS; a model similar to the previously designed simulation models of González et al. (2008); Good & McPhee (1999); Wang & Hull (1994 & 1996); and Wilczynski & Hull (1994). The simulation bike was represented by a mechanical system of ten rigid bodies linked together with rotational and linear joints, springs and dampers. One of the most significant differences between Bu et al's (2009) study, and the previously designed simulations, was the decision to use a complex rider model for the simulation. This was created using LifeMOD (a plug-in module to ADAMS) - a simulation model created to emulate human motion. The rider was modelled on a twenty-six year old, 1.75 m tall male, weighing 65 kg.

Bu et al. (2009) created a two-dimensional simulation model to cycle over of a sine-wave road surface with 25 mm amplitude and 500 mm wavelength. The model was constrained in such a way that the tyres (created from a spring and damper configuration) were unable to leave the ground and only the front wheel was able to move in both the horizontal and vertical direction (the rear wheel was allowed only to move in the vertical direction). The acceleration at the handlebar, saddle and rear axis was measured and the root-mean-square (RMS) accelerations calculated.

As with Wang & Hull's (1994 &1996) simulation, Bu et al's (2009) dynamic simulation model was also validated through experimental tests. One subject, whose weight and height were equivalent to the simulation cyclist, rode at a constant velocity on a concrete surface with the same sine-wave amplitude and wavelength as that of the simulation model. Vibration measurements were recorded using acceleration transducers mounted on the handlebars, saddle and the rear axis and the RMS accelerations were again calculated. On comparing the simulation and experimental results it was found that the handlebar and rear axis RMS accelerations gave similar values for both the mechanical and simulation tests. Conversely, there was a significant difference (57 %) in the values obtained for the saddle RMS acceleration during the simulation and experimental tests. Bu et al. (2009) cite possible reasons for this difference in RMS acceleration values as being attributed to the simulation model being two-dimensional; the tyres being constrained to the ground; tyre rebound not being included in the design; and the main frame of the mountain bike consisting of one rigid body. All - with the exception of the model being two-dimensional - of Bu et al's (2009) suggested reasons could be overcome through adapting and altering the simulation model. An actual tyre model (not simply a spring/damper configuration) could be created, whose design would allow the tyres to leave the ground, and the main frame of the bike could be split into numerous bodies. These adaptations to the simulation design would present a truer representation of cycling conditions. The initial reason cited by Bu et al. (2009) regarding the simulation model being represented in a two-dimensional form, is more difficult to alter. Three-dimensional simulations are much more complex to simulate, attributed to the actuality that bikes are stabilised by a gyroscopic action and require constant rider input to maintain stability (Sharma et al., 2005).

Bu et al. (2009) - as with González et al. (2008); Good & McPhee (2000) and Wang & Hull (1997) - used the created simulation model as a design optimisation tool. The simulation was optimised for improved vibrational comfort through reducing the RMS accelerations at the pelvis and feet of the cyclist. Bu et al. (2009) combined the RMS pelvis and feet accelerations and used a system of trial and error to reduce the overall RMS value (pelvis and feet values combined). The obtained RMS value was subsequently compared to the results of a second order (stepwise regression) mathematical model, with both sets of results differing only by a small degree, thus verifying that the vibrational comfort and design variables is accurately described by the mathematical model.

# 3. Questionnaire

## 3.1. Questionnaire Design

The questionnaire used in the current study was designed to establish which type of bike cyclists chose to ride and how this in turn affects riding style. Furthermore, it was designed to gain an insight into rider opinions on the different types of suspension systems available. Oppenheim (1992) defines some advantages of the questionnaire to include: low cost of data collection; low cost of processing; and ability to reach respondents who are widely dispersed. Consequently, a questionnaire was considered the best method of collecting data in the current study as respondents came from throughout the United Kingdom.

The principles used in designing the current questionnaire were both quantitative and qualitative. Quantitative designs can be either experimental or descriptive. Hopkins (2002) states that in a descriptive study, no attempt is made to change behaviour or conditions – things are measured as they are. This is true of the current study as only the findings which are derived from the questionnaire will be reported on. In light of this, it was decided that a descriptive study would be used for the initial part of the questionnaire as it would be the most appropriate method to obtain the relevant information. However, it was decided that a qualitative approach would also be adopted for the more subjective information obtained from the open question on riding style. As advocated by Munroe-Chandler (2005) there can be tremendous value in combining qualitative and quantitative data gathering techniques (i.e., mixed methods). Such was the case in Gould et al’s (2002) study with Olympic athletes, which gained valuable information by combining focus groups, surveys and telephone interviews.

## 3.2. Sample

The target population for the survey was both downhill and cross-country mountain bikers ranging from amateur level to the top competitors in the UCI World Championships. More than one location was chosen in order to ensure a more representative sample. Samples were chosen from mountain bikers at local amateur races in Scotland; professional racers at the 2005 World Cup Race; and from amateur and semi-professionals cyclists from various mountain biking clubs across the United Kingdom.

The sample size was considered and three hundred mountain bikers were selected. This sample size was chosen as it was felt that a larger sample size would be more representative of the population. This is supported by Oppenheim (1992) who stipulates that small samples in quantitative research are unlikely to yield results of significance.

## 3.3. Pilot testing the Questionnaire

The importance of pilot testing the questionnaire cannot be underestimated (Oppenheim, 1992). Henderson et al. (1987) explain that pilot testing involves an organised review of the content of the questionnaire to ensure that it includes everything it should and does not include any irrelevant information. In view of this, the current questionnaire was piloted by ten amateur mountain bikers who would not be included in the sample. The feedback and results were beneficial as it highlighted the strengths and weaknesses of the questionnaire. All of the questions were interpreted by the respondents as intended.

In the initial draft of the questionnaire, one question asked: *Do you use front suspension? Yes/No.* All the piloting respondents answered yes to this question therefore, it was decided that the question should be altered to specify the exact type of bike used: hardtail or fully suspended (question 7). The exact type of suspension used by respondents was considered an important factor, therefore, an alternative question was included in the questionnaire: Question Nine: *Which make of front suspension do you use?* In the unlikely result that a rider did not use a front suspension system, this question could be left blank.

## 3.4. Data Analysis

The collection of data is a crucial part of the research process and how that data is analysed is equally important. The closed questions were factual and were number coded and analysed in the form of descriptive statistics. The graphs were produced on Excel to provide visual evidence of the results.

The open-ended questions were analysed using a qualitative approach which required a more lengthy process of analysis once all the data was collected. All of the responses were analysed and colour-coding was used to identify prevalent themes which emerged from the data. These main themes will be identified and discussed in the results and discussion section of the chapter.

## 3.5. Response Rate

The overall response rate for the questionnaire was high: 260 out of 300. Mountain bikers at local amateur racing events in Scotland accounted for the largest proportion of the questionnaires answered. The overall response rate of 86.7% was considered high enough to eliminate serious response bias. The majority of respondents were cross-country cyclists, although some downhill cyclists did participate in the survey. Out of the 183 respondents from race events, many expanded verbally on their answers, significantly helping to decide which direction the project should take.

## 3.6. Quantitative Results

The quantitative results related to the closed questions will firstly be analysed and the themes from the qualitative results will subsequently be identified; both will then be discussed.

A total of 260 respondents replied to the questionnaire out of a possible 300. 150 questionnaires were distributed to both downhill and cross-country mountain bikers at local amateur and semi-professional races in Scotland: 141 were returned, giving a response rate of ninety-four percent. Fifty questionnaires were distributed to professional racers at the 2005 World Cup Race: forty-two were returned, giving a response rate of eighty-four percent. Finally, 100 questionnaires were distributed to cyclists from amateur and semi-professional mountain biking clubs across the United Kingdom: seventy-seven were returned, giving a response rate of seventy-seven percent.

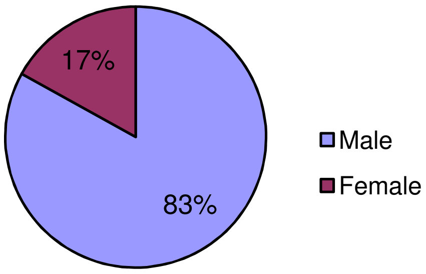


*Figure 3-1: Sex (Question 1)*

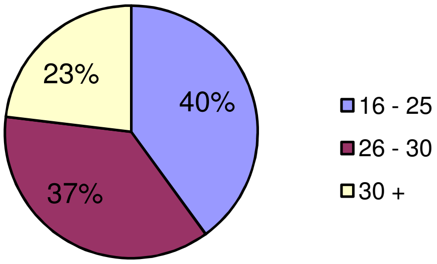


*Figure 3-2: Age (Question 2)*

The sample represented both male and female cyclists of a variety of ages. Males accounted for the majority of respondents with eighty-three percent (216) answering the questionnaire, compared to only seventeen percent (44) of females (Figure 3-1). Figure 3-2 illustrates that the majority of respondents - forty percent (104) - were aged between sixteen and twenty-five; thirty-seven percent (96) were aged between twenty-six and thirty; and twenty-three percent (60) were over thirty years old.

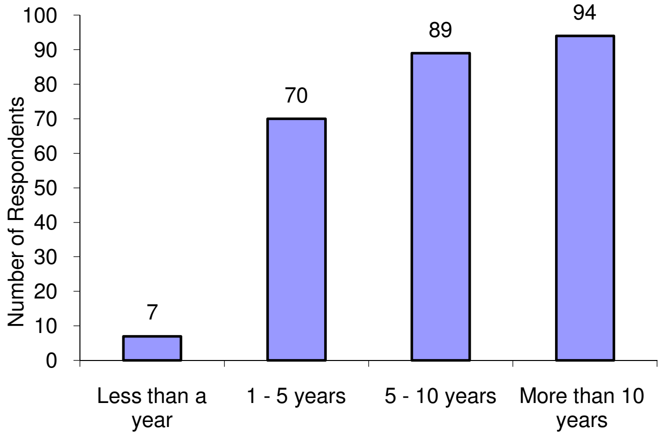


*Figure 3-3: How long have you been cycling? (Question 3)*

Question three was designed to ascertain the length of time the respondents have been cycling as highlighted by the graph in figure 3-3 the sample represented cyclists with a range of experience and length of time cycling, but was weighed toward the more experienced cyclist with thirty-six percent (94) of respondents having more than ten years cycling experience; thirty-four percent (89) five to ten years; twenty-seven percent (70) one to five years; and only three percent (7) with less than one year's experience.

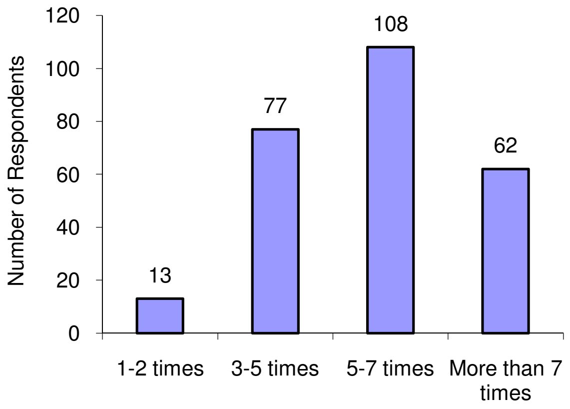


*Figure 3-4: How often do you cycle per week? (Question 4)*

Question four was designed to establish how often the riders cycled per week: once or twice a week; three to five times; five to seven times; or more than seven times per week. Figure 3-4 illustrates that five percent (13) of respondents cycle once or twice a week; thirty percent (77) cycle three to five times; forty-one percent (108) five to seven times; and twenty-four (62) cycle more than seven times per week.

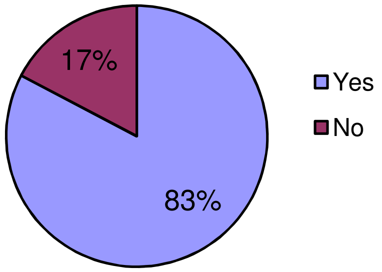


*Figure 3-5: Do you take part in cycling races? (Question 5)*

As illustrated in Figure 3-5, it was found that the vast majority of respondents, eighty-three percent (215), took part in cycling races, with only seventeen percent (45) of respondents answering ‘no’ to this question.

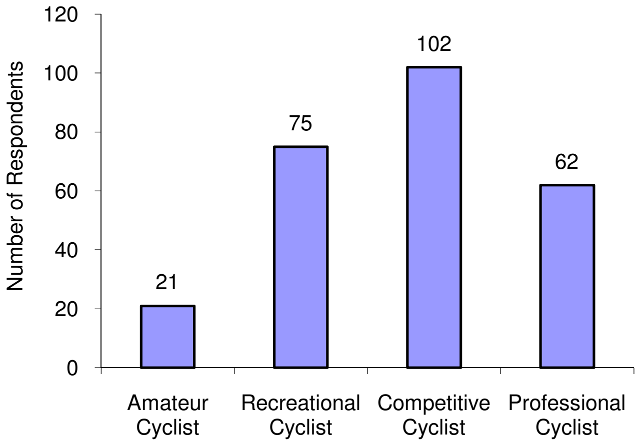


*Figure 3-6: At which level do you race? (Question 6)*

The cyclists who answered ‘yes’ to question five raced at a range of levels: eight percent (21) were amateur cyclists; twenty-nine percent (75) recreational cyclists; thirty-nine percent (102) competitive cyclists; and twenty-four percent (62) professional cyclists (Figure 3-6).

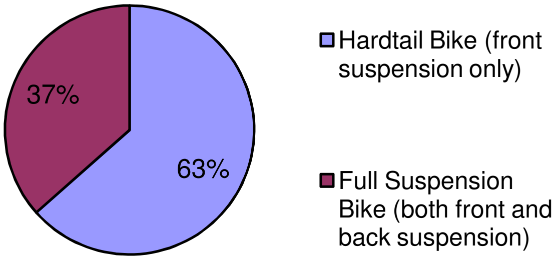


*Figure 3-7: Which type of bike do you ride? (Question 7)*

Question seven (Figure 3-7) asked respondents to choose which bike they rode: a hardtail or fully suspended mountain bike. A rigid frame bike was not given as an option for this question as the pilot-testing of the questionnaire showed that no cyclists used this type of bike. Respondents did have the option to leave this question unanswered if they did not use any form of suspension; this was, however, not the case as all respondents rode a bike with either front, or front and rear suspension. It was found that out of those asked the majority, sixty-three percent (165), rode hardtail bikes, and only thirty-seven percent (95) rode fully suspended bikes.

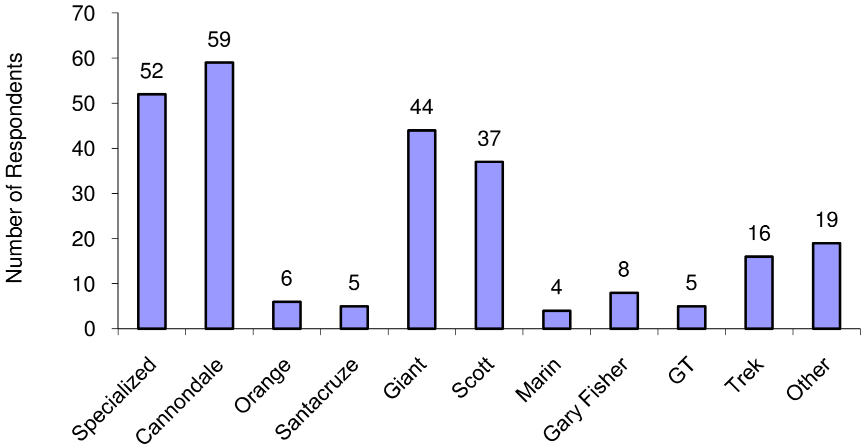


*Figure 3-8: Which make of bike do you ride most often? (Question 8)*

Figure 3-8 displays the following findings: twenty percent (52) of respondents rode Specialized bikes; twenty-three percent (59) cycled on a Cannondale; three percent (6) rode on an Orange; two percent (5) indicated that they rode on a Santacruze; seventeen percent (44) rode Giant mountain bikes; fifteen percent (37) cycled on a Scott mountain bike; two percent (4) rode a Marin; three percent (8) on a Gary Fisher; two percent (5) cycled on a GT; six percent on a Trek (16); and eight percent (19) of respondents stipulated that they rode a different make of bike from the ones available to choose from.

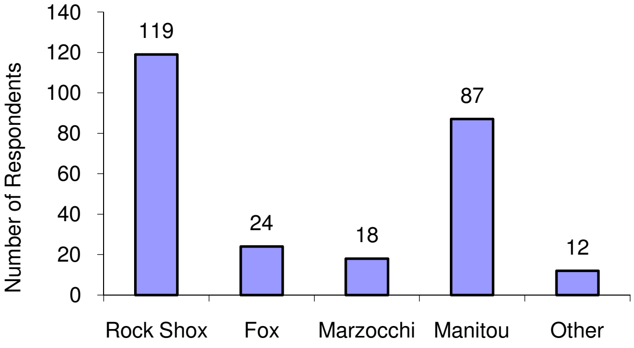


*Figure 3-9: Which make of front suspension you use? (Question 9)*

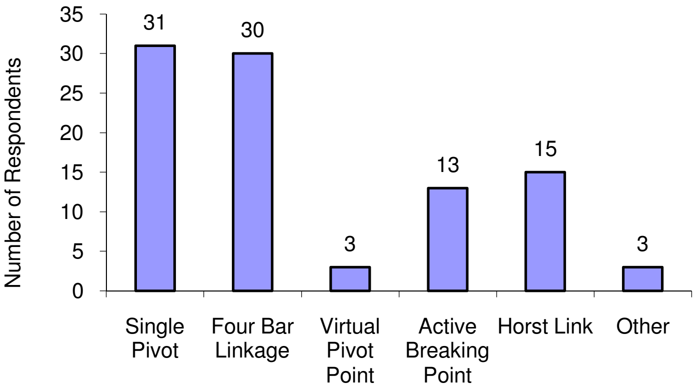


*Figure 3-10:* Which make of rear suspension do you use? (Question 10)

Questions nine and ten sought to establish the model of front and rear suspension systems that the cyclists use. When considering the front suspension, the majority of cyclists, forty-six percent (119), used a Rock Shocks front suspension system; nine percent (24) used a Fox front suspension system; seven percent (18) used a Marzocchi system; thirty-four percent (87) used a Manitou system; and five percent (12) used a different type of front suspension system. The results obtained from question ten were lower as only ninety-five out of the 260 cyclists rode fully suspended bikes. The majority, thirty-three percent (31), of those cyclists who rode fully suspended bikes used the Single Pivot rear suspension design; thirty-two percent (30) used a Four Bar Linkage design; sixteen percent (15) a Horst Link design; fourteen percent (13) an Active

Breaking Pivot; three percent (3) a Virtual Pivot Point rear suspension design; and the number of cyclists who rode a bike with an alternative type of rear suspension design made up three percent (3) of the total figure.

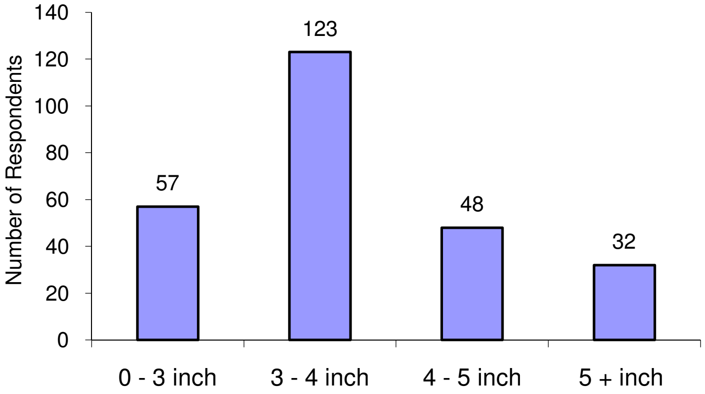


*Figure 3-11: How much travel do you allow your front suspension? (Question 11)*

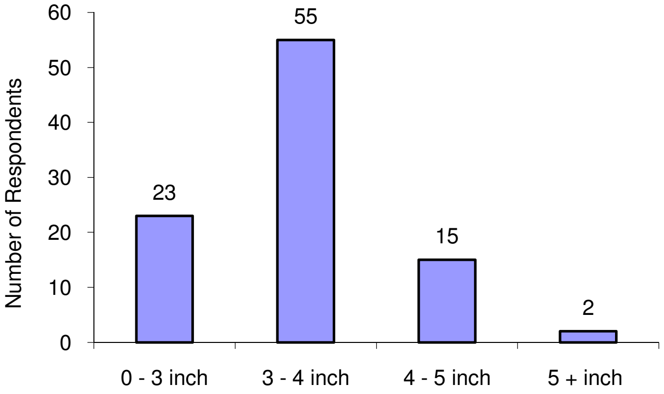


*Figure 3-12: How much travel do you allow your rear suspension? (Question 12)*

All respondents answered question eleven relating to the amount of travel that the front suspension allows; the results of which are illustrated in Figure 3-11. Twenty-two percent (57) of respondents allow zero to three inches of travel on their front suspension; forty-seven percent (123) allow three to four inches; nineteen percent (48) four to five inches; and twelve percent (32) allow over five inches of travel on their front suspension. As only ninety-five out of the 260 respondents rode fully suspended bikes, this same number answered question twelve, as displayed in Figure 3-12. The majority of the ninety-five respondents, fifty-eight percent (55), responded that they allow three to four inches of travel on the rear suspension system; twenty-four percent (23) stipulated that they allow zero to three inches of travel; sixteen percent (15) of respondents allow four to five inches of travel; and only three percent (2) stated that they allow a rear suspension travel of over five inches.

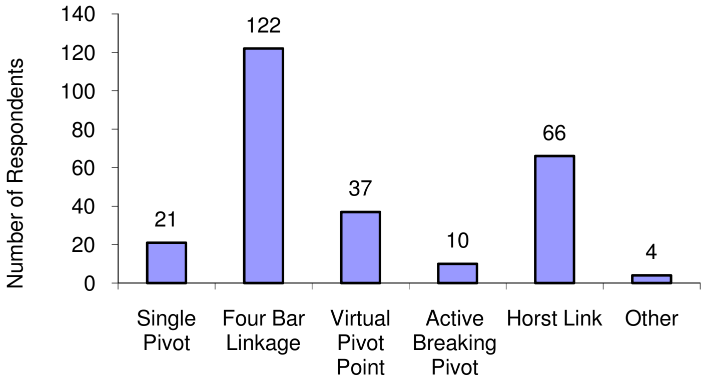


*Figure 3-13: Which rear suspension system do you feel is most effective? (Question 13)*

The sample indicates - as shown in Figure 3-13 - that out of the 260 cyclists, forty-seven percent (122) believed that the Four Bar Linkage system was the most effective rear suspension system; twenty-five percent (66) stated that the Horst Link rear suspension system was the most effective; fourteen percent (37) felt that the Virtual Pivot Point rear suspension system was the most effective, eight percent (21) believed the Single Pivot system to be most efficient; and the Active Breaking Pivot system accounted for four percent (10) of the total number of respondents.  Only two percent (4) of respondents answered that a different type of rear suspension system was the most effective.

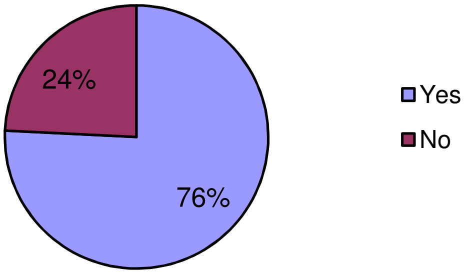


*Figure 3-14: When riding a full suspension bike do you feel a bobbing effect when riding uphill? (Question 14)*

Question fourteen was designed to establish if cyclists felt a bobbing effect when riding uphill: only twenty-four percent (197) of respondents answered ‘no’ to this question, with the majority, seventy-six percent (63), stipulating that they did feel a bobbing effect when cycling uphill.

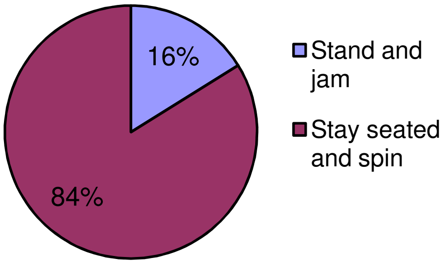


*Figure 3-15: When you are riding uphill do you prefer to stand and jam or stay seated and spin? (Question 15)*

Question fifteen sought to establish the cyclists’ riding style when cycling uphill. The findings from this question (Figure 3-15) highlight that the majority of respondents - eighty-four percent (218) - prefer to remain seated and spin the crank when cycling uphill, while only sixteen percent (42) of respondents prefer to stand and use an uneven pedal stroke.

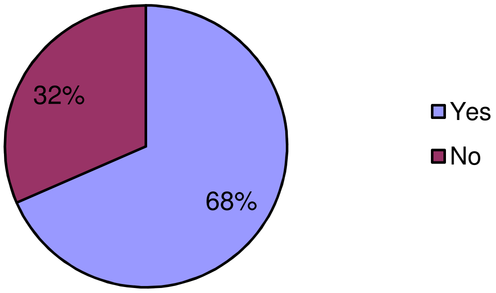


*Figure 3-16: Do you use a different technique when riding a full suspension bike compared to a hardtail bike? (Question 16)*

Figure 3-16 illustrates that the majority of cyclists - sixty-eight percent (178) - use a different technique when riding on a fully suspended bike compared to a hardtail bike, while thirty-two percent (82) of respondents indicated that they do not alter their riding technique when cycling on a fully suspended bike.

## 3.7. Qualitative Results

Question seventeen will be analysed in a qualitative way; the main responses which emerged from the analysis are outlined below. Many of the respondents answered the two parts to question seventeen with similar responses, only using different phrases and terms. Through the use of colour-coding analysis of the answers, the prevalent themes were established and are outlined. When specifically referring to a fully suspended or hardtail bike, this is also indicated.

Question Seventeen (a) *Please briefly describe your riding technique and body positioning whilst riding your bike uphill (i.e. do you remain seated; which way do you shift your weight etc)*. Responses from cyclists were:

**Answers Specifically Relating to Full Suspension Bikes:**

- Minimise upper body movement
- Try to keep a more even pedal stroke
- Less shifting of weight
- More traction with the ground

**Answers Specifically Relating to Hardtail Bikes:**

- Ride out of saddle
- Use upper body to apply more force to the pedals
- Shift body weight from side to side
- Pedal as hard as you can without having to concentrate on an even pedal stroke
- Pull up on handlebars using upper body

**Answers Relating to Both Full Suspension & Hardtail Bikes:**

- Stay seated rather than stand
- Constant speed maintained
- High cadence
- Lean slightly forward on the bike towards the handlebars and start the climb in a low gear
- Drive tyres into the ground
- Accelerate on approach to the hill
- Bend elbows
- Spread weight over bike
- Maintain traction at the rear wheel
- Relax body

Question Seventeen (b) Please briefly describe your riding technique and body positioning whilst riding your bike *downhill* (i.e. do you remain seated; which way do you shift your weight etc.). Responses from cyclists were:

**Answers Specifically Relating to Full Suspension Bikes:**

- More direct route over obstacles
- Faster over rough terrain

**Answers Specifically Relating to Hardtail Bikes:**

- Allow body to absorb the bumps
- Choose the path with fewer bumps

**Answers Relating to Both Full Suspension & Hardtail Bikes:**

- Pre-select correct gear
- Look well ahead
- Lower centre of gravity
- Get off the saddle and move to the rear of the bike
- Keep body loose
- Weight fully centred on pedals
- Keep pedals level
- Always use rear break
- Push handlebars away from body
- Extend arms

## 3.8. Discussion

The first two questions of the questionnaire sought to establish the demography of respondents, with the following questions three to six seeking to ascertain the cycling experience of those respondents. Of those cyclists who responded to the questionnaire, eighty-three percent were male mountain bikers. Similarly, Harmon (2006) distributed 882 questionnaires, which sought to discover the demography of the UK mountain bike community, and found that female participation amounted for only seven percent of respondents. The majority of respondents of the current questionnaire were aged between sixteen and twenty-five years old (40%); however, there was only a slight three percent difference between this age group and that of the twenty-six to thirty year old age group. The analysis of the questionnaire responses also found that thirty-six percent of the cyclists had more than ten years experience, yet once again the difference in numbers between those who had been cycling for between five and ten years was a marginal two percent. These findings are all somewhat unsurprising as the majority of amateur and semi-professional mountain-biking athletes are young males in their twenties who have been involved in cycling from a young age and whose fitness levels are at their peak.

The questionnaire findings support those of Impellizzeri et al. (2005) who undertook a study with fifteen male off-road cyclists with a mean age of 25.5 years and found that their off-road cycling experience amounted to an average 9.9 years. Similarly, Harmon's (2006) study of the demographic information of the UK mountain bike community, found that the mean age of participants in competitive mountain bike events was twenty-six years old.

Forty-one percent of the mountain bikers who completed the questionnaire cycled between five and seven times per week, again a finding that is not wholly surprising as the majority (39%) of respondents were competitive cyclists who took part in cycling races. Impellizzeri et al. (2002) maintain that off-road cyclists usually compete at least once a week for nine months of the year. In order to maintain the peak fitness levels needed for competitive races it would therefore be necessary for competitors to undertake regular training sessions.

Sixty-three percent of respondents rode hardtail bikes, compared to only thirty-seven percent of respondents who rode fully suspended bikes; a finding that supports Nielens & Lejeune's (2004) statement that most cross-country racers still prefer to use hardtail bikes over fully suspended bikes. The response to question seven is interesting as, although suspensions have been greatly improved to become lighter, more efficient, reliable and affordable for many riders (Nielens & Lejeune, 2001), many cyclists still prefer a hardtail design over that of a full suspension system.

The model of bike which respondents highlighted as riding most often are bike types that are mass produced - namely Specialized, Cannondale, Giant and Scott. Another factor to consider when evaluating the responses to question eight is that often professional cyclists, who in this case make up twenty-four percent of the total number of respondents, are sponsored by bike companies and are advised on which bike to ride.

As front suspensions have become standard equipment on mountain bikes (Leventon, 1993) all respondents answered question nine; as expected, not one of the cyclists rode a rigid frame bike. The Rock Shox and Manitou front suspension systems accounted for the highest number of responses, with forty-six and thirty-four percent of respondents using these systems respectively. This result is perhaps unsurprising when considered alongside Fordham et al's (2004) study which proved that Rock Shox and Monitou supply seventy-four percent of all bike models with front suspension.

As only ninety-five out of the 260 respondents rode a bike with a full suspension system, only this number of mountain bikers answered question ten. The results showed that the majority (32%) of respondents used a rear suspension system with a Four Bar Linkage Design, with a marginal difference of only 1% for the Single Pivot design. This finding supports the view of Gonzalez et al. (2008) who stipulate that the Four Bar Linkage rear suspension system is one of the most widely used rear suspension designs in racing off-road bikes.

The majority of respondents allow three to four inches travel on both their front and rear suspension systems: forty-seven percent of the 260 cyclists allow this amount for the front suspension, and fifty-eight of the ninety-five cyclists allow this amount for the rear suspension. This finding coincides with results found in Lopes & McCormack's (2005) research which illustrated that when cycling on a cross-country race, a travel of three to four inches should be allowed on the front suspension whether riding on a fully suspended or hardtail bike. Respondents of the questionnaire who gave an answer of greater than five inches of travel were downhill mountain bikers.

The Four Bar Linkage (47 %) and the Horst Link (25 %) are the two rear suspension system designs that are perceived by respondents to be the most effective type available. This is an expected result as these systems are perceived to be more efficient than other types of rear suspension design. Gonzalez et al. (2008) expressed that the Single Pivot suspension design has been superseded by modern designs such as the Four Bar Linkage. The Four Bar Linkage rear suspension design also accounts for one type of design used most often by the respondents; therefore it is logical that this is also the preferred choice of rear suspension design.

When asked whether cyclists felt a 'bobbing' effect when cycling uphill on a full suspension bike (Question 14), seventy-six percent answered 'yes' compared to only twenty-four percent who responded that they did not experience any bobbing when cycling uphill. This outcome was expected as fully suspended mountain bikes are not broadly accepted by off-road racers and it is thought that they dissipate the cyclist's energy through small oscillatory movements of the rear suspension, namely 'bobbing' (Gonzalez et al. (2008). However, Nielens & Lejeune (2004) suggest that cyclists' generated power that is dissipated by suspensions, 'bobbing', is minimal and probably negligible on most terrains. Those cyclists who responded that they felt no bobbing effect when cycling uphill on a fully suspended bike may have cycled on one of the rear suspension systems which are thought to lessen the 'bobbing' effect.

Eighty-four percent of mountain bikers responded that, when cycling uphill, they preferred to remain seated and pedal at a constant rate; another expected result as Ryschon & Stray-Gundersen (1991) maintain that seated cycling is metabolically more efficient than standing cycling. Nielens & Lejeune (2000) also support this, stating that riders rarely stand on their pedals because of the loss of traction of the rear wheel in that position.

As the majority of respondents answered that they felt a 'bobbing' effect whilst cycling on a fully suspended bike, it is not surprising that sixty-eight percent maintain that they adopt a different riding style whilst cycling on a fully suspended bike. Since it is believed that a fully suspended bike is able to travel a smoother path, as only the wheels follow the contours of the terrain, improving control and traction (Nielens & Lejeune, 2004), it would be reasonable to assume that a cyclist would adopt a differing riding style to benefit from these advantages.

The qualitative results for the open-ended question (Question 17) gave respondents the freedom to convey, in their own words, their own riding technique whilst cycling uphill and downhill. The responses obtained from cyclists using both fully suspended and hardtail bikes were primarily similar for cycling uphill, with only a small number of differences being identified between the two bike types. One difference to emerge was that cyclists stipulated that they attempted to minimize upper body movements whilst cycling on a fully suspended bike. This is possibly in order to reduce any ‘bobbing’ effect which may occur as a result of the rear suspension system; an effect which is detrimental to a cyclist’s performance. Needle & Hull (1997) maintain that rider induced losses are exhibited through a bobbing of the suspension. Similarly, cyclists who rode fully suspended bikes responded that they shifted their weight less whilst riding uphill; again a factor which may help to reduce any ‘bobbing’ effect which may occur.

Cyclists who rode on fully suspended bikes also stated that they adopted an even pedal stroke when cycling uphill. A limited number of cyclists riding hardtail bikes also outlined this as a riding technique which they employed, however it was the vast majority of cyclists riding fully suspended bikes who gave this response. Karchin & Hull (2002) give one possible explanation for this, stating that a variation in the crank torque causes an increase in the tension in the chain which creates a moment which extends the suspension. An extension of the suspension can use up a small amount of the rider’s energy, thus giving one explanation as to why cyclists prefer to use an even pedal stroke whilst cycling uphill. Those respondents who rode fully suspended bikes also specified that they maintain more traction with the ground when cycling uphill. Ishii et al. (2003) supports these views, stipulating that a rear suspension system may assist in keeping the rear tyre in contact with the ground so that loss of velocity is minimised while pedalling over rough terrain.

Differences in responses from cyclists riding uphill on hardtail bikes, compared to cycling uphill on fully suspended bikes, were that cyclists on hardtail bikes stipulated that they prefer to cycle out of the saddle. Additionally, the cyclists on hardtail bikes stated that they use their upper body to apply more force to the pedals; a factor which results in a shift of body weight and more force being exerted on the pedal. All of these factors coincide with cycling whilst in the standing position and are perhaps surprising responses as literature surrounding body positioning and mountain biking suggests that seated cycling is metabolically more efficient than standing cycling (Ryschon & Stray-Gundersen, 1991). However, it is important to note that the majority of cyclists who gave these responses for uphill cycling on a hardtail mountain bike were amateur cyclists and few professional cyclists cycling on hardtail bikes gave these responses in regards to their riding techniques.

The majority of responses relating to riding techniques adopted for uphill cycling on both fully suspended and hardtail bikes were similar. The majority of respondents stipulated that they accelerated on the approach to a hill and started a climb in a low gear, before attempting to maintain a constant speed during the ascent. Both cyclists on hardtail and fully suspended bikes also responded that they would lean forward slightly on the bike in order to spread their weight. This is perhaps unsurprising as leaning forward allows more weight to be applied to the front wheel of the bike which in turn results in better traction.

The qualitative results relating to riding downhill on both the hardtail and fully suspended bikes highlight many similarities in the riding styles adopted. Only a few differences are outlined by respondents; the most notable from cyclists riding on a fully suspended bike downhill. These cyclists maintained that they would choose a more direct route down the track and could maintain higher speeds over rough terrain. Literature supports these responses: Anon (1992) stipulates that vibrational discomfort associated with riding a bike over rough terrain has been known to contribute to rider fatigue. De Lorenzo and Hull (1999) highlight that riding bikes with suspensions isolate the cyclists from such vibrations. Nielens & Lejeune's (2001) research coincides with this, asserting that fully-suspended, compared to hardtail bikes, allow higher speeds in descents.

Conversely, respondents cycling on hardtail bikes gave specific answers relating to their riding technique whilst cycling downhill. Two distinct differences were that they chose to cycle on the route with least resistance and that they allowed their body, and not the suspension system, to absorb any bumps. Coinciding with this

Needle & Hull (1997) maintain that the dissipative elements are the arms and legs of the rider as well as the shock absorbers. It is perhaps surprising that only a small number of those cyclists riding downhill on fully suspended bikes responded that they would choose a path of least resistance. It could be assumed that even whilst riding a fully suspended bike downhill that a path with fewer bumps would allow the cyclist to maintain a higher speed.

In analysing responses from cyclists riding downhill on both the hardtail and fully suspended bikes, answers were found to be similar from both groups of cyclist: all cyclists responded that they lowered their centre of gravity and shifted their weight to the rear of the bike when cycling downhill. Both groups of cyclists also cited that they keep their body loose and their weight fully centred on both pedals (keeping them level) whilst cycling downhill. A reason for cyclists of both hardtail and fully suspended bikes adopting these riding techniques are that these styles allow the cyclist to be better balanced on the bike and allow the weight to be placed towards the rear of the bike, thus preventing the rider from falling over the handlebars.

# 4. Roller Rig

## 4.1. Objectives

A focal objective of the experimental tests on the roller rig was to investigate the effects on rider performance when cycling on a hardtail bike on a rough surface compared to a fully suspended bike on the same rough surface through measuring a subject's physiological and psychological variables. A number of subjects were tested under two cycling conditions - cycling on a fully suspended bike with bumps attached to the rig and cycling on a hardtail bike with bumps attached to the rig - and the results of the two bikes were compared to investigate which bike type was most beneficial to the rider. The subjects' $VO_2$, heart rate, Rating of Perceived Exertion (RPE) and comfort rating were recorded to determine if a difference in a subject's physiological and psychological variables could be identified between cycling on the fully suspended compared to the hardtail bike. A further objective of the experimental tests on the roller rig was to investigate rider performance through determining the difference between the mechanical variables of the hardtail and fully suspended bike. This was carried out through measuring the acceleration, velocity, displacement and force exerted at various points on the mountain bikes and the roller rig.

The roller rig used for the experimental tests had been previously designed by Titlestad et al. (2006) so as to isolate the rear wheel impact of a mountain bike in order to investigate the effects of rear wheel suspension systems (refer to Titlestad et al. (2006) for a full detailed description of the initial roller rig design). The roller rig was then adapted for the purpose of the current research. All of the tests were conducted in a controlled laboratory environment so that they could be repeated and accurately compared.

## 4.2. Experimental Tests

In order to meet the objectives of the experimental roller rig tests, it was decided that the most appropriate form of experimentation would involve a series of three tests: a run down test; a familiarisation test; and a comparative test (all three test protocols were presented to the ethics committee of Glasgow University and permission was granted to carry all three out). All three tests were sub-maximal in order to ensure that the subjects (prior to recording any variables) reached steady-state conditions.

When conducting the run down test the subjects were asked to refrain from pedalling and to allow the bike to come to rest from a pre-determined velocity. The time it took for each bike (hardtail and fully suspended) to come to rest was recorded and indicated the decrease in velocity due to the impact with the bumps. The run down test was then carried out on the roller with a smooth surface with a friction brake applied (the friction brake was used for the run down test only). The results acquired from the run down test on the roller rig with bumps attached were then compared to the results of the run down test when cycling on a smooth roller with a friction brake applied. This was to ascertain if equivalent run down times were reached for the four cycling conditions: cycling on a fully suspended bike with bumps attached to the rig; cycling on a fully suspended bike on a smooth surface; cycling on a hardtail bike with bumps attached to the rig; and cycling on a hardtail bike on a smooth surface.

The second test protocol was developed for the roller rig to establish if there was a learning and familiarisation effect when riding on the rig in a laboratory environment. If laboratory tests are repeated on several occasions, a subject's physiological responses may be modified by three concurrent processes: learning, habituation and training. Learning can lead to an increase in performance; it may be demonstrated as an improvement in efficiency due to the repetition of a task. Habituation is a form of 'negative conditioning' which can lead to decreased anxiety in the experimental situation. Training leads to an increase in tolerance to exercise - independent of anxiety level. Shepard (1969) indicates that subjects should be familiarised with the apparatus prior to any test in order to minimise these three effects. Therefore, a test had to be conducted to establish if a familiarisation period should be incorporated into the test design. Additionally, it was important to establish if a learning or familiarisation effect occurred after subsequent tests under laboratory conditions. For the familiarisation test, the same subject was asked to ride the same bike numerous times (either the hardtail or the fully suspended) under the same conditions on the roller rig with two bumps attached to ascertain if a learning effect could be observed. The analysis of this familiarisation effect is measured by comparing the subject's $VO_2$, heart rate, RPE and comfort rating scales for each of the tests then performing statistical analysis on the results to establish if the subject improves over subsequent visits.

The comparative test protocol was developed to compare the hardtail and fully suspended bike on the roller rig by exploring any correlations between the physiological, psychological and mechanical data (such as the power applied to the cranks in relation to a subject's energy expenditure), and to determine which bike was most effective under a laboratory controlled environment on a rough surface. The comparative tests were carried out only on the roller rig with bumps attached, and not on the roller rig with a smooth surface. This was decided as previous tests on the smooth surface roller rig did not highlight any differences between the hardtail and fully suspended bikes (Titlestad et al., 2006). Similar to the familiarisation test, the subjects' $VO_2$, heart rate, RPE and comfort rating were measured during the comparative tests, in addition to eight mechanical measurements: the acceleration at the front and rear of the bike; the velocity of the crank and roller; the force exerted on the pedals and the front bracket; and bump and pedal position.

## 4.3. Methodology

### 4.3.1. Rig Design

The roller rig was designed to reduce as many of the variables involved in cycling as possible in order to allow for a simplified analysis of how the suspension systems perform. The roller rig holds the bicycle steady at the front axle while allowing the rear wheel to drive a heavy roller as illustrated in Figure 4-1. It was decided that tests conducted with the front fork held rigid while the rear wheel was driven against a heavy roller would offer advantages of a better simulation of the rear wheel dynamics (Titlestad et al., 2006).

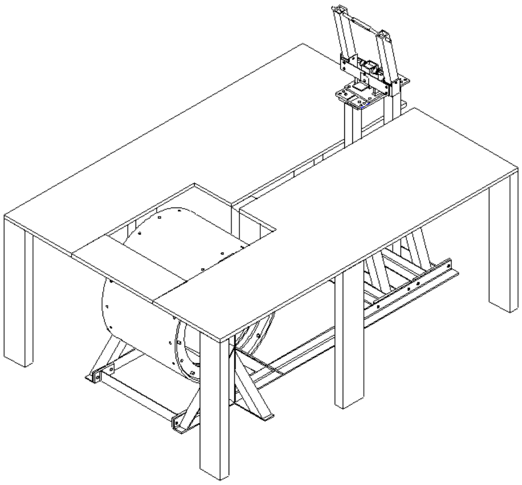


*Figure 4-1: Roller Rig*

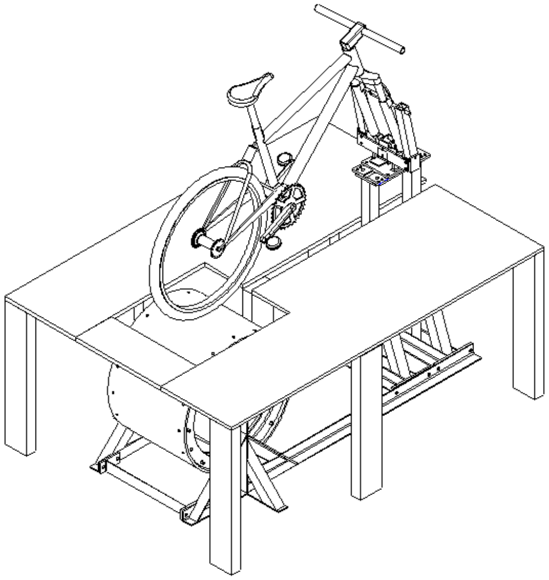


*Figure 4-2: Roller Rig with bike*

The main components of the roller rig comprise of: the roller; the front axle support bracket; the framework of the rig and the standing platform, as illustrated in Figures 4-1 and 4-2. In order to represent a rough outdoor trail, two wooden blocks were attached to the roller to replicate two bumps. The height of each bump (70 mm by 30 mm with an equivalent linear spacing of 0.96 m) was intended to represent an extreme example of riding on a rough trail which would consequently highlight any differences between the two types of suspension systems (refer to Titlestad et al. (2006) for a full detailed description of the initial roller rig design).

### 4.3.2. Bicycles

As the current study was sponsored by John White Bikes, two bikes were received on loan for testing; both of which had a similar frame size and geometry. The main difference between the two bikes was the design of the main frame: the rear triangle of the fully suspended bike (Figure 4-3) had a different design to that of the hardtail bike (Figure 4-3) so as to accommodate the rear suspension spring and damper unit. The fully suspended bike consisted of a single-swing rear suspension design.

*Figure 4-3: Marin Mount Vision (fully suspended)*

*Figure 4-4: Marin Rocky Ridge (hardtail)*

Additionally, the fully suspended bike was five kilograms heavier than the hardtail bike due to the added support required for the rear suspension. Both bikes were fitted with the same oil damped coil spring front shock absorbers (Manitou Magnum R), with pre-load set for an average rider with a weight of between sixty and seventy-five kilograms; this preload and damping remained constant throughout the tests. The same rear wheel (Shimano XT hub, Mavric 222 rim and Marin Quake 7.1 XC tyre) and tyre pressure (50 psi) were used for all of the tests.

### 4.3.3. Instrumentation and Mechanical Measurements

A total of eight mechanical measurements were taken during the experimental tests:

- Rotational velocity of the crank arms (measured using an optical sensor and disc)
- Rotational velocity of the roller (measured using an optical sensor and disc)
- Force exerted on the pedals (measured through strain gauges)
- Force exerted on the front axle (measured through strain gauges)

- Vertical acceleration at the rear of the bike (measured by an accelerometer placed under the saddle)
- Vertical acceleration at the front of the bike (measured by an accelerometer placed above the handlebars)
- Bump position (measured by using a position indicator switch)
- Pedal position (measured by using a position indicator switch)

To accurately measure the rotational velocity of the crank and the roller, two 58 slot discs were designed to pass through optical sensors. The new disks were laser cut from aluminium, thus giving a far more accurate measurement of the rotational velocity compared to the original plastic disks used by (Titlestad et al., 2006) which gave inaccurate results. The pulse frequency from the optical sensor was converted to a voltage with a frequency to voltage converter; the velocity was then calculated after the corresponding voltage had been established.

The force exerted on the pedals and the front axle of the bike was measured through the use of strain gauges. The gauges were arranged in a full Wheatstone bridge configuration to compensate for any change in temperature. They were then placed on cantilever beams on the crank arms and the front bracket of the bike which enabled the force exerted on the pedals and the front of the bike to be ascertained and compared. The strain gauges were calibrated by applying an exact force to the pedals and the front bracket so a relationship between the force and the corresponding output voltage could be established.

The vertical acceleration at the front and rear of the bikes was recorded using accelerometers placed under the saddle and above the handlebars; from this the velocity and displacement could also be determined. The seat accelerometer was fitted to the seat post under the saddle of the bike using a bolt specifically designed for this purpose. The handlebar accelerometer was mounted on the top of the steerer tube, also with a bolt specifically designed for this purpose.

Pedal position and bump indicator switches were also placed on the roller rig and crank so that the position of the pedal and bumps could be determined throughout testing. These switches produced a small voltage when the switch passed the sensor.

All of the measurements were recorded via a laptop using an analogue to digital converter and recorded using code written in Lab View. A sampling frequency of 100 HZ was chosen as this ensured that an accurate representation of the results could be produced. The data was then analysed and converted using Matlab code.

### 4.3.4. Physiological Measurements

#### 4.3.4.1. Heart Rate

Heart rate displays a linear relationship between a subject's workload and $O_2$ consumption (Astrand & Rodahl, 1986). Each subject's heart rate was recorded (using a polar heart rate monitor) every 45 s into each minute of every test. The mean value of the last two recordings was taken as the representative value for each test.

#### 4.3.4.2. Oxygen Consumption ($VO_2$)

As each of the tests was sub-maximal, this ensured that ventilation increased linearly with oxygen consumption and $CO_2$ production. Ventilation averages between twenty to twenty-five litres of air for each litre of $O_2$ consumed (Wasserman, 1994). This change in relationship is measurable by recording the volume of $CO_2$ produced to $O_2$ consumed. This $VCO_2/VO_2$ ratio is known as the Respiratory Exchange Ratio for volumes exchanged between body and atmosphere.

Each subject's $VO_2$ was measured in the fifth, sixth, ninth and tenth minutes of each test. In order to ensure that the tests were as repeatable as possible, the Douglas bag technique was used. This involved collecting one-minute samples of air and analysing the collected air immediately after each test as shown in Figure 4-5.

*Figure 4-5: Subject on Roller Rig*

A mouthpiece and a nose clip were chosen over a facemask, as this would ensure all the air from the subject was collected. The expired air was analysed using a Servomex 570A $O_2$ analyser (Servomex, Crowborough, UK) and a PK Morgan TD 801A $CO_2$ analyser (Morgan, Rainham, UK). Both analysers were calibrated before testing with gases of known concentrations. Gas volumes were measured using a Parkinson Cowan (Cranlea, Birmingham, UK) meter calibrated against a Tissot spirometer (Collins, Massachusetts, USA).

### 4.3.5. Psychology Measurements

#### 4.3.5.1. Rating of Perceived Exertion (RPE)

The Rating of Perceived Exertion scale (RPE) was first introduced in 1970 by Borg. The scale, containing fifteen grades from six to twenty, allows a subject to rate the degree of their exertion during an activity (six is the easiest workload and twenty is the hardest workload). Borg (1982) asserts that the values of the RPE scale grow comparatively linearly with the workload, and that there is a correlation between RPE and heart rate. RPE is now widely used in research and a number of factors are known to influence its use: cognition, motivation, emotion, learning, environmental and task variables on perceived exertion.

For the purpose of the current tests, the RPE scale was displayed in front of the subject who was asked to point to the number that best described the current level of exertion. The subject's RPE was recorded at the third, sixth and ninth minutes of each test.

#### 4.3.5.2. Comfort Rating

Comfort was assessed using a scale outlined by Seifert et al. (1997). The scale ranges from level one (very uncomfortable) to level five (very comfortable). This comfort scale was also displayed on a board in front of the subject who was asked to point to the number that best described the current level of overall comfort. As with the levels of RPE, the subject’s comfort level was recorded at the third, sixth and ninth minute of each test.

## 4.4. Run Down Test

### 4.4.1. Method

Two cyclists (aged 21 and 22) - one weighing 64 kg and one weighing 72 kg - carried out the run down tests on both the fully suspended and hardtail bike on the rig with a smooth roller with a friction belt attached, and on the roller with bumps attached. The subjects were instructed to ride each bike on both the smooth surface and the surface with bumps attached at a velocity of 15 km/h. The subjects were then instructed to refrain from pedalling and to allow the bike to come to rest whilst holding the pedals stationary and remaining seated. The decrease in the velocity of the roller was electronically recorded for each test against the time it took for this decrease, as displayed in Figure 4-6. The test was conducted to establish if the run down times for each bike on the roller rig with the friction belt attached are comparable to the rundown times for each bike on the roller rig with bumps attached.

### 4.4.2. Run Down Test Results

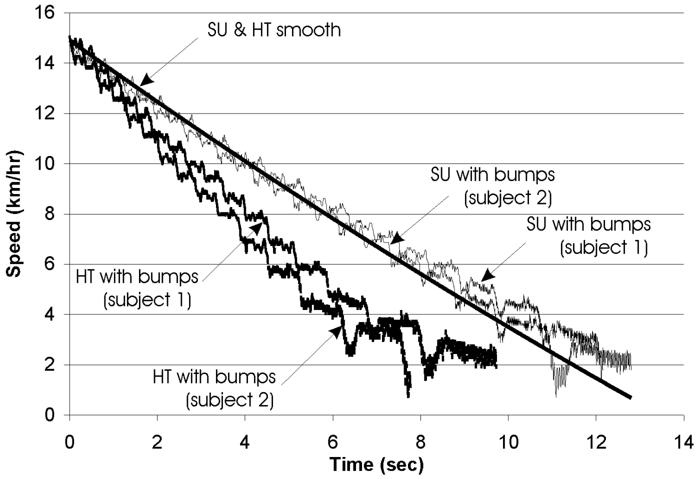


*Figure 4-6: Run down test results*

Figure 4-6 illustrates that the run down times for both bikes on the roller rig with a smooth surface are similar to those obtained for the fully suspended bicycle on the rough surface. This demonstrates that the resistance exerted by the friction belt is similar to that resistance encountered when on the fully suspended bike on the rough track. The run down times for the hardtail bike are significantly shorter, indicating that when cycling on this bike the cyclist experiences more resistance than when on the fully suspended bike; this is true for travelling over the surface with bumps. The gradient of the curves in Figure 4-6 is a measure of the deceleration of the bicycle during the run down test. To obtain an estimate of the resistance force acting to slow the bicycle down, the deceleration is multiplied by the combined mass of the subject and the bicycle. The resistance acting against the roller rig with bumps was calculated in this way and found to be 32 N and 46 N for the fully suspended and hardtail bike respectively. This results in a 44 %

greater resistance acting against the hardtail bike compared to the fully suspended bike - at a speed of 12 km/h this represents an additional 50 W of power required by the cyclist to maintain this constant speed.

## 4.5. Familiarisation Test

### 4.5.1. Method

6 subjects - aged between 21 and 30 old and weighing between 64 kg and 80 kg - participated in this test to investigate the familiarisation effect of riding on the roller rig with bumps attached. Each subject was tested on 3 separate occasions on the same bike (either the hardtail or fully suspended bike) with a minimum of two days between each test. Three subjects were tested on the fully suspended bike, and three on the hardtail bike. Each subject attended the laboratory at the same time of day for each of the experiments and was instructed to refrain from eating three hours prior to conducting the tests. Additionally, each subject was asked not to exercise on the day prior to the tests in order to ensure that their body was in the same physiological state for each test.

In order to ensure that the results of the familiarisation tests were repeatable, the bike set-up for each individual was established at the first test and remained the same for each subsequent test. The saddle height was set so that the cyclist's leg was straight when the pedal was at its lowest position; this height was recorded and used for the subject’s subsequent tests. On the initial visit to the laboratory, each subject was instructed on the use of the measuring equipment and on the RPE and comfort scales. The subject was then instructed to cycle at a speed of between 10 km/h and 15 km/h which could be maintained comfortably for ten minutes; this same speed was maintained for all subsequent tests. To allow for the subjects’ different riding styles, each cyclist was permitted to ride in the rear gear of their choice (the front gear was fixed due to the instrumentation placed on the crank) that was to be kept constant for each subsequent test.

Each subject was instructed to remain seated on the bike at all times during testing to ensure that the body mass was primarily supported through the suspension system and not through the subject's legs. This instruction was given so as to ensure that the tests were repeatable and to eliminate any uncontrollable variables. This also helped to minimise inertial effects associated with body movements which could affect the operation of the suspension systems.

At the beginning and end of each test, load readings were taken for a ten second time period to allow for comparison with the load readings taken when the cyclist was in motion. To achieve these, subjects were instructed to refrain from pedaling for the first and last 10 s of the test. After the initial 10 s of the test, the subjects cycled until their chosen speed (of between 10 km/h and 15 km/h) was reached; this speed remained constant throughout the test. A cyclometer placed on the handlebars of the bike allowed each subject to monitor their speed which was measured through the use of the optical sensor placed on the roller of the rig.

Each subject's heart rate was recorded every 45 s into each minute of each test by observing the heart rate monitor. One-minute samples of expired air were collected during the fifth, sixth, ninth and tenth minutes of all tests in order to calculate the $VO_2$. The RPE and comfort scales were recorded at the third, sixth and ninth minute of each test.

## 4.6. Familiarisation Test Results

As the familiarisation test was undertaken to ascertain if a familiarisation effect occurred after a subject undertook subsequent identical tests on the same bike, only the physiological and psychological results were required to determine this. In this respect, only those results deemed most relevant are displayed and discussed in this section: the full data set from the familiarisation test can be seen in Appendix B. Table 4-1 displays the physiological and psychological results from the familiarisation tests to establish if the subjects improved their performance on any of the bikes on the roller rig after subsequent attempts. For both the hardtail and fully suspended bike, the mean of the subjects' $VO_{2,}$ heart rate, RPE and comfort ratings was recorded on each of the three visits. The probability (p) values and standard deviation are also displayed in Table 4-1. The probability statement used for the purpose of the experimental tests on the roller rig is $p < 0.05$ or $p > 0.05$; the purpose of this statistical test is to evaluate the null hypothesis at a specific level of probability (for example $p < 0.05$). In other words, do the tests between the hardtail and fully suspended bike differ significantly ($p <0.05$) so that these differences would not be attributable to a chance occurrence more than five times in a 100 (Thomas & Nelson, 1996). The two values for the hardtail and fully suspended bikes differ significantly if the p value is less than 0.05. To calculate the p values obtained in the familiarisation test, a simple analysis of variance (ANOVA test) was carried out. The type of test used for the current study was a repeated measures ANOVA; this involved the analysis of each subject's $VO_{2,}$ heart rate, RPE and comfort rating scale on their successive visits to the laboratory to ascertain if a familiarisation effect occurred during subsequent visits.

Thomas & Nelson (1996) state that the standard deviation recordings give an estimate of the variability, or spread, of the values of the group of subjects around the mean. If the standard deviation is large, the mean may not be a good representation. The equation used to calculate the standard deviation for the purpose of the current study is outlined in Equation 4-1, where X is the subject's

$VO_2$, heart rate, RPE or comfort rating measurement; M is the mean and n is the number of subjects.

$$s = \sqrt{\Sigma ( X - M )^2 / ( n - 1 )}$$

*Equation 4-1: Calculate Standard Deviation*

*Table 4-1: Familiarisation Test Results*

| **Measurement** | **Bike** | **P** | **Mean, and standard deviation of recordings** | | |
|---|---|---|---|---|---|
| | | | **Test Number** | | |
| | | | **1** | **2** | **3** |
| $VO_2$ (ml _ kg$^{-1}$ _ min$^{-1}$) | HT | 0.88 | 32.9, s=5.0 | 32.7, s=4.7 | 32.1, s=5.5 |
| | SU | 0.92 | 20.6, s=3.1 | 20.3, s=4.2 | 20.7, s=4.0 |
| Heart rate (beats _ min$^{-1}$) | HT | 0.9 | 155.7, s=16.2 | 159.8, s=9.3 | 158.8, s=7.8 |
| | SU | 0.57 | 119.5, s=16.6 | 121.5, s=17.5 | 126.7, s=10.7 |
| RPE | HT | 0.43 | 10.8, s=1.5 | 10.2, s=2.3 | 10.8, s=2.5 |
| | SU | 0.29 | 9.8, s=0.8 | 11, s=1.0 | 11.8, s=2.0 |
| Comfort | HT | 0.21 | 2.6, s=1.4 | 2.9, s=1.5 | 2.4, s=1.3 |
| | SU | 0.22 | 3.8, s=0.8 | 3.4, s=0.8 | 3.1, s=0.2 |

HT: Hardtail
SU: Fully Suspended
P: Probability
s: standard deviation

To summarise, the results in Table 4-1 show that no familiarisation effect occurs when a subject performs subsequent tests on the roller rig. There is little difference between each of the mean values for all of the tests on the hardtail and on the fully suspended bike. The largest values obtained between the means can be identified for the results relating to the subjects' comfort ratings on the fully suspended bike between the first and third test: the first test has a mean value twenty-three percent greater than the third test. However, as the p value is greater than 0.05 for this finding, this renders the result statistically insignificant. As there in no trend for improvement over time for these subjects for any of the measurements taken, it can be concluded that no familiarisation effect occurs when cycling on the roller rig over subsequent visits to the laboratory.

## 4.7. Comparative Test

### 4.7.1. Method

6 subjects, aged between 22 and 31 years old and weighing between 74 kg to 94 kg, were used for the comparative test. The objective of this test series was to investigate the effects on rider performance when cycling on a hardtail bike on a rough surface compared to a fully suspended bike on the same rough surface on the roller rig. Each subject carried out two tests on the roller rig: one cycling on the fully suspended bike on the roller rig with bumps attached, and one cycling on the hardtail bike on the roller rig with bumps attached. This resulted in a total of twelve sets of results for analysis. The test protocol for the comparative test was identical to that of the familiarisation test. Each subject attended the laboratory at the same time of day for each of the two tests and was asked to refrain from exercising on the day prior to the tests. The subjects were instructed to cycle at a speed of between 10 km/h and 15 km/h which could be maintained comfortably for ten minutes. Each cyclist was permitted to ride in the rear gear of their choice; and each subject was instructed to remain seated on the bike at all times during testing. In order to eliminate any bias within the comparative tests, three subjects carried out the test firstly on the hardtail bike followed by the fully suspended bike. Conversely, three subjects carried out the test firstly on the fully suspended bike, followed by the hardtail bike.

Identical to the protocol undertaken for the familiarisation test, at the beginning and end of each of the comparative tests on the hardtail and fully suspended bikes, load readings were taken for a ten second time period to allow for comparison with the load readings taken when the cyclist was in motion. Again, as was identical to the familiarisation test protocol, each subject's heart rate was recorded every 45 s into each minute of each test by observing the heart rate monitor. One-minute samples of expired air were collected during the fifth, sixth, ninth and tenth minutes of all tests in order to calculate the $VO_2$ and The RPE and comfort scales were recorded at the third, sixth and ninth minute of each of the comparative tests.

In addition to the physiology and psychological measurements that were taken during the comparative tests, mechanical measurements were additionally taken for comparisons to be made between the hardtail and fully suspended bikes. The rotational velocity of the crank arms and roller; the force exerted on the pedals; the vertical acceleration at the rear and front of the bike; and bump and pedal position were all recorded during each of the tests.

### 4.7.2. Measurement Stability

In order to ascertain that each subject's physiology had met steady state conditions - as anticipated during a sub- maximal test - a repeated measure analysis of variance test was performed on results. The most appropriate statistical method for this approach is the repeated measures ANOVA test which analyses the same results on the same individuals on successive occasions such as a series of test trials (Thomas & Nelson, 1996). The test was performed on the subjects' $VO_2$ and heart rate levels at the fifth, sixth, ninth and tenth minutes of testing, and on the RPE and comfort rating levels taken at the third, sixth, and tenth minutes of testing on both the hardtail and fully suspended bike. The results of the ANOVA are displayed in Table 4-2.

*Table 4-2: Analysis of stability of measurements during tests*

|  |  |  | Average across participants at: |  |  |  |  |
|---|---|---|---|---|---|---|---|
| Measure | Bike | P | 3 min | 5 min | 6 min | 9 min | 10 min |
| VO2 (ml _ kg$^{-1}$ _ min$^{-1}$) | HT | 0.91 |  | 32.3 | 32.6 | 32.1 | 32.1 |
|  | SU | 0.008 |  | 20.6 | 22.9 | 21.7 | 21.5 |
| Heart rate (beats _ min$^{-1}$) | HT | 0.47 |  | 154.2 | 152.3 | 153.7 | 153.7 |
|  | SU | 0.045 |  | 120.3 | 119.5 | 121.8 | 119.8 |
| RPE | HT | <0.001 | 11.3 |  | 12.1 |  | 12.6 |
|  | SU | <0.001 | 9.9 |  | 10.8 |  | 11.3 |
| Comfort | HT | 0.001 | 2.6 |  | 2.3 |  | 1.9 |
|  | SU | 0.024 | 3.7 |  | 3.4 |  | 3.3 |

The results of the ANOVA test indicate that there is no significant difference in the results recorded for $VO_2$ and heart rate levels during the test on the hardtail bike, whereas on the fully suspended bike there is a significant difference for both physiological measurements. This would indicate that steady state conditions were met for subjects cycling on the hardtail bike, and not the fully suspended bike. However, as the effect size is small for the results of $VO_2$ and heart rate on the fully suspended bike, this indicates that steady physiological state conditions have been met.

Table 4-2 also shows that, as the test progresses, there is a consistent trend for the RPE values to increase as comfort levels decrease. This is a result of the rider becoming slightly more uncomfortable as the test proceeds (in particular on the hardtail bike), and subjects feel that they are cycling harder, despite steady state conditions being met. A single representative test value was required for comparisons and analysis of RPE and comfort rating levels, therefore the mean of the three readings (taken during the third, sixth and tenth minutes) was used for this purpose.

### 4.7.3. Comparative Test Physiological and Psychological Results

Table 4-3 displays the difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort ratings whilst cycling on the hardtail compared to the fully suspended, bike. This was calculated by subtracting the mean values obtained from the subjects cycling on the fully suspended bike from the mean values obtained from subjects cycling on the hardtail bike. The standard deviation and p values for these results are also highlighted in Table 4-3. For the comparative tests, a null hypothesis two-tailed dependent t test was applied to calculate the probability (p) that the differences measured are purely the result of chance. A dependent t test is a test of the significance of differences between means of two sets of values (for the hardtail and fully suspended bikes) that are related, such as when the subjects are measured on two occasions (Thomas & Nelson, 1996). The calculation used for the dependent t test is outlined in Formula 4-2, where D is the post-test minus the pretest for each subject and N is the number of paired observations.

$$t = \frac{\Sigma D}{\sqrt{[N \Sigma D^2 - (\Sigma D)^2] / (N - 1)]}}$$

*Equation 4-2: Dependant t-test calculation*

Low probabilities ($p < .05$) indicate that the measured effect in the sample (of six subjects) is evidence of a real significance in the results. The size of the differences is indicated by effect size which is also displayed in Table 4-3. Thomas & Nelson (1996) stipulate that the effect size indicates the meaningfulness (the importance or practical significance of an effect or relationship) of the findings; it is the standardised value, recorded by calculating the difference between two means and dividing this by the standard deviation. An effect size of less than 0.2 is considered small; 0.5 is considered moderate; and 0.8 or greater is considered large - thus a greater effect size coincides with a more meaningful result.

*Table 4-3: The difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort rating obtained by comparing the hardtail and fully suspended bikes.*

| | $VO_2$ (ml/kg/min) | Heart Rate (beats/min) | RPE | Comfort |
|---|---|---|---|---|
| Sample size | 6 | 6 | 6 | 6 |
| Difference between the means | 8.1 | 28.9 | 3.7 | -1.8 |
| Standard deviation | 4.8 | 13.8 | 1.8 | 0.7 |
| p-value | 0.009 | 0.037 | 0.004 | 0.001 |
| Effect size | 1.8 | 1.8 | 2.3 | -2.2 |

N.B.: All differences are obtained through subtracting (-) the means obtained from cycling on the fully suspended bike from the means obtained from cycling on the hardtail bike.

Figures 4-7 to 4-10 are scatter plot graphs of the results obtained for each subject's $VO_2$, heart rate, RPE and comfort rating when cycling on the hardtail and fully suspended bikes. The scatter plots illustrate an additional way in which the results from the physiology and psychological measurements can be displayed. Each point on the scatter graph represents one subject: the value recorded for the hardtail bike is displayed on the vertical axis, and the value recorded for the fully suspended bike is displayed on the horizontal axis.

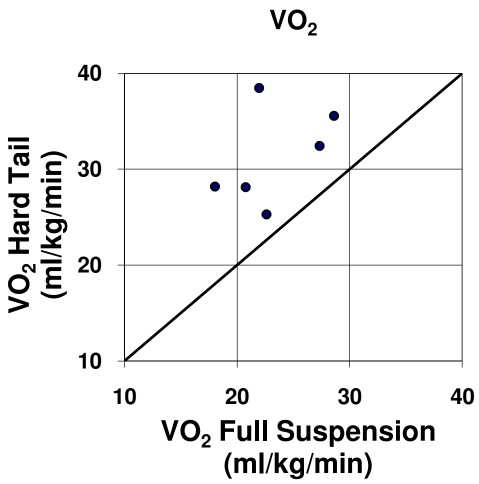


Figure 4-7: $VO_2$ Comparison

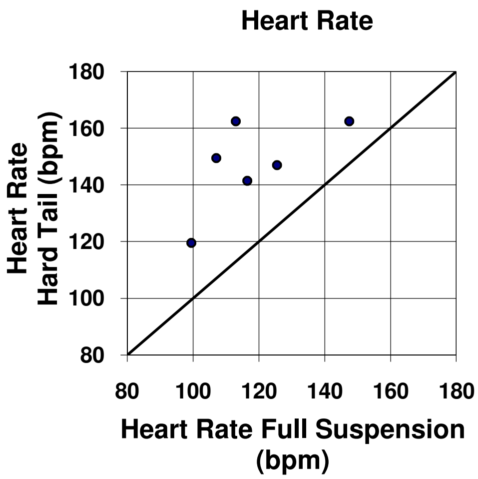


Figure 4-8: Heart rate Comparison

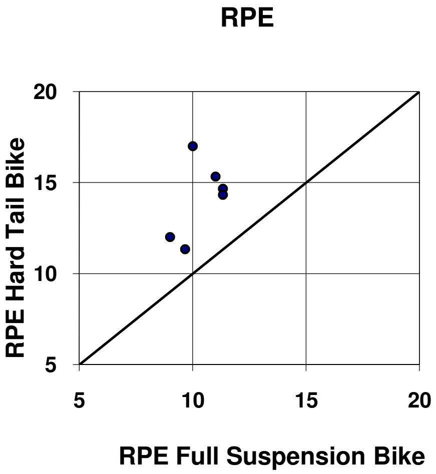


Figure 4-9: RPE Comparison

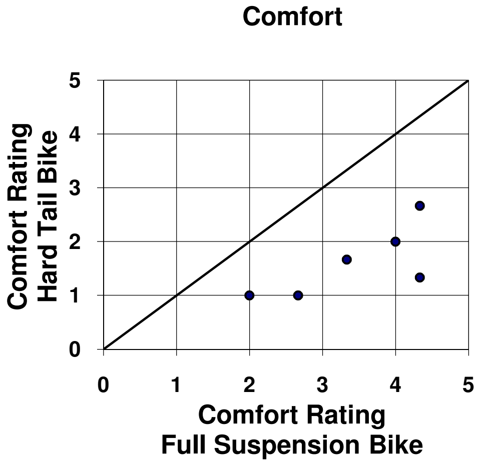


Figure 4-10: Comfort Comparison

Through analysing the results displayed in Table 4-3 and Figures 4-7 to 4-10, differences between the hardtail and fully suspended bike (when cycling over a rough surface) are highlighted. Table 4-3 presents the difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort rating whilst cycling on the hardtail compared to the fully suspended bike. All of the differences between the means for the physiological and psychological measurements are greater for the hardtail bike; thus indicating that (on average) all of the subjects experienced a higher $VO_2$, heart rate, RPE and lower comfort level (8.1; 28.9; 3.7; -1.8

difference in the means respectively) whilst riding on the hardtail bike on the roller rig with bumps attached. The lower comfort rating is represented through the negative value obtained through the difference in the means for the hardtail compared to the fully suspended bike, as (on average) all subjects were more comfortable on the fully suspended bike. As the p values for each of the difference in means are less than 0.05, this indicates that these differences are significant findings. The effect size of the difference in means, as illustrated in Table 4-3, varies from 1.8 to 2.3, supporting the claim that these results are meaningful.

The scatter plot graphs (Figures 4-7 to 4-10) clearly display the results of the physiological and psychological measurements for each individual subject, and coincide with the results outlined in Table 4-3. Each subject was found to have a lower heart rate, $VO_2$, RPE, and gave a higher comfort rating level when cycling on the fully suspended bike compared to the hardtail bike. The points above the equality line on the scatter plot graphs indicate the higher readings obtained for the hardtail bike (with the exception of the readings for comfort level which fall below the equality line as all subjects gave a lower comfort when cycling on the fully suspended bike). No anomalies are highlighted in the scatter plot graphs. The results from Table 4-3 and Figures 4-7 to 4-10 indicate that the fully suspended bike uses less of the rider's energy than the hardtail bike whilst cycling on rough terrain under these test conditions on the roller rig where only rear wheel impact is considered.

### 4.7.4. Comparative Test Mechanical Results

The mechanical results for the tests on the roller rig with bumps attached are all presented in tabulated form, and are displayed as an average of all of the six subject's mean values. Tables 4-4 and 4-5 present the findings relating to the power through, and force exerted on, the crank. Both Tables 4-4 and 4-5 display the average maximum and minimum power and force values for all six subjects; the average mean for all six subjects; and the range between the average maximum and minimum values for all six subjects. The average maximum values were calculated through taking the first 300 readings from the maximum turning points of the graphs produced by the readings from the strain gauges. The average minimum values were calculated using the same technique, but by taking the first 300 readings from the minimum turning points of the graphs produced from the results obtained from the strain gauges. The readings from only the maximum and minimum turning points of the graphs produced by the strain gauge readings were used so as to reduce any anomalies in the data - such as any irregular sharp rises and falls in the graphs.

Additionally, Tables 4-4 and 4-5 display the differences between the average maximum, minimum, mean and range values for power and force exerted on the crank. The power through the crank is calculated by multiplying the force exerted on the crank by the rotational velocity of the crank. The differences were obtained through subtracting the means obtained from cycling on the fully suspended bike from the means obtained from cycling on the hardtail bike. These differences have been calculated to compare the hardtail and fully suspended bikes. The percentage ratings highlight the improvement obtained through the use of a rear suspension. The standard deviation and p values are also given for each result as a means of comparing the findings.

*Table 4-4: Power through Crank*

| | **Hardtail Power (W)** | **Fully Suspended Power (W)** |
|---|---|---|
| Min Power | 7.925<br>s=1.488 | 7.545<br>s=1.092 |
| Max Power | 224.619<br>s=15.931 | 214.676<br>s=16.46 |
| Mean Power | 118.326<br>s=45.263 | 76.026<br>s=14.512 |
| Range between Max & Min | 216.694<br>s=16.465 | 207.13<br>s=17.07 |

| | **Hardtail subtract (-) Fully Suspended Power (W)** | |
|---|---|---|
| Difference between Min Power | 0.38<br>s=1.151 p=0.44 | 4.79 %* |
| Difference between Max Power | 9.944<br>s=8.947 p=0.049 | 4.43 %* |
| Difference between Mean Power | 42.3<br>s=44.053 p=0.07 | 35.75 %* |
| Difference in Range between Max & Min Power | 9.564<br>s=8.48 p=0.049 | 4.41 %* |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

The average results for the amount of power applied to the pedals by the subjects when riding on both bike types is illustrated in Table 4-4 through multiplying the force exerted on the pedals by the tangential pedal velocity. The most notable difference between the subjects on both bikes is the higher average power required to cycle on the hardtail bike at the same constant speed compared to cycling on the fully suspended bike. On average, a subject required 35.75 % more power to cycle on the hardtail bike compared to the fully suspended bike; however, as the standard deviation is large and the p value for this difference in average power between the two bikes is greater than 0.05, this renders this finding statistically meaningless. A smaller variation in the results between the two bikes for the average maximum power required to remain at the constant chosen speed can be identified: a 4.43 % lower maximum power is required for a subject riding on a fully suspended bike compared to a hardtail bike. In this instance, as the p value is smaller than 0.05, this result is statistically meaningful. A similar result is obtained for the average minimum power required to remain cycling at a constant speed: 4.79 % less power is required for the fully suspended bike compared to the hardtail. However, as the p value for this result is higher than 0.05, this finding is statistically insignificant. Table 4-5 displays the average maximum and minimum force exerted on the crank; the average mean force exerted on the crank; the range between the average minimum and maximum values; and the average velocity of the crank. Similarly, as with the average results obtained from the amount of power applied through the crank (Table 4-4), the differences of the averages for the force exerted on the pedals between the hardtail and fully suspended bike are also displayed in Table 4-5.

*Table 4-5: Force exerted on crank*

| | **Hardtail Force (N)** | **Fully Suspended Force (N)** |
|---|---|---|
| Min Force | 6.583 | 6.713 |
| | s=0.637 | s=0.543 |
| Max Force | 208.22 | 199.154 |
| | s=15.835 | s=17.376 |
| Mean Force | 110.809 | 68.007 |
| | s=30.336 | s=13.4 |
| Range between Max & Min | 201.637 | 192.44 |
| | s=16.15 | s=17.72 |
| Average Velocity (m/s) | 0.537 | 0.566 |
| | s=0.106 | s=0.081 |

| | **Hardtail subtract (-) Fully Suspended Force (N)** | |
|---|---|---|
| Difference between Min Force | -0.13 | 1.98 %* |
| | s = 0.319 p= 0.35 | |
| Difference between Max Force | 9.066 | 4.35 %* |
| | s= 9.305 p= 0.07 | |
| Difference between Mean Force | 42.803 | 38.36 %* |
| | s=24.785 p=0.016 | |
| Difference in Range between Max & Min | 9.19 | 4.56 %* |
| | s=9.302 p=0.065 | |
| Difference between Average Velocity (m/s) | -0.029 | 5.40 %* |
| | s=0.138 p=0.617 | |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

Table 4-5 illustrates that the average mean force exerted on the crank is 38.36% less when cycling on the fully suspended bike compared to the hardtail bike. As the p value for this result is lower than 0.05, this result is statistically meaningful. The average difference between the maximum force exerted on the crank produces a similar value to the difference in range between the maximum and minimum force (4.35 % and 4.56 % respectively), with both percentage values indicating the increase in force that is exerted on the pedals whilst riding on the hardtail bike compared to the fully suspended bike. These two results are, however, statistically insignificant as the p values for both are greater than 0.05. Similarly, the result pertaining to the difference in the average minimum force exerted on the crank is also statistically insignificant as the p value is 0.35. The difference between the average velocity of the crank is 5.4 % lower when cycling on the fully suspended bike compared to the hardtail bike. Although this is a relevant finding, the p value greater than 0.05 renders this result statistically insignificant.

Figures 4-11 and 4-12 display the results for the amount of force exerted by one subject on both the hardtail (Figure 4-11) and fully suspended bike (Figure 4-12). The graphs also display the time and how much force is exerted when the pedals pass the pedal indicator, and when the rear wheel comes into contact with the bump. An indicator bump switch was attached to only one of the bumps, as indicated in Figures 4-11 and 4-12.

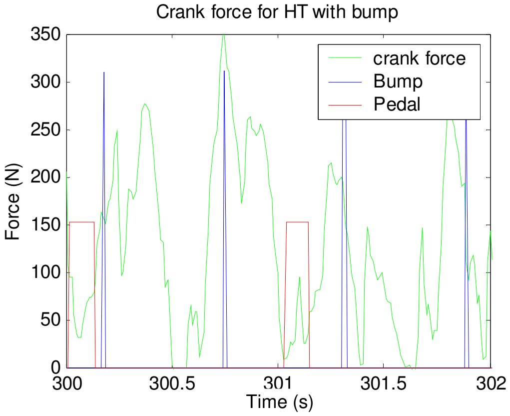


*Figure 4-11: Crank force exerted on the pedals for the hardtail bike on the roller rig on a rough surface.*

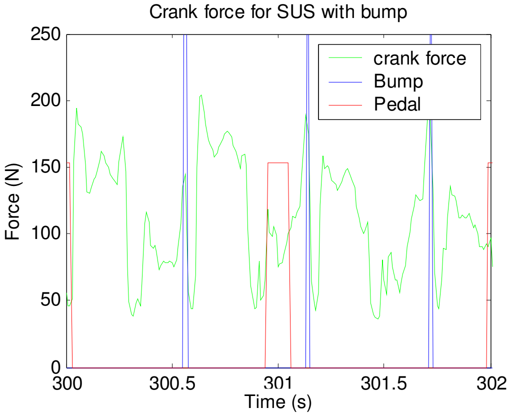


*Figure 4-12: Crank force exerted on the pedals for the fully suspended bike on the roller rig on a rough surface.*

The graphs illustrate that the least amount of force is exerted on the pedals immediately after contact with the bump. Conversely, when actual contact with the bump occurs, the rider must apply the highest force to overcome the obstacle. As can be observed from Figures 4-11, 4-12 and table 4-5, on average the rider exerts more force on the pedals of the hardtail bike compared to the fully suspended bike. A possible reason for this is that the rear suspension absorbs some of the impact force resulting in less force being required to overcome the obstacle. The graphs for both bikes are similarly shaped, although it is evident that a higher maximum and lower minimum turning point exist for the cyclist on the hardtail bike. The maximum amount of force exerted on the pedals is 350 N and 200 N for cycling on the hardtail and fully suspended bikes respectively. This finding demonstrates a significant difference between both bikes. As aforementioned, less force is exerted on the pedals of the fully suspended bike, compared to the hardtail, when contact with the bump occurs. Additionally, Figure 4-12 highlights that a greater oscillation is apparent for the fully suspended bike following contact with the bump - this is a result of the rear suspension of the bike oscillating. Another factor that determines the amount of force exerted on the crank is the position of the pedals - the maximum force exerted on the pedals occurs when they are in a horizontal position. However, this is not made fully apparent from Figures 4-11 and 4-12 as the overriding factor which determines the amount of exerted force is the rough surface.

Tables 4-6 to 4-11 display the results calculated from the findings recorded at both the front and rear accelerometers of the fully suspended and hardtail bikes. Similar to the results for the power through, and force exerted on, the crank (Tables 4-4 and 4-5), the average maximum and minimum acceleration, velocity and displacement of the handlebars and seat were calculated through taking the first 300 readings from the maximum and minimum turning points of the graphs produced by the accelerometer. However, in contrast to the results relating to the pedals (Tables 4-4 and 4-5), the mean averages have not been included in the results displayed in Tables 4-6 to 4-11. The mean averages would equate to approximately zero for the velocity, acceleration and displacement of the seat and handlebars due to the positive and negative values that are obtained when calculating the results. Consequently, the average root mean squared (RMS) value has been calculated to compensate for this. As with the results displayed in Tables 4-4 and 4-5, the lower sections of Tables 4-6 to 4-11 compare the findings from the accelerometers on the fully suspended and hardtail bike. Tables 4-6 to 4-11 also outline the percentage differences between the results; the standard deviations; and p values from the results of the t-test.

*Table 4-6: Acceleration at the handlebars*

| | **Hardtail Acceleration (m/s^2)** | **Fully Suspended Acceleration (m/s^2)** |
|---|---|---|
| Min Acceleration | -1.129 | -1.104 |
| | s=0.045 | s=0.045 |
| Max Acceleration | 1.29 | 1.261 |
| | s=0.075 | s=0.096 |
| Range between Max & Min | 2.41 | 2.365 |
| | s=0.109 | s=0.134 |
| RMS | 0.489 | 0.336 |
| | s=0.118 | s=0.053 |

| | **Hardtail subtract (-) Fully Suspended Acceleration (m/s^2)** | |
|---|---|---|
| Difference between Min Acceleration | -0.025 | 2.21 %* |
| | s=0.048 p=0.249 | |
| Difference between Max Acceleration | 0.029 | 2.21 %* |
| | s=0.046 p=0.18 | |
| Difference in Range between Max & Min | 0.054 | 2.21 %* |
| | s=0.093 p=0.209 | |
| Difference between RMS | 0.153 | 31.25 %* |
| | s=0.094 p=0.019 | |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

Table 4-6 displays the average readings obtained from the accelerometers placed at the handlebars of the hardtail and fully suspended bike. The results outline that the average minimum acceleration of the handlebars of the hardtail bike is 2.21 % lower than that of the fully suspended bike, and that the maximum acceleration at the handlebars of the hardtail bike is 2.21 % higher than that of the fully suspended bike. Consequently, the range between the average maximum and minimum values for the acceleration of the handlebars is 2.21 % higher for the hardtail bike compared to the fully suspended bike. Despite these findings, the p values (all greater than 0.05) render these results insignificant. In contrast, the result obtained for the average difference between the acceleration of the handlebars of both bikes is statistically significant: the acceleration of the handlebars is 31.25 % lower whilst cycling on the fully suspended bike compared to the hardtail bike.

Figures 4-13 to 4-24 illustrate that both bikes move vertically in the positive and negative direction. Consequently, the averages of the positive and negative values do not provide useful data from which to draw conclusions. Subsequently, the root mean squared (RMS) is used to calculate the averages - making all of the values positive so an average may be obtained for the acceleration, velocity and displacement.

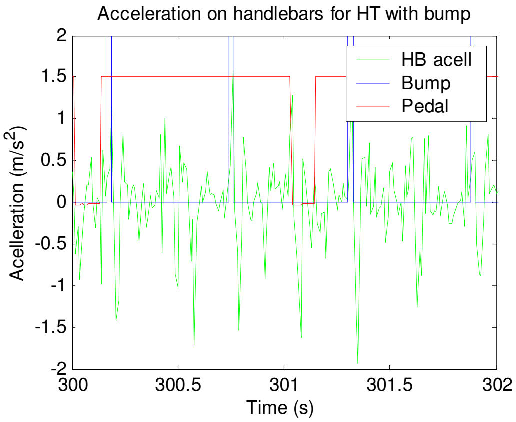


*Figure 4-13: Acceleration of the handlebars for the hardtail bike on the roller rig on a rough surface*

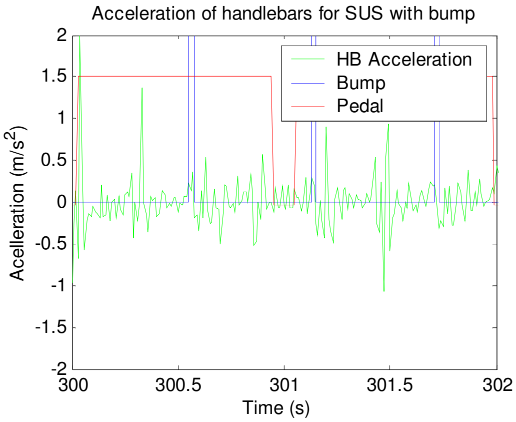


*Figure 4-14: Acceleration of the handlebars for the fully suspended bike on the roller rig on a rough surface*

Figures 4-13 and 4-14 illustrate the acceleration of the handlebars of both the hardtail and fully suspended bikes. The acceleration of the handlebars of the hardtail bike is greater than that of the fully suspended bike. For both bikes, the greatest minimum turning point of the graphs (Figures 4-13 and 4-14) occurs immediately after the wheel contacts the bump; followed by the maximum acceleration after contact of the rear wheel with the ground. There is however, a significant difference ($p$ value $< 0.05$) between the results obtained for the average difference in RMS between the acceleration of the handlebars of both bikes: the acceleration of the handlebars is 31.25 % lower whilst cycling on the fully suspended bike compared to the hardtail bike (Table 4-6). As the hardtail bike has no rear suspension to absorb bump impact, the rider's weight is forced forward onto the front of the bike, thus attributing to the higher handlebar acceleration results obtained for the hardtail bike.

*Table 4-7: Acceleration at the seat*

| | Hardtail Acceleration (m/s^2) | Fully Suspended Acceleration (m/s^2) |
|---|---|---|
| Min Acceleration | -3.164 | -3.14 |
| | s=0.139 | s=0.143 |
| Max Acceleration | 5.686 | 5.61 |
| | s=0.216 | s=0.282 |
| Range between Max & Min | 8.85 | 8.752 |
| | s=0.35 | s=0.143 |
| RMS | 1.596 | 1.279 |
| | s=0.249 | s=0.158 |

| | Hardtail subtract (-) Fully Suspended Acceleration (m/s^2) | |
|---|---|---|
| Difference between Min Acceleration | -0.024 | 0.75 %* |
| | s=0.035 p=0.15 | |
| Difference between Max Acceleration | 0.074 | 1.31 %* |
| | s=0.118 p=0.179 | |
| Difference in Range between Max & Min | 0.098 | 1.11 %* |
| | s=0.136 p=0.137 | |
| Difference between RMS | 0.317 | 19.89 %* |
| | s=0.208 p=0.022 | |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

Table 4-7 displays the mean results found through measuring the acceleration at the seat of the fully suspended and hardtail bike during the experimentations. The average minimum acceleration of the seat of the hardtail bike is greater (by 0.75 %) than that of the fully suspended bike. Coinciding with this finding, the average maximum acceleration of the seat of the hardtail bike is also greater (by 1.31 %) than that of the fully suspended bike. However for both of these results, the p value is greater than 0.05, indicating that the results are statistically insignificant. The difference in range between the maximum and minimum acceleration of the hardtail and fully suspended bike indicate that the acceleration of the seat is 1.11 % greater whilst cycling on the hardtail bike compared to the fully suspended bike. The p value for this result is, however, 0.137; rendering this result statistically insignificant. The difference between the RMS values has been calculated to represent the average mean seat acceleration for both the hardtail and fully suspended bike. The findings from this indicate that the average mean acceleration of the seat of the hardtail bike is 19.89 % greater than that of the fully suspended bike. This result is rendered statistically significant as the p value is calculated to be less than 0.05.

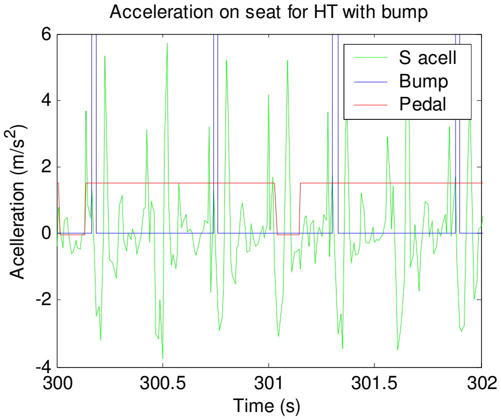


*Figure 4-15: Acceleration of the seat for the hardtail bike on the roller rig on a rough surface.*

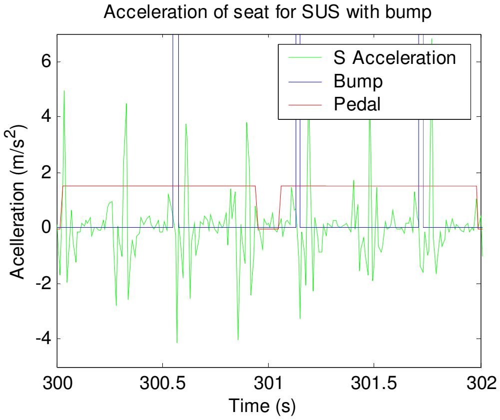


*Figure 4-16: Acceleration of the seat for the fully suspended bike on the roller rig on a rough surface*

Figures 4-15 and 4-16 display the results obtained from the accelerometer placed under the seat of the hardtail and fully suspended bike of one subject during testing. From the graphs it is apparent that, for both bikes, the acceleration of the saddle reaches a peak when the initial contact between the bump and rear wheel occurs. This is then followed by the maximum acceleration in the negative direction occurring after the wheel leaves the bump. Interestingly, the acceleration of the saddle of the fully suspended bike is lower, compared to the hardtail bike, when initial contact with the bump occurs. Following impact with the bump, there is a significant peak in the acceleration of the saddle when the rear wheel of the hardtail bike impacts with the ground. Although a similar peak can be observed when the fully suspended bike impacts with the ground, this is of a smaller magnitude than that measured for the hardtail bike. Both bikes present a slight bobbing effect prior to landing after contact with the bump occurs, as illustrated in Figures 4-15 and 4-16. However, this bobbing effect is more apparent after landing on the fully suspended bike compared to the hardtail bike.

In comparing the acceleration of the front of each bike (handlebar acceleration; Table 4-6) to the acceleration of the rear of each bike (saddle acceleration; Table 4-7), it was found that the acceleration at the front of the bike is far less than that of the rear. The RMS value for the front acceleration of the hardtail bike is only 30.64 % of that value recorded for the rear acceleration of the hardtail bike. This is also true for the RMS value of the fully suspended bike which has a front acceleration of 26.27 % of the value recorded for the rear acceleration. This is perhaps an expected result as the roller rig is held rigid at the front forks and only the rear wheel comes into contact with the bump.

The average velocity readings obtained from the accelerometers placed at the handlebars of the hardtail and fully suspended bikes are displayed in Table 4-8. The results indicate that there is a 2.88 % difference between the average minimum velocities measured at the handlebars of both bikes (the handlebars of the hardtail bike move with a greater velocity in the negative direction). The average maximum velocity measured at the handlebars is also greater (by 4.5 %) whilst cycling on the hardtail bike in comparison to the fully suspended bike. These results are, however, statistically insignificant as the p values for each are greater than 0.05. Conversely, the results for the difference in average velocity of the handlebars of both bikes highlight a significant difference between the two bikes, which is also statistically meaningful as the p value falls below 0.05. This result shows that the handlebars of the hardtail bike have a 50.05 % higher velocity than the fully suspended bike.

*Table 4-8: Velocity at the handlebars*

| | **Hardtail Velocity (m/s)** | **Fully Suspended Velocity (m/s)** |
|---|---|---|
| Min Velocity | -0.125<br>s=0.006 | -0.121<br>s=0.097 |
| Max Velocity | 0.146<br>s=0.009 | 0.139<br>s=0.007 |
| Range between Max & Min | 0.271<br>s=0.013 | 0.261<br>s=0.014 |
| RMS | 0.084<br>s=0.026 | 0.042<br>s=0.011 |

| | **Hardtail subtract (-) Fully Suspended Velocity (m/s)** | |
|---|---|---|
| Difference between Min Velocity | -0.004<br>s=0.007 p=0.229 | 2.88 %* |
| Difference between Max Velocity | 0.007<br>s=0.046 p=0.138 | 4.50 %* |
| Difference in Range between Max & Min | 0.010<br>s=0.016 p=0.168 | 3.75 %* |
| Difference in RMS | 0.042<br>s=0.023 p=0.014 | 50.05 %* |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

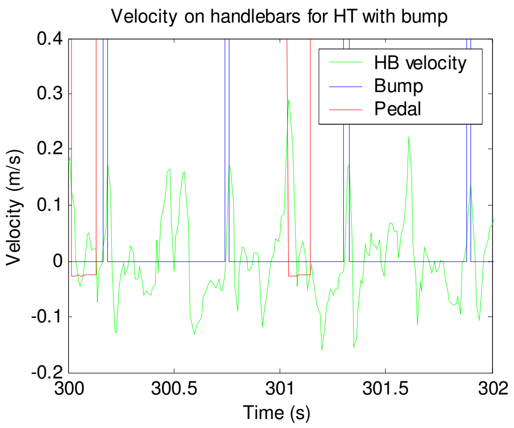


Figure 4-17: Velocity at the handlebars for the hardtail bike on the roller rig on a rough surface.

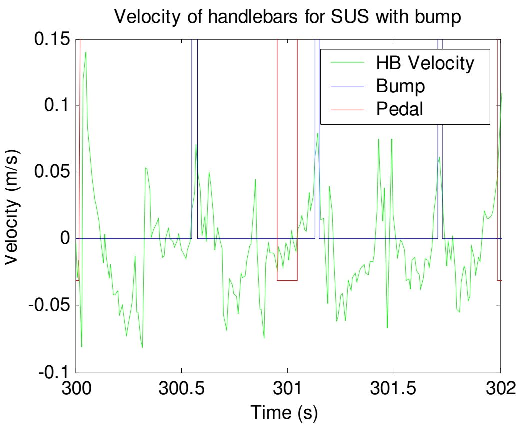


Figure 4-18: Velocity at the handlebars for the fully suspended bike on the roller rig on a rough surface.

Figures 4-17 and 4-18 display the velocity of the handlebars of the fully suspended and hardtail mountain bikes on the roller rig for one subject only. The maximum velocity occurs immediately when the bike impacts with the bump. Following this impact, both graphs indicate that the maximum negative velocity occurs directly after impact when the wheel comes into contact with the ground. Although the graphs are similar in shape, the results for the velocity of the handlebars of the hardtail bike are significantly higher than the fully suspended bike.

Table 4-9 displays the average results obtained from the accelerometers used to measure the velocity of the seats of both the hardtail and fully suspended bike. The displayed results illustrate that the average minimum and maximum velocity of the seat is greater (by 3.01 % and 2.37 % respectively) for the hardtail bike compared to whilst cycling on the fully suspended bike. Correspondingly, the difference in the range between these average maximum and minimum values for the velocity of the seat is 2.72 % greater for the hardtail bike compared to the fully suspended bike. Yet, as the p values for the average difference in the minimum, maximum and range of these values of the seat velocity are all greater than 0.05, these results are statistically insignificant. Conversely, the difference between the average RMS values is statistically significant and illustrates that the average velocity of the seat on the fully suspended bike is 38.46 % less than that of the hardtail bike. This highlights that the seat of the fully suspended bike moves at a slower velocity than that of the hardtail bike, resulting in an increase in comfort whilst cycling on the fully suspended bike over a bumpy surface. This finding coincides with the results for the comfort scale ratings - all subjects rated the fully suspended bike as more comfortable than the hardtail bike when riding over rough terrain (Figure 4-10).

*Table 4-9: Velocity at the seat*

| | **Hardtail Velocity (m/s)** | **Fully Suspended Velocity (m/s)** |
|---|---|---|
| Min Velocity | -0.513<br>s=0.025 | -0.497<br>s=0.03 |
| Max Velocity | 0.424<br>s=0.014 | 0.414<br>s=0.017 |
| Range between Max & Min | 0.937<br>s=0.038 | 0.911<br>s=0.047 |
| RMS | 0.223<br>s=0.041 | 0.137<br>s=0.01 |

| | **Hardtail subtract (-) Fully Suspended Velocity (m/s)** | |
|---|---|---|
| Difference between Min Velocity | -0.015<br>s=0.028 p=0.22 | 3.01 %* |
| Difference between Max Velocity | 0.01<br>s=0.014 p=0.133 | 2.37 %* |
| Difference in Range between Max & Min | 0.026<br>s=0.041 p=0.183 | 2.72 %* |
| Difference between RMS | 0.0857<br>s=0.04 p=0.01 | 38.46 %* |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

Table 4-9 of Chapter 4 illustrates that the hardtail bike has a 38.46 % higher RMS saddle velocity compared to the fully suspended bike; a significant finding due to the p value of less than 0.05. The minimum vertical velocity of the seat is 3.01 % less for the hardtail bike, and the maximum vertical velocity is 2.37 % greater for the fully suspended bike. The difference in range between the maximum and minimum values for saddle velocity is 2.72 % higher for the hardtail bike compared to the fully suspended bike. Once again, these results highlight a significant advantage for the fully suspended bike over the hardtail bike for cycling on rough terrain.

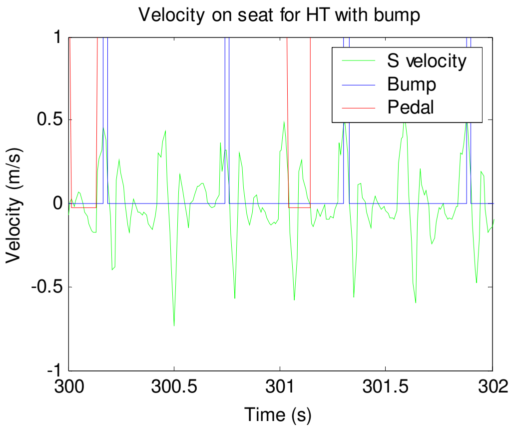


*Figure 4-19: Velocity at the seat for the hardtail bike on the roller rig on a rough surface.*

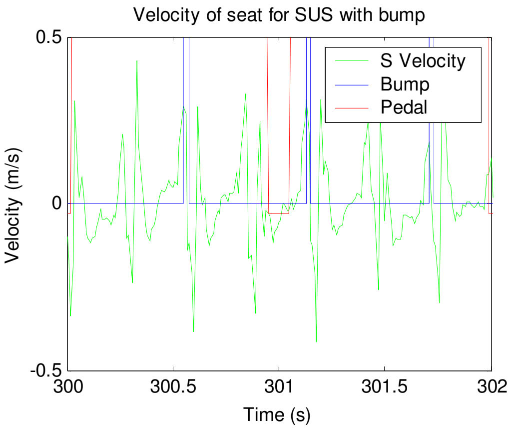


*Figure 4-20: Velocity at the seat for the fully suspended bike on the roller rig on a rough surface.*

The velocity of the saddles of the fully suspended and hardtail mountain bikes on the roller rig (for one subject only) are illustrated in Figures 4-19 and 4-20. Similar to the results for the velocity of the handlebars, the maximum velocity of the saddle occurs on at contact with the bump. The maximum negative velocity occurs directly after impact when the wheel once again comes into contact with the ground. Figures 4-19 and 4-20 indicate that the velocity of both the seat and handlebars of the hardtail bike are higher in both the positive and negative direction than the velocities obtained from the seat and handlebars of the fully suspended bike.

Similar to the findings comparing the acceleration of the front of each bike to the acceleration of the rear of each bike, it was found that the velocity at the front of each bike (handlebar velocity; Table 4-8) is less than the velocity at the rear of each bike (saddle velocity; Table 4-9). The RMS value for the velocity measured at the handlebars of the hardtail bike is only 37.67 % of the result measured for the velocity at the saddle of the hardtail bike. This is also true for the RMS value for the fully suspended bike which has a handlebar velocity of 30.66 % of the value recorded for the saddle velocity.

*Table 4-10: Displacement at the handlebars*

| | **Hardtail Distance (m)** | **Fully Suspended Distance (m)** |
|---|---|---|
| Min Displacement | -0.004 | -0.004 |
| | s=0.0002 | s=0.0002 |
| Max Displacement | 0.004 | 0.0036 |
| | s=0.0003 | s=0.0002 |
| Range between Max & Min | 0.008 | 0.007 |
| | s=0.0005 | s=0.0004 |
| RMS | 0.003 | 0.002 |
| | s=0.001 | s=0.001 |

| | **Hardtail subtract (-) Fully Suspended Distance (m)** | |
|---|---|---|
| Difference between Min Displacement | -0.0001 | 2.63 %* |
| | s=0.00015 p=0.154 | |
| Difference between Max Displacement | 0.00017 | 4.55 %* |
| | s=0.0002 p=0.115 | |
| Difference in Range between Max & Min | 0.00027 | 3.59 %* |
| | s=0.0004 p=0.122 | |
| Difference in RMS | 0.0015 | 43.91 %* |
| | s=0.001 p=0.015 | |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

Table 4-10 presents the average results for the displacement of the handlebars of both bikes measured by the accelerometers placed above the steerer tubes. The values indicate the distance that the handlebars travel when the rear wheel impacts with the bump. The results in Table 4-10 highlight that there is an average difference of 2.63 % between the minimum displacements of the handlebars on both bikes - with the handlebars of the hardtail bike producing a larger displacement in the negative direction than that of the fully suspended bike. Similarly, the average maximum displacement of the handlebars is 4.55 % greater when cycling on the hardtail bike compared to the fully suspended bike.

The difference in the range between these maximum and minimum values is 3.59 % greater for the hardtail bike, thus indicating that there is a larger displacement of the handlebars whilst cycling on the hardtail bike. Despite these findings, these results remain statistically insignificant as each holds a p value of less than 0.05. Conversely, the difference in the displacements of the handlebars of both bikes is statistically significant and a handlebar displacement 43.91 % larger for the hardtail bike compared to the fully suspended bike is recorded. This percentage equates to a handlebar displacement of the hardtail bike which is 1.5 mm greater than that of the fully suspended bike.

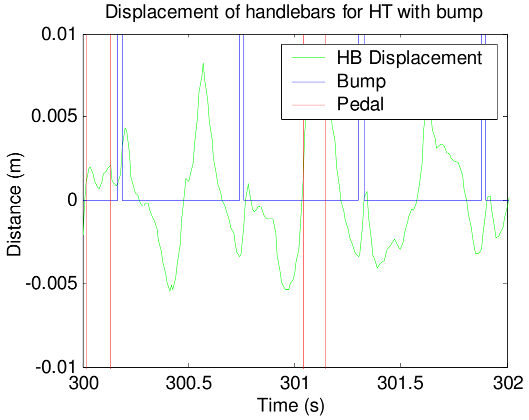


*Figure 4-21: Displacement at the handlebars for the hardtail bike on the roller rig on a rough surface.*

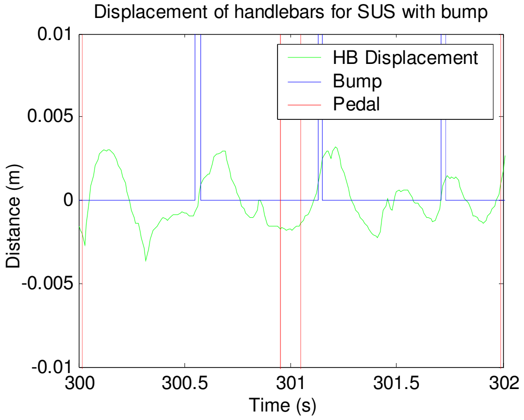


*Figure 4-22: Displacement at the handlebars for the fully suspended bike on the roller rig on a rough surface.*

Figures 4-21 and 4-22 illustrate the displacement of the handlebars of the hardtail and fully suspended bikes when contact with the bump occurs. The maximum displacement occurs on contact with the bump, followed by the minimum displacement as the bike comes into contact with the ground once again. From analysis of the graphs, it is apparent that the displacement results are greater for the hardtail bike than the fully suspended bike, indicating that more movement occurs at the front of the hardtail bike compared to the fully suspended bike.

The RMS value for handlebar displacement of both of the bikes was calculated to be 43.91 % greater for the hardtail bike compared to the fully suspended bike (a significant finding producing a p value of less than 0.05). Only a slight difference is apparent between the minimum displacements of the two bikes: 0.1 mm, equating to an average minimum displacement of 2.63 % less for the hardtail bike compared to the fully suspended bike. The average maximum displacement produces a slightly higher difference of 4.55 % greater maximum displacement for the hardtail bike (yet the difference is not statistically significant). The range between the maximum and minimum values is 3.59 % higher for the fully suspended bike compared to the hardtail bike.

*Table 4-11: Displacement at the seat*

| | Hardtail Displacement (m) | Fully Suspended Displacement (m) |
|---|---|---|
| Min Displacement | -0.007 | -0.007 |
| | s=0.0002 | s=0.0003 |
| Max Displacement | 0.011 | 0.01 |
| | s=0.0004 | s=0.0005 |
| Range between Max & Min | 0.017 | 0.017 |
| | s=0.0005 | s=0.0007 |
| RMS | 0.006 | 0.004 |
| | s=0.001 | s=0 |

| | Hardtail subtract (-) Fully Suspended Displacement (m) | |
|---|---|---|
| Difference between Min Displacement | -0.0001 | 1.75 %* |
| | s=0.0001 p=0.1 | |
| Difference between Max Displacement | 0.0004 | 3.72 %* |
| | s=0.0006 p=0.158 | |
| Difference between Max & Min Range | 0.0005 | 2.97 %* |
| | s=0.0007 p=0.143 | |
| Difference between RMS | 0.002 | 32.82 %* |
| | s=0.002 p=0.034 | |

*** : % Improvement by fitting suspension = 100*(average diff. / HT mean)**

The average results obtained through measuring the displacement of the seats of both the hardtail and fully suspended bikes are displayed in Table 4-11. The results highlight that the average maximum displacement of the seat of the hardtail bike is 3.72 % higher than that of the fully suspended bike, and that the average minimum displacement of the seat of the hardtail bike is 1.75 % lower than that of the fully suspended bike. However, these results are not statistically significant due to the high p values obtained for each. Conversely, the result obtained for the difference in the RMS values representing the average seat displacements is (having produced a p value of less than 0.05) statistically significantly. This result indicates that there are real differences between the fully suspended and hardtail bike: the average seat displacement is 32.82 % greater whilst cycling on the hardtail bike compared to the fully suspended bike; this equates to a displacement of 2 mm higher than that of the fully suspended bike.

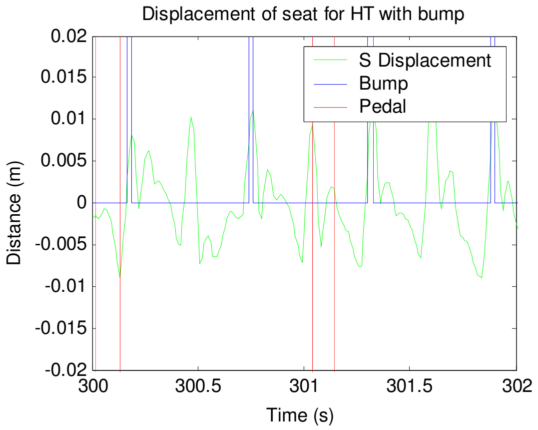


*Figure 4-23: Displacement of the seat for the hardtail bike on the roller rig on a rough surface.*

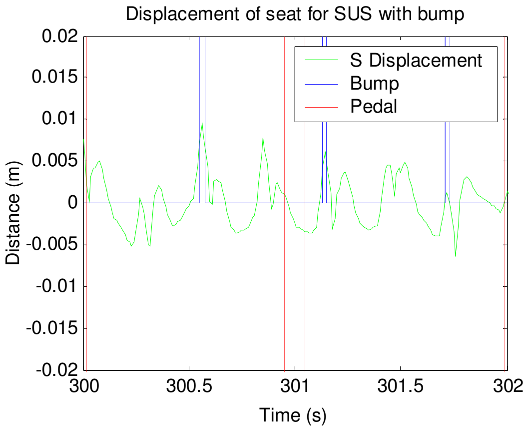


*Figure 4-24: Displacement of the seat for the fully suspended bike on the roller rig on a rough surface.*

Figures 4-23 and 4-24 present the results for the displacement of the seats of the hardtail and fully suspended bike for one subject only. The maximum displacement occurs at the point of impact between the rear wheel and the bump. The maximum displacement in the negative direction occurs after contact with the bump. The graph for the fully suspended bike (Figure 4-24) results in a smoother displacement than that of the hardtail bike, highlighting that less oscillation occurs whilst cycling on the fully suspended bike. These results concur with the lower comfort ratings given for subjects cycling on the fully suspended bike, compared to the hardtail bike, on the roller rig (Figure 4-10), thus indicating that the rear of the fully suspended bike moves to a lesser degree than the hardtail bike.

The maximum and minimum turning points for the seat displacement of both the hardtail and fully suspended bike are similar, with a range between the maximum and minimum turning points of 17.5 mm for the hardtail bike and 17 mm for the fully suspended bike (Table 4-11). However, the average seat displacement, according to the RMS value for the hardtail bike is 6 mm compared to 4 mm for the fully suspended bike. This equates to a 32.82 % difference between the saddle displacement of the hardtail and fully suspended bike; a significant finding as the p value is less than 0.05. This finding correlates with the physiological and psychological results recorded during the experiments on the roller rig, in which higher levels of $VO_2$ were recorded for subjects cycling on the hardtail bike and where all subjects rated the fully suspended bike as more comfortable than the hardtail bike

# 5. Rolling Road Rig

## 5.1. Objectives

The key objective of the rolling road rig experiments was to conduct controlled laboratory tests which further investigated the effects on rider performance when cycling on a hardtail bike compared to a fully suspended bike on a rough, and smooth, surface. Previous research and experimentation in the current study highlighted contradictions in this area: the results from the cyclists' questionnaires (Appendix A) highlighted that the majority of respondents (63 %) still chose to ride a hardtail bike rather than a fully suspended bike, and that seventy-six percent of respondents experienced a bobbing effect whilst cycling on a fully suspended bike. Conversely, the results from the roller rig experimental tests illustrated that the fully suspended bike (compared to the hardtail bike) provided significant physiological and psychological advantages to the rider when cycling on a rough surface. As the results from the questionnaires contradicted those from the roller rig experiments, it was decided that further research and experimentation should be undertaken in order to support, or indeed contradict, the previously conducted research and testing on the roller rig.

A possible reason for the encountered discrepancies between the questionnaire and roller rig results may be attributed to the design of the initial roller rig. Although the roller rig provided an adequate starting point for the current research as it succeeded in eliminating many of the variables involved in cycling, and gave repeatable results for determining the effects of rear wheel impact on the rear suspension system, it was essential to conduct the experiments on a rig which presented the cyclist with a closer representation of true riding conditions. In this respect, a further objective of the rolling road rig experiments was to design and develop a rig which simulated outdoor riding conditions more closely than the previously used roller rig.

## 5.2. Design Considerations

When considering the design of the rolling road rig and subsequent testing, it was important to explore those aspects of the roller rig which did not represent mountain bike riding conditions accurately so that alternative features could be implemented into the design of the new rolling road rig.  A contributing factor to the problems surrounding the design of the previously used roller rig was that no front wheel was incorporated into its design, and thus it did not represent a realistic model of a bike.  Under normal cycling conditions the rider would travel over any impending bumps with both the front and rear wheel; something which was not considered in the design of the roller rig.  Consequently, in order to understand the effect that cycling on rough terrain has on the dynamics of a suspension system, it is also vital to examine how the suspension reacts after the front wheel comes into contact with a bump.

An additional aspect of the roller rig experiments to be considered was the size, shape and frequency of the bumps that the subjects encountered during testing. After completion of the tests on the roller rig, each subject was asked for their opinions and suggestions on how the rig could be improved to match cycling outside more closely: all subjects agreed that the height and shape of the bumps was too severe.  Additionally, the subjects concluded that if they were to encounter such bumps (whilst cycling off-road) of the magnitude used for the roller rig tests, they would attempt to cycle around them if possible.  Each subject also stipulated that - relative to a cross-country track - the bump frequency was exaggerated for the purpose of testing on the roller rig.  Yet another aspect relating to the tests on the previously used roller rig was the concern that the subjects could not see the impending bumps which were placed on the roller - in true riding conditions, a cyclist is able to view any impending bumps and attempt to avoid them if possible.

All of the concerns surrounding the design of the initial roller rig, and subsequent testing on it, were taken into consideration during the design of the rolling road rig. It was imperative to design and develop a rig which would allow tests to be conducted that addressed the gaps in research - found through the analysis of the research in the literature review and findings of the questionnaire. The initial stages of the design process of the rolling road rig identified these gaps in research and subsequently they were recorded in the form of a tree chart (Appendix D) which allowed the areas of development to be identified easily. After analysis of all previous research and test results: literature contained within the literature review; questionnaire results; and physiological, psychological and mechanical results from the roller rig experiments, it was concluded that the new rig should be designed to present as close a representation as possible to cycling on rough terrain under true outdoor riding conditions. Further reflections also concluded that the new rig should include additional instrumentation (to that of the roller rig) so all possible mechanical, physiological and psychological aspects of riding on both the hardtail and fully suspended bikes could be analysed, and that the rig should allow for the testing of any bike and suspension system type to allow for the implementation of future work. As a result of considering the previous research and testing relating to the current study, it was possible to determine a weighted objectives method to be used as a protocol for the design of the rolling road rig. The weighted objectives method used for the rolling road rig is illustrated in Table 5-2.

## 5.3. Conceptual Design

The conceptual design process for the rolling road rig is primarily concerned with the generation of solutions to satisfy the weighted objectives method (Table 5-2). Various solutions were generated for the purpose of the current study to ensure that the most appropriate design was chosen for the rig. The initial design methodology of the rolling road rig involved designing several concepts and reflecting upon their strengths and weaknesses until the most suitable design could be ascertained. When considering the conceptual designs, it was important to focus on a design which considered the objectives of the experimental rolling road rig tests. In order to establish which design was the most effective for the needs of the current project, a morphological chart (Table 5-1) was used to ensure all elements of the design (as set out in the weighted objectives method) were covered. A morphological chart aims to highlight all theoretically conceivable solutions to a problem: all parameters that may occur in the final rig design are identified and categorised. For the purpose of the current study, the solutions were analysed and evaluated and design concepts were developed (all of the design concepts are illustrated in Appendix E).

*Table 5-1: Morphological Chart*

| Solutions<br>Sub-functions | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Track | Wooden slats | Rubber belt | Metal slats | Roller | Rollers | Hydraulic jack |
| What the track runs on | Rollers | PTFE | Other plastic surface | Wood | Metal | Lubricated surface |
| Frame design | Adjustable height | Adjustable width | Non-adjustable | Adjustable height and width | | |
| Power source | Human | Motor | Human and motor | | | |
| How bike is held | Front wheel | Rear wheel | Frame | Handlebars | Seat | Not held |
| Bumps | Wooden | Rubber | Hydraulic jack | Metal | None | |
| How bumps attached | Adhesive | Bolts | clips | Welding | | |
| How to prevent belt from slipping | Metal chain | Holes in rubber | Roller friction | Motor | | |
| Bump shape | Triangle | Round | Rounded edges | Chamfered edges | Square | Rectangle |
| Match inertial effects of riding outdoors | Flywheel | Weight of track | Motor | Weight of rollers | | |
| Frame design | Metal plate | Wooden batons | Metal Angle | Metal box sections | Adjustable height | |
| How to stop moving during testing | Frame weight | Bolted to floor | Bolted to wall | Large feet | | |

*Table 5-2: Weighted Objectives Method*

| | **Concepts rated 1-5 ( 5 being the highest )** | | | | | | |
|---|---|---|---|---|---|---|---|
| Criteria | Concept A | Concept B | Concept C | Concept D | Concept E | Concept F | Concept G |
| Safety | 4 | 4 | 5 | 4 | 3 | 2 | 3 |
| See bumps coming | 5 | 5 | 2 | 4 | 5 | 5 | 5 |
| Stable | 4 | 3 | 4 | 3 | 3 | 2 | 4 |
| Can be used as fixed and free | 3 | 3 | 0 | 3 | 4 | 0 | 4 |
| Irregular bumps | 3 | 3 | 0 | 3 | 3 | 3 | 3 |
| Cyclist can use their own riding style | 3 | 3 | 1 | 4 | 3 | 5 | 5 |
| Feels natural | 3 | 3 | 2 | 3 | 4 | 4 | 4 |
| Riders movement can be examined | 4 | 4 | 2 | 4 | 4 | 5 | 5 |
| Forces applied to the bikes can be studied easily | 4 | 4 | 5 | 4 | 4 | 3 | 3 |
| Physiology of rider can be recorded | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Traction can be measured | 3 | 3 | 3 | 3 | 3 | 2 | 2 |
| Bump frequency and height changing | 4 | 4 | 1 | 4 | 4 | 4 | 4 |
| Suspension can be studied | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Overall time recorded | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Force applied to pedals recorded | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Bike movement can be analysed | 3 | 3 | 1 | 3 | 3 | 4 | 4 |
| Speed can be measured accurately | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Cost | 3 | 2 | 5 | 2 | 3 | 2 | 2 |
| **Total** | 68 | 66 | 53 | 67 | 68 | 63 | 70 |

The weighted objectives method was used to establish which rig design would be most suitable by rating the designs against the most significant criteria for the rig. The weighted objectives method for the rig (Table 5-2) indicated that concept G (Figure 5-1) was the most appropriate concept to satisfy all of the criteria for the new rig. This rig design solution (Figure 5-1) resulted in the formation of a multidimensional matrix (illustrated by the grey shaded boxes of the morphological chart in Table 5-1) which highlighted the most suitable design solutions for the rolling road rig.

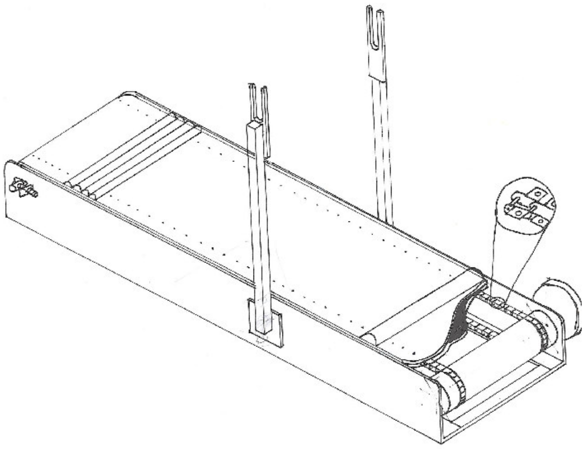


*Figure 5-1: Concept G*

It was decided that concept G (Figure 5-1) would be the most effective test rig to develop, as it would provide a bridge between the initial roller rig and outdoor riding conditions. The new rig design would run without a power supply and instead be driven using the rear wheel of the bike. The rig design would allow for experiments using any bike type - allowing both the movement of the front and rear wheels and suspensions to be considered. Additionally, the rig would allow for a more realistic representation of an outdoor track due to the wider spacing of any bumps attached to it, and would also allow the subjects to observe any approaching bumps before impact occurred with the wheels.

## 5.4. Rig Design Development

Once the rig design had been determined (Figure 5-1), it was fundamental to the design process to improve and develop its design through the use of computer software packages; namely Solid Edge and DADS. Various factors were considered during this process: safety; repeatability of experiments; ease of use for subjects without having to partake in any prior training on the rig; and the position of the bike on the rig (it was ascertained that the bike must be held in a vertical position to aid the subjects' balance). Previous tests (Berry et al., 1993; Berry et al., 2000; Ishii et al., 2003; Kooijman & Schwab, 2009; MacRae et al., 2000) involved subjects cycling on a treadmill without apparatus to hold the bike steady - a design consideration deemed hazardous and less likely to produce repeatable experimental results. A design feature such as this would also require periods of familiarisation training in order for subjects to conduct tests. For the design of the rig in current study, it was therefore necessary to develop a rig which not only held the bike steady, but also allowed the bike to move vertically so a test on a rolling road could be carried out safely with repeatable results. After consideration, it was deemed that the most appropriate places to hold the bike steady were at the handlebars or the front wheel of the bike; however, it was essential to carry out further DADS simulations in order to determine if holding the rig in these positions would alter the dynamics of the bike.

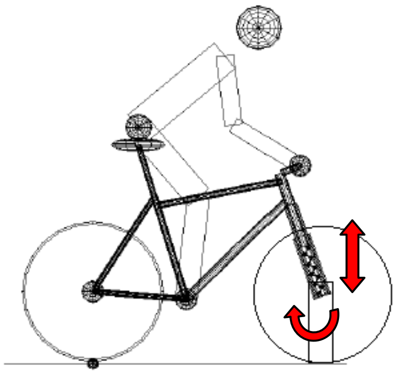


*Figure 5-2: Simulation held at front wheel hub*

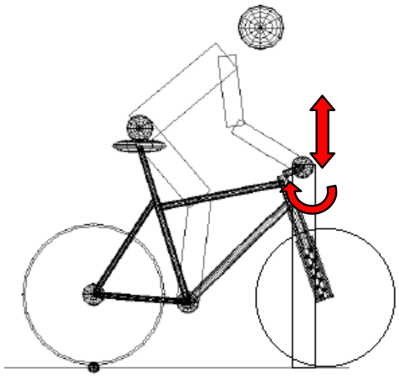


*Figure 5-3: Simulation held at handlebars*

The bike and rider models created to carry out these investigatory simulations were identical to those used for the dynamic simulation tests in Chapter 7 of the current research. In order to represent the rolling road, a bump was placed under the bike's wheels. A total of three simulations were carried out and compared to find the optimal position in which to hold the bike steady. Initially, the bike was allowed to travel over the bump - unsupported by the rig - as would be the case in an outdoor trail. The bike was then restrained at the front wheel hub with the use of a translational/rotational joint - this fixed the front forks in the horizontal plane while still allowing the bike to travel vertically and rotate about a perpendicular axis. The third simulation also restrained the bike, but this time at the handlebars - also with a translational/rotational joint. The results from the simulated bike travelling over the bump, unsupported by the rig, were subsequently compared to the results from the simulations with the bikes restrained at either the handlebars or front wheel.

Figure 5-4 illustrates one set of results from the dynamic simulations: the vertical motion of the front wheel for each of the three scenarios when travelling over a bump; similar results were also obtained for the motion of the rear wheel.

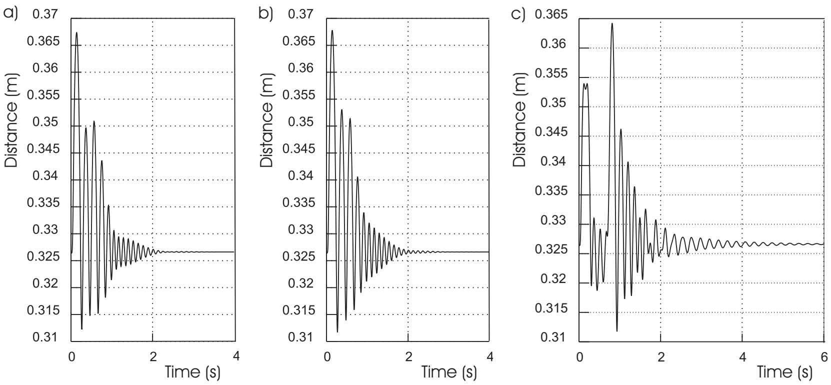


*Figure 5-4: Simulated front wheel 'y position' with a) no restraint; b) restraint at handlebars; and c) restraint at front hub.*

Figure 5-4 demonstrates that the vertical motion of the front wheel is similar for both the simulated bike being held steady at the handlebars, and for the unrestrained bike. This finding concludes that a bike held steady at the handlebars gives a closer representation of the dynamic properties of an unrestrained bike. Consequently, it was decided that this design feature would remain for Concept G (Figure 5-1) as it was deemed that this was the closest representation of true outdoor riding conditions that could be achieved without using an unrestrained bike.

Another consideration - to ensure that the rolling road rig design and experiments were as close a representation as possible to true outdoor riding conditions - was to make certain that cycling on the rig would closely match the inertia to riding a bike outdoors. In order to enable this, a calculation - outlined in Appendix F - was used and resulted in the finding that the most appropriate solution was the inclusion of two steel discs with a width of 46 mm and a radius of 240 mm in the design of the rig.

Figure 5-5 shows the development of Concept G with additional design considerations: the rolling road is produced from a six-metre long rubber conveyor belt passing over rollers at each end, ensuring that the rider can clearly see the track and any impending obstacles. The handlebars are held using metal brackets, allowing for a vertical and rotational motion of the bike and ensuring that the rider is not required to balance the bike in a stationary position. Although the rolling road rig has been designed to represent as realistic a representation of cycling outdoors as possible - many of the variables involved in cycling outdoors have been reduced to ensure that the experiments on the rig are repeatable and controlled: the only variable taken into consideration is the type of suspension used for experimentation.

## 5.5. Rig Construction

### 5.5.1. Rolling Road Belt and Running Surface

Once the design of the rolling road rig had been established, its construction had to be considered. Commonly, treadmill belts run on a lubricated steel surface; however, as the treadmill used for the purpose of the current study was self-driven, the friction between the rubber and steel would require more effort from the rider when carrying out testing. Taking into account this high friction, a layer of PTFE was considered for the surface; however, the friction would still present a problem to the cyclist. It was therefore decided that the most suitable option was to allow the wheels to run on a series of rollers. A total of six rollers were used for the rig: three rollers placed under the front wheel, and three under the rear wheel. Each roller was designed to be large enough for the bumps to travel around it, yet still provide enough friction to avoid the bike becoming unsteady when impact with the bumps occurred. As this type of roller was not a standard component, it was necessary for it to be custom built.

### 5.5.2. Bumps

As it was decided that rollers were to be placed under the treadmill belt, it was imperative that any bumps which were to be attached to the belt would have to be designed to prevent any distortion of the track when the wheel impacted with them. Consequently, bumps with two sections - a base and rounded edge - were designed. The base of each bump consisted of a slat of wood (3 x 70 x 800 mm) which prevented the track from bending when impact occurred with the wheels of the bike. Attached to the top of the wooden slat was the rounded edge (30 x 30 x 800 mm). In order to make each bump feel as realistic as possible when cycling over it, each rounded edge had a ten millimetre radius. Two identical bumps were placed on the track 3 m apart. To ensure that the bumps could travel around the end of the rollers with ease, they were attached to the belt of the treadmill by three bolts and countersunk into the wood. The decision to use bolts - in replace of adhesive - to attach the bumps meant that they could be easily removed between tests.

### 5.5.3. Frame

The frame of the rig comprised of several components which could be split into various sections for ease of transportation. The steel frame of the rig was developed to ensure that no vibration would occur during testing (movement of the frame was a concern during the tests on the roller rig). In order to counteract any stretching of the belt which would occur, tensioners were placed on either side of the frame and pushed against the external bearings to ensure the belt was maintained tight at all times. Handlebar guides were designed and constructed to ensure that the handlebars could not reach the bottom of, or escape from, the bracket regardless of how vigorous the cyclist was cycling. Inserts were designed to attach to the ends of both handlebars to ensure that they were wide enough to fit into the brackets. The inserts were made from aluminium with PTFE bearings - this enabled the handlebars to move with little friction occurring between the rig and the bike. Stabiliser ropes were additionally added to the brake stanchions of the rig frame to ensure that the bike remained centralised and stable throughout testing.

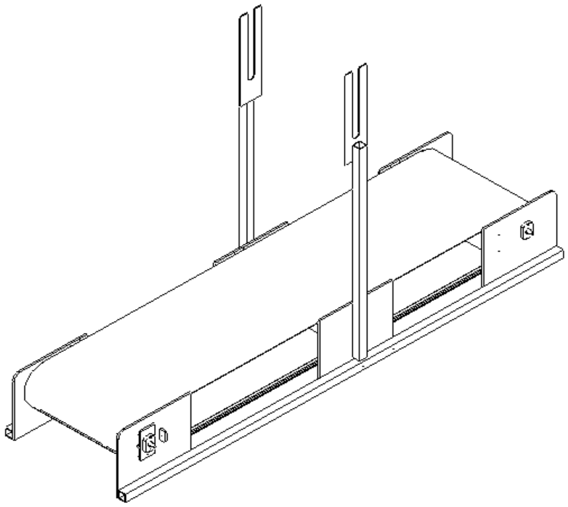


*Figure 5-5: Rolling Road Rig designed in CAD*

The rolling road rig was designed and constructed to be self-powered by the subjects' cycling motions. The rig provides a suitable representation of a trail in terms of the inertial effects: the resistance represents a rider cycling into a head wind with the equivalent wind speed of 11.4 m/s, or riding up a 7.3 degree slope. The equations to illustrate this are shown in Appendix G.

### 5.5.4. Bikes

Unlike the tests undertaken on the roller rig, only one mountain bike was used for the purpose of testing on the rolling road rig: a fully suspended Marin Mount Vision bike (Figure 5-6). This would allow for a more controlled, repeatable result as opposed to using two bikes, due to the reduction of the variables between the tests. To emulate a hardtail bike during testing, a specially developed steel spacer was used to replace the rear suspension spring and damper. This ensured that all aspects relative to the bikes were kept uniform throughout the tests.

*Figure 5-6: Marin Mount Vision Mountain Bike*

## 5.6. Mechanical Measurements

One advantage of using a laboratory based test rig is that it can be fully instrumented. The instrumentation used for tests on the roller rig gave satisfactory results, yet as problems were encountered during testing, it was necessary for much of the electronic equipment to be redesigned for reliability and ease of use. Furthermore, for the purpose of testing on the rolling road rig, additional dynamic properties were to be investigated.

A total of thirteen mechanical measurements were recorded from the instrumentation on the rolling road rig and bike:

- Handlebar acceleration
- Saddle acceleration
- Vertical force exerted on saddle
- Force exerted on pedals
- Rotational velocity of the crank arms
- Rotational velocity of the front roller
- Rear bump position
- Front bump position
- Pedal position
- Vertical force exerted on right handlebar
- Vertical force exerted on left handlebar
- Horizontal force exerted on right handlebar
- Horizontal force exerted on left handlebar

The location from which these readings have been recorded on the rolling road rig and bike are illustrated in Figure 5-7.

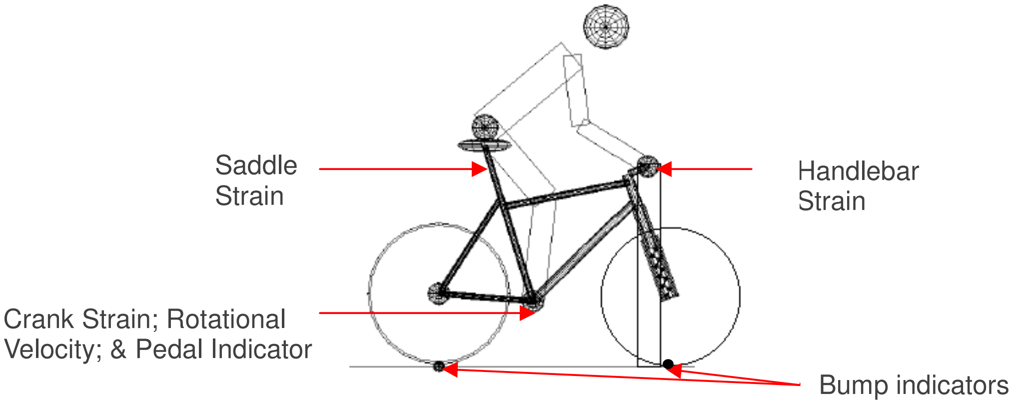


*Figure 5-7: Location of Mechanical Measurements*

The force exerted on the pedals by the cyclist is measured through the use of strain gauges (placed on the crank arms of the bike) with a telemetry system designed specifically for the purpose of the current research. The unit is powered through a DC power unit fed via two sprung bushes that run on slip rings mounted on the rear of the chain wheel, as illustrated in Figure 5-9. This was deemed the most effective way to transmit the power through to the gauges of the crank. The gauges are in the form of a Wheatstone bridge configuration and are mounted on the torque reaction arm (part of the crank assembly) as illustrated in Figure 5-8. Signals are fed directly to an amplifier before reaching a voltage to frequency converter.

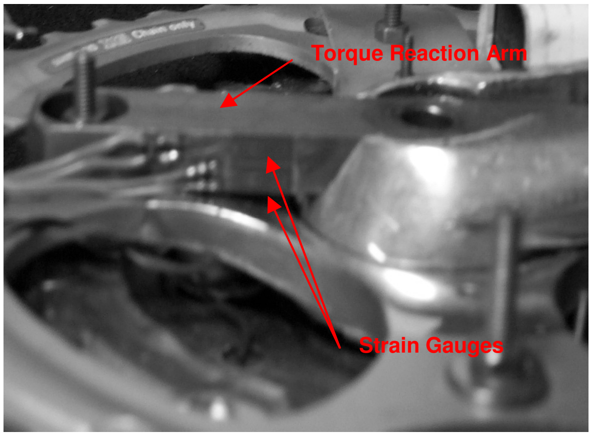


*Figure 5-8: Crank showing Strain Gauge*

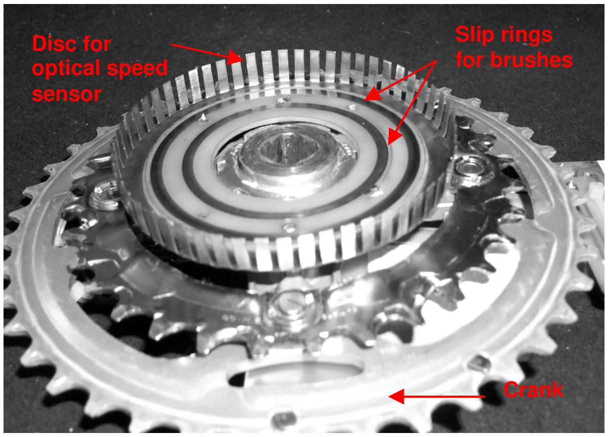


*Figure 5-9: Crank showing Slip Rings*

The output from the strain gauges is applied to a forty five millimetre long helical antenna which is attached to the outside of the pedal. The receiver unit is entirely separate from the bike instrumentation and is powered from the mains. This is connected to both a frequency to voltage converter, and to the signal receiver. The output from the receiver unit is a copy of the amplified strain. To enable the strain gauges to be calibrated, the rear wheel of the bike is clamped in a fixed position, thus ensuring that the crank arms are placed in a horizontal position. Weights were then hung from the pedal to give the corresponding voltage from the strain gauge output. Consequently, a linear relationship can be established for all loads exerted on the crank. A more detailed description of the electronic equipment and the electronic schematics is illustrated in Appendix H.

### 5.6.1. Handlebar force

The vertical and horizontal force exerted on the handlebars will indicate how much force a rider exerts on the handlebars at various points during testing. The most effective way to measure the vertical force is again through the use of strain gauges placed in a full Wheatstone bridge configuration positioned directly above and below each handlebar. The horizontal force is also measured through the use of strain gauges placed in a full Wheatstone bridge configuration, but positioned at the front and rear of the handlebars. All of the corresponding strain gauges are connected directly to a frequency to voltage converter, and to the signal receiver. The output of the strain gauges is a copy of the amplified strain. The strain gauges used to measure both the vertical and horizontal force exerted on the handlebars were calibrated through hanging a load from the handlebar and recording the corresponding strain gauge output. These corresponding values were plotted on a graph and a linear relationship was established between the two values.

### 5.6.2. Saddle Force

The force exerted on the saddle is also measured through the use of strain gauges placed in a full Wheatstone bridge configuration placed on the stem of the seat tube - again connected to a voltage to frequency converter and connected to the signal receiver. The output from the strain gauges is, once more, a copy of the amplified strain. The strain gauges were calibrated using a load (weights) applied to the seat and the corresponding strain gauge output was plotted against this value. This enabled a linear relationship to be established between the load and the strain gauge outputs.

### 5.6.3. Handlebar and Saddle Acceleration

In order to measure the handlebar and saddle acceleration, accelerometers were positioned above the handlebars and below the seat post; positions that were selected as they lie directly above the front and rear suspension system. Once the acceleration has been recorded it is consequently possible to calculate the velocity and displacement of the bike at these points.

### 5.6.4. Rotational Velocity of the Crank Arms and Front Roller

The velocity the crank arms and front roller are recorded to indicate if a rider’s cadence alters as a result of cycling on a fully suspended compared to a hardtail bike. The rotational velocity of the crank arm is measured by means of an aluminium disk consisting of 52 slots which pass through an optical sensor to accurately measure the velocity. A second identical disk is placed on the outside of the front roller with a corresponding optical sensor to measure the velocity of the roller.

### 5.6.5. Pedal, Front Bump and Rear Bump Position

Light sensors display the position of the bumps on the roller relative to the other mechanical measurements. The light sensors used to indicate the front and rear bump position at a given time are placed directly below the middle of the front and rear wheel. A metallic strip placed directly below the bumps displays a signal as it passes the light sensor - enabling the position to be recorded. In a similar way, a magnetic sensor is used to indicate pedal position - a magnetic switch produces a signal after each revolution of the crank.

### 5.6.6. Data Output

All of the readings obtained from the measurements were displayed on a laptop via an A to D converter. A program was developed using Lab View to record the data and display the results as each test was run. A sampling frequency of 100 Hz was used as this frequency ensured that precise measurements could be recorded. Analysis of the results was compiled through the use of Matlab and Excel which were used to produce statistical information on all of the results obtained through testing.

## 5.7. Physiological Measurements

### 5.7.1. Heart Rate

Heart rate is monitored and recorded (using a polar heart rate monitor - S710) every 45 s into each minute of every test. The mean value of the last two recordings was taken as the representative value for each test. For full details of heart rate refer to section 4.3.4.1.

### 5.7.2. Oxygen Consumption ($VO_2$)

Similar to the subjects being tested on the roller rig, oxygen consumption is measured using the Douglas Bag technique, as illustrated in Figure 5-10. Expired air samples are collected for four, sixty second intervals (third, fourth, tenth and eleventh minutes). The bag of expired air is analysed immediately after collection for $O_2$ and $CO_2$ by a Servomex 1440 analyser - the total air volume in the Douglas bag is measured using a Harvard dry gas meter. For full details of oxygen consumption refer to section 4.3.4.2.

*Figure 5-10: A subject with a mouth piece connected to a Douglas bag*

## 5.8. Psychological Measurements

### 5.8.1. Rating of Perceived Exertion (RPE)

Each subject's RPE was recorded at the third, sixth and ninth minute of each test. For full details of RPE refer to section 4.3.5.1.

### 5.8.2. Comfort Rating

The comfort rating scale used for testing on the rolling road rig is identical to that used for testing on the roller rig (see section 4.3.5.2 for full details). Each subject's comfort level was recorded at the third, sixth and ninth minute of each test.

## 5.9. Run Down Test

### 5.9.1. Method

Similar to the methodology of the roller rig experiments, a run down test was carried out on the rolling road rig to indicate the deceleration of the rolling road track. The run down test was carried out on the hardtail bike on the smooth and rough rolling road, and on the fully suspended bike on both the smooth and rough rolling road. The results from each run down test were compared to ascertain if equivalent run down times were reached for the four cycling conditions.

One subject, aged twenty three and weighing seventy kilograms, carried out the run down tests on both the fully suspended and hardtail bike on the rolling road rig with the smooth and rough surface. The subject was instructed to ride each bike on both the smooth surface and the surface with bumps attached at a velocity of 10 km/h. The subject was then instructed to refrain from pedalling and to allow the bike to come to rest whilst holding the pedals stationary and remaining seated. The decrease in the velocity of the rolling road was electronically recorded for each test against the time it took for this decrease, as displayed in Figures 5-11 and 5-12. The run down test was conducted to establish if the run down times for each bike on both surface types of the rolling road rig are comparable to the rundown times for each bike on the smooth and rough surfaced roller rig.

### 5.9.2. Run Down Test Results

Figures 5-11 and 5-12 illustrate the run down times obtained for the subject cycling on the hardtail and fully suspended bike on the smooth and rough surfaced rolling road rig respectively. The graphs (Figures 5-11 and 5-12) have comparable gradients, representing the deceleration of both the hardtail and fully suspended bikes on each of the two cycling surfaces on the rolling road rig. The gradients allow an estimate of the resistance force to be calculated.

The resistance force of the fully suspended and hardtail bike on the rough surfaced was calculated (as in section 4.4.2.) to be 42.5 N and 41.8 N respectively, and 41 N for both bike types on the smooth surfaced rolling road rig. These results indicate that the force resistance of the hardtail bike is 1.6 % greater than the fully suspended bike on the rough surface.

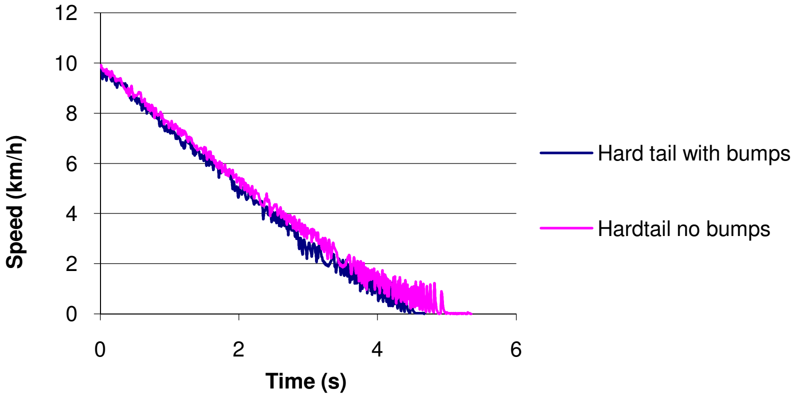


*Figure 5-11: Run down test results for the hardtail bike*

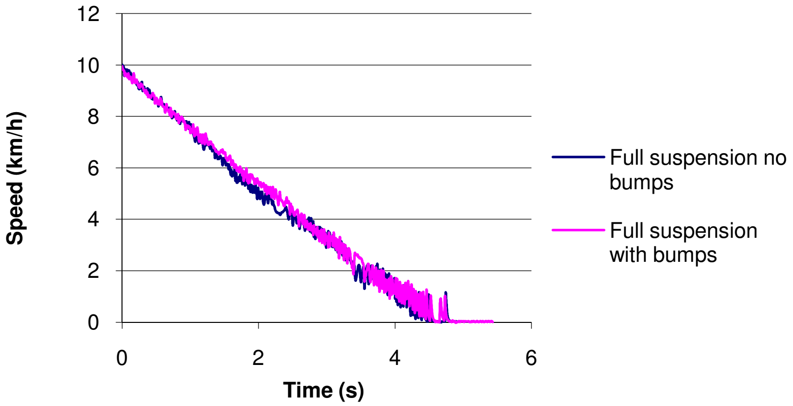


*Figure 5-12: Run down results for the fully suspended bike*

## 5.10. Comparative Test

### 5.10.1. Subjects

The experimental protocol was reviewed and approved by the ethics committee at Glasgow University. Each subject was informed of the purpose and risks of the study and completed a physical activity questionnaire and signed a consent form prior to undertaking any tests. All subjects were advised that they could withdraw from testing at any time. Eight male subjects (average age 26 ± 2.37 years with an average weight of 70.8 kg ± 10.2) were chosen to participate in the experiments: all were in good health at the time of testing and carried out at least two aerobic training sessions per week. All had ridden mountain bikes previously - some at competition level.

### 5.10.2. Method

Each subject undertook a total of four tests: cycling on the fully suspended bike on the surface with no bumps; cycling on the hardtail bike on the surface with no bumps; cycling on the fully suspended bike on the surface with bumps; and cycling on the hardtail bike on the surface with bumps. Each subject carried out the tests on two separate days: two on one day, and two on another. The order in which each subject was tested was randomised to prevent any bias. In order to ensure that the tests were repeatable, each subject completed testing at the same time of day for each subsequent visit to the laboratory. Subjects were instructed to refrain from exercise for at least twenty four hours prior to testing, and instructed not to eat for up to three hours prior to testing in order to reduce the chance of these factors affecting the results. Each subject's seat height was determined at the initial visit to the laboratory and was maintained for all subsequent trials - as was the rear gear of their choice. Tyre pressure was kept at 40 psi throughout all the tests.

On each visit to the laboratory each subject completed a four-minute running warm up on a regular treadmill at 8 km/h. Following this, a 6 min familiarisation test was completed which accustomed the subject to the testing conditions - during this time the subject was asked to cycle at a speed of 8 km/h and to maintain this speed for the duration of the 12 min test. As preliminary tests carried out on the roller rig highlighted that no familiarisation effect occurred after subsequent testing using a rig under laboratory conditions, a six min familiarisation period was deemed sufficient. The heart rate of the cyclists was monitored during the familiarisation test to ensure that each subject was cycling at a sub-maximal level.

Following the completion of the warm-up and familiarisation tests, a subject was instructed to wait until their heart rate returned to an 'at rest level' before commencing the experiment. Subjects were instructed to remain seated throughout the duration of the test and to maintain their speed at 8 km/h. During the 10 s of the test, the subject was instructed to remain motionless so that zero readings from the mechanical instrumentation could be recorded. After 12 mins the subject was instructed to decelerate until the bike came to rest and to remain motionless for a further 10 s whilst the zero readings were once again recorded.

## 5.11. Physiological and Psychological Results

The physiological and psychological results for $VO_2$, heart rate, RPE and comfort rating are presented in this chapter. The analysis of the results sought to establish whether there was a statistically significant difference between the physiological and psychological results recorded for a subject whilst cycling on the hardtail bike compared to the fully suspended bike on the rolling road rig.

### 5.11.1. Measurement Stability

As with the test results obtained from the roller rig, it was also important to ascertain that each subject's physiology had met steady state conditions during tests on the rolling road rig. Table 5-3 displays the results of the statistical analysis (ANOVA tests) performed on the subjects' physiological and psychological results to ascertain if they are statistically valid. A detailed description of the repeated measures ANOVA test is outlined in section 4.7.1.2 of the current study. Table 5-3 displays the results of the repeated measures analysis of variance, performed on the subjects' measurements of $VO_2$ and heart rate at the fifth, sixth, ninth and tenth minute of testing on both the hardtail and fully suspended bike, and the RPE and comfort level ratings at the third, sixth and tenth minute of testing - also on both the hardtail and fully suspended bike. The results determine the extent to which steady state conditions were achieved during each test.

*Table 5-3: Analysis of stability of measurements during tests*

|  |  |  | **Average across participants at:** |  |  |  |  |
|---|---|---|---|---|---|---|---|
| **Measure** | **Bike** | **P** | **3 min** | **5 min** | **6 min** | **9 min** | **10 min** |
| $VO_2$ (ml _ kg$^{-1}$ _ min$^{-1}$) | HT | 0.87 |  | 31.9 | 31.8 | 32.1 | 31.7 |
|  | SU | 0.46 |  | 31.7 | 31.8 | 32.5 | 31.7 |
| Heart rate (beats _ min$^{-1}$) | HT | <0.001 |  | 130 | 130.3 | 131.5 | 133.3 |
|  | SU | <0.001 |  | 128.9 | 131.3 | 132.8 | 132.8 |
| RPE | HT | 0.008 | 10.9 |  | 11.3 |  | 11.8 |
|  | SU | 0.084 | 10 |  | 10.6 |  | 10.5 |
| Comfort | HT | 0.044 | 3.1 |  | 2.9 |  | 2.8 |
|  | SU | 0.025 | 3.6 |  | 3.4 |  | 3.5 |

Table 5-3 indicates that there is no significant difference for subjects' $VO_2$ measurements whilst cycling on the hardtail and fully suspended bike, indicating that steady state conditions have been met. Subjects' measurements for heart rate - recorded whilst cycling on the hardtail and fully suspended bike - show that a significant difference is apparent, indicating that steady state conditions have not been met. However, as the effect size is small, this is representative of steady state conditions having been met.

Table 5-3 also shows that the RPE ratings increase as the test progresses, as subjects feel that they are cycling harder. Simultaneously, comfort ratings decrease; a result of the subject becoming slightly more uncomfortable as the test proceeds (in particular on the hardtail bike). A single representative test value was required for comparisons and analysis of RPE and comfort rating levels, therefore the mean of the three readings (taken during the third, sixth and tenth minutes) was used for this purpose.

### 5.11.2. Statistical Significance of Results

Similar to the results obtained from the roller rig tests, a null hypothesis two-tailed dependent paired t-test was also applied to the results obtained from the rolling road rig experiments in order to calculate the probability that any differences measured between the hardtail and fully suspended bikes are purely the result of chance. The results of the null hypothesis two-tailed dependent paired t-test are displayed in Table 5-4. Low probabilities (p values less than 0.05) indicate that the measured effect in the sample (of eight subjects) is evidence of a real significance in results. The effect size indicates the size of the differences (a detailed description of the dependent t test, probabilities, and effect size is outlined in section 4.7.3).

*Table 5-4: The difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort rating (whilst cycling on the smooth surface and surface with bumps) obtained by comparing the hardtail and fully suspended bikes.*

| | $VO_2$ (ml/kg/min) | Heart rate (beats/min) | RPE | Comfort |
|---|---|---|---|---|
| **Test series 1 (bumps)** | | | | |
| Sample size | 8 | 8 | 8 | 8 |
| Mean of differences | 0.6 | 1 | 1.5 | -0.8 |
| Standard deviation | 1.25 | 2.52 | 1.8 | 2 |
| P-value | 0.25 | 0.31 | 0.05 | 0.33 |
| Effect size | 0.45 | 0.38 | 0.83 | -0.37 |
| | | | | |
| **Test series 1 ( no bumps)** | | | | |
| Sample size | 8 | 8 | 8 | 8 |
| Mean of differences | -0.6 | -1.4 | 0.5 | -0.4 |
| Standard deviation | 1.38 | 4.63 | 1.68 | 1.44 |
| P-value | 0.26 | 0.43 | 0.47 | 0.44 |
| Effect size | -0.48 | -0.41 | 0.05 | 0.34 |

N.B.: All differences are obtained through subtracting (-) the means obtained from cycling on the fully suspended bike from the means obtained from cycling on the hardtail bike.

Table 5-4 displays the difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort ratings for the hardtail and fully suspended bike on both the smooth surface and the surface with bumps for comparison. The effect size between each pair of means was calculated as were the p values. As all of the calculated p values are greater than 0.05 (with the exception of the mean of the subjects' RPE during the test on the surface with bumps which is equal to 0.05), this indicates that no statistical significant difference is found between riding a fully suspended bike and a hardtail bike on the rolling road rig on either surface type.

When more than one variable is considered in the analysis of results, a dependent t-test is no longer valid. When two independent variables are to be investigated - in this case the type of suspension system and the road surface - a factorial ANOVA calculation must be used. The p values calculated from the subjects' $VO_2$, heart rate, RPE and comfort ratings from this two-way factorial ANOVA calculation are displayed in Table 5-5. The results show that there are no significant statistical differences between cycling on a bike with a hardtail or full suspension system as all p values are greater than 0.05. Similarly, no statistically significant difference is apparent as a result of the interaction of the suspension system and the track surface, as the p values are all greater than 0.05. Conversely, a significant difference is apparent between cycling on a smooth and rough surface for measurements of $VO_2$, RPE and comfort rating, obtaining p values 0.018; 0.021; and 0.018 respectively.

*Table 5-5: p values from the ANOVA test considering the type of suspension and type of surface as variables.*

| | **p Values** | | | |
|---|---|---|---|---|
| | **$VO_2$** | **Heart Rate** | **RPE** | **Comfort** |
| True variance due to the Suspension System (hardtail or fully suspended) | 0.987 | 0.956 | 0.096 | 0.195 |
| True variance due to the track surface (bumps or no bumps) | 0.018 | 0.367 | 0.021 | 0.018 |
| True variance due to the interaction of Suspension System and the track surface | 0.594 | 0.751 | 0.367 | 0.733 |

*Table 5-6: Mean values for the subjects' $VO_2$, heart rate, RPE and comfort rating.*

| Suspension | Variable | Bumps | No Bumps |
|---|---|---|---|
| | | | |
| Hardtail bicycle | $VO_2$ (ml/kg/min) | 33.54 | 30.26 |
| | Heart rate (beats/min) | 133.53 | 129 |
| | RPE | 12.29 | 10.38 |
| | Comfort | 2.33 | 3.54 |
| | | | |
| Full suspension bicycle | $VO_2$ (ml/kg/min) | 32.98 | 30.86 |
| | Heart rate (beats/min) | 132.56 | 130.38 |
| | RPE | 10.79 | 9.92 |
| | Comfort | 3.08 | 3.96 |

Table 5-6 indicates the mean values gained for both the fully suspended and hardtail system for all of the physiology and psychology results (of $VO_2$, heart rate, RPE and comfort rating). The physiology and psychology results from the series of tests for subjects cycling on the hardtail and fully suspended bikes on both surface types on the rolling road rig are plotted in Figures 5-13 to 5-16. Each point on the graph represents one participant; the values recorded on the vertical axis are for the hardtail bike, and those recorded on the horizontal axis are for the fully suspended bike. The points above the equality line on the scatter graphs indicate the higher readings obtained for the hardtail bike.

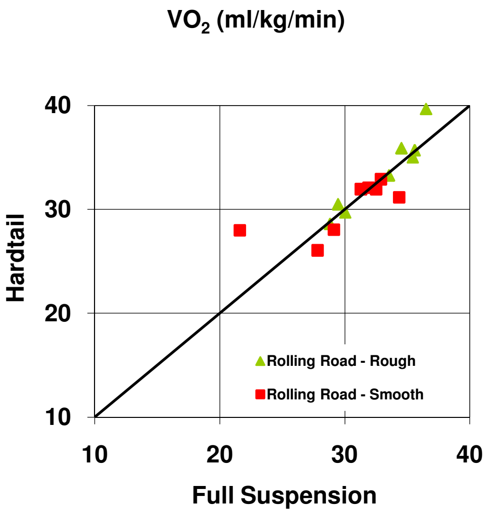


*Figure 5-13: Comparison of VO$_2$ results for the hardtail and fully suspended bike on both surface types on the rolling road rig.*

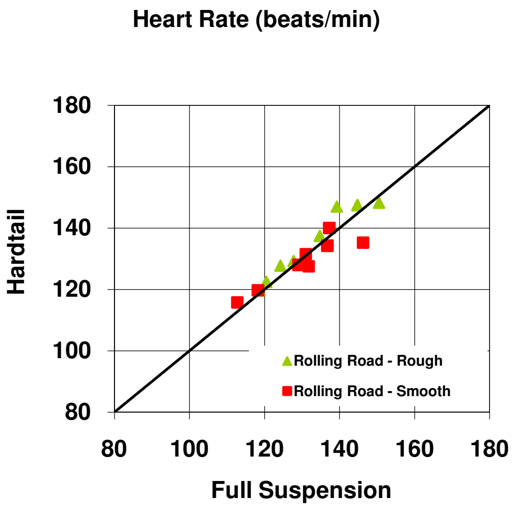


*Figure 5-14: Comparison of heart rate results for the hardtail and fully suspended bike on both surface types on the rolling road rig.*

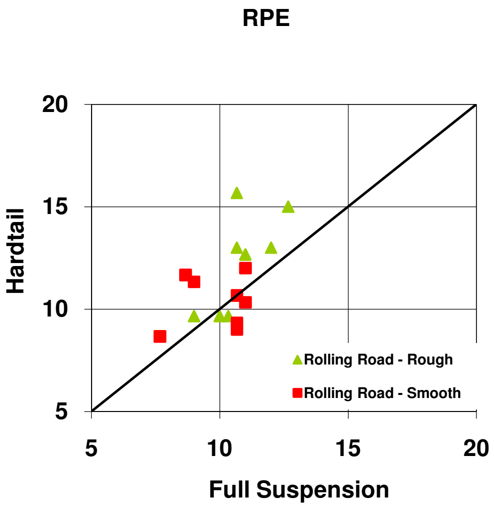


*Figure 5-15: Comparison of RPE results for the hardtail and fully suspended bike on both surface types on the rolling road rig.*

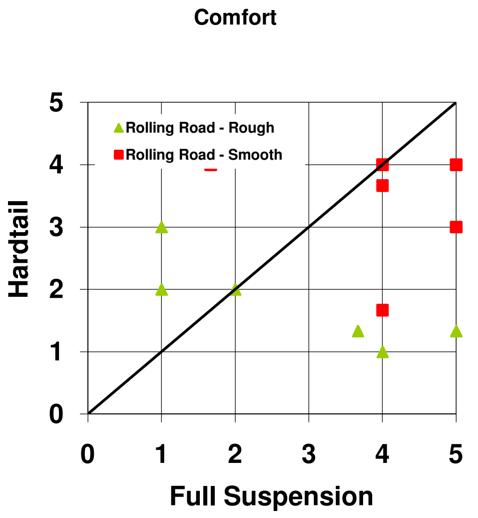


*Figure 5-16: Comparison of comfort rating results for the hardtail and fully suspended bike on both surface types on the rolling road rig.*

Figures 5-13 and 5-14 coincide with the findings displayed in Tables 5-3, 5-4, 5-5 and 5-6: there is no significant statistical difference between cycling on a hardtail or fully suspended bike on a smooth surface or on a surface with bumps. The points (representing the participants of the tests) show no clear bias to either suspension system for the measurements of $VO_2$ and heart rate. Conversely, Figure 5-15 highlights that RPE is greater for subjects cycling on the hardtail bike, thus in this respect the fully suspended bike presents an advantage over the hardtail. Additionally, as highlighted in Figure 5-16, subjects rated cycling on the fully suspended bike as more comfortable than cycling on the hardtail bike.

The physiology and psychology results from the roller rig tests and the rolling road rig tests are plotted in Figures 5-18 to 5-19 in order to highlight any similarities or differences between the results. Each point represents one participant: the values for the hardtail bike are recorded on the vertical axis, and the values for the full suspension bike are recorded on the horizontal axis. Points above the equality line indicate the higher readings for the hardtail bike.

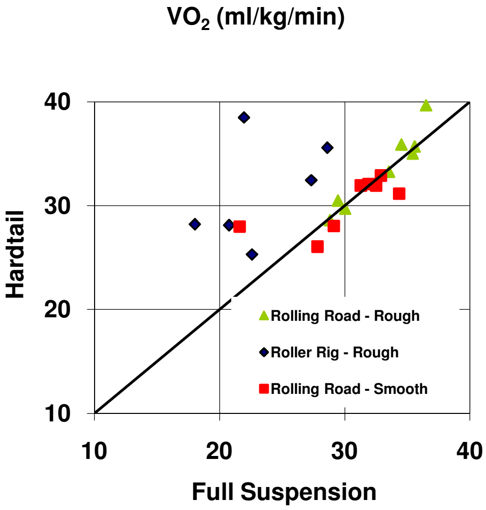


*Figure 5-17: Comparison of $VO_2$ results for the hardtail and fully suspended bike for the rolling road rig compared to the roller rig.*

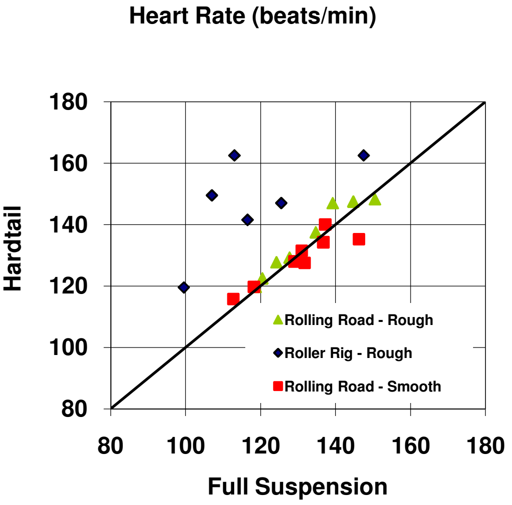
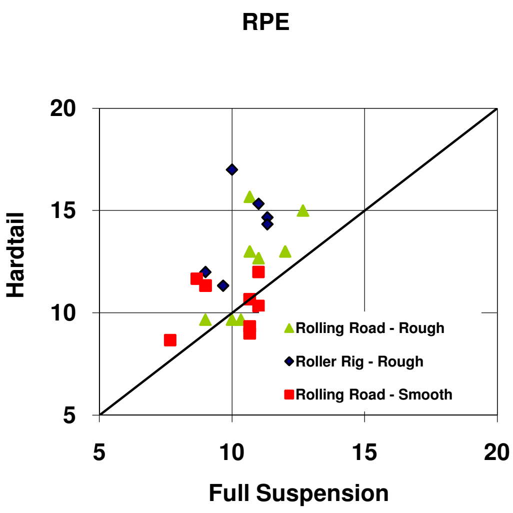


*Figure 5-18: Comparison of heart rate results for the hardtail and fully suspended bike for the rolling road rig compared to the roller rig.*



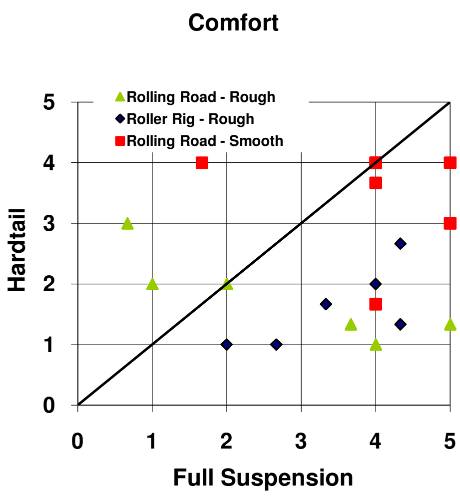


*Figure 5-19: Comparison of RPE results for the hardtail and fully suspended bike for the rolling road rig compared to the roller rig.*

*Figure 5-20: Comparison of comfort rating results for the hardtail and fully suspended bike for the rolling road rig compared to the roller rig.*

Figures 5-18 to 5-19 allow for a clear comparison of results between testing on the roller rig and rolling road rig. The findings for $VO_2$ and heart rate (Figures 5-18 and 5-17) display a clear difference between the roller rig and the rolling road rig: the tests on the rolling road rig do not highlight any significant differences between the hardtail and fully suspended bike on either surface (bumps or no bumps), and the tests on the roller rig highlight that all subjects riding the hardtail bike (on the surface with bumps) recorded a higher $VO_2$ and heart rate level. The findings relating to RPE and comfort - Figures 5-20 and 5-19 respectively - highlight that the majority of all participants in both rig tests perceived their RPE to be higher, and their comfort rating lower, whilst cycling on the hardtail bike, thus signifying that the fully suspended bike presents an advantage to the rider in terms of RPE and comfort.

## 5.12. Mechanical Results

The mechanical results from the tests on the rolling road rig on both the smooth and rough surface are displayed in tabulated form (Tables 5-7 to 5-19). The results display the average maximum and minimum values for all eight test subjects and were analysed using Matlab and Excel. Similar to the mechanical results from the roller rig tests, only those mechanical results deemed most relevant from the rolling road rig tests are presented in this chapter for analysis – the full set of mechanical results can be viewed in Appendix C.

As with the results obtained from the physiology and psychology tests, a null hypothesis two-tailed dependent paired t-test was also applied to the mechanical results from the rolling road rig tests to calculate the probability that the differences measured between the hardtail and full suspension bikes are purely the result of chance. The standard deviation and p values obtained from this test are displayed in Tables 5-7 to 5-19. The tables also depict the average minimum and maximum values for the eight subjects; the average mean for the subjects; and the average range between the minimum and maximum values. The average maximum and minimum values are calculated by taking the average of the largest and smallest turning points of the graphs (produced by the mechanical instrumentation throughout the tests) respectively. All values displayed are calculated for the tests conducted on the hardtail bike on both the smooth and rough surface, and for the tests carried out on the fully suspended bike on the smooth surface and on the surface with bumps. The results obtained from the two suspension systems are also compared and displayed in the Tables to indicate which bike gives the optimal performance on each surface. This is achieved by subtracting the means obtained from cycling on the fully suspended bike from the means obtained from cycling on the hardtail bike.

Table 5-7 displays the findings relating to the power applied to the crank by the rider for both the hardtail and fully suspended bikes; this is calculated by multiplying the crank force measurements, obtained from the strain gauges, with the rotational velocity of the crank, measured via the optical sensor. The only statistically significant finding (with a p value of less than 0.05) from Table 5-7 relates to the difference in mean power between the two bikes when cycling on the smooth surface: the finding shows that cycling on the hardtail bike provides a slight advantage to the rider when cycling on the rolling road rig with a smooth surface. As all other results produced p values greater than 0.05, this renders these results statistically insignificant.

*Table 5-7: Power through the Crank*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension type:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Power (W) | | | | |
| Average minimum | 47.2 | 50.2 | 39.3 | 40.3 |
| | s=10.32 | s=9.06 | s=6.89 | s=7.51 |
| Average maximum | 79 | 81.7 | 129 | 127.1 |
| | s=6.4 | s=7.02 | s=6.97 | s=4.97 |
| Range max/min | 31.8 | 31.5 | 89.7 | 86.8 |
| | s=6.69 | s=6.87 | s=7.07 | s=7.99 |
| Mean power | 68.1 | 70.5 | 68.7 | 68 |
| | s=5.76 | s=5.56 | s=6.66 | s=7.67 |
| **Hardtail subtract (-) Full Suspension** | | | | |
| Difference in avg Min | -3 | (-6.4%)* | -1 | (-2.5%)* |
| | s=6.9 | P=0.258 | s=9.83 | P=0.783 |
| Difference in avg Max | -2.7 | (-3.4%)* | 1.9 | (1.5%)* |
| | s=5.34 | P=0.195 | s=10.03 | P=0.607 |
| Diff in range max/min | 0.294 | (0.9%)* | 2.9 | (3.24%)* |
| | s=3.15 | P=0.799 | s=13.52 | P=0.563 |
| Diff in mean power | -2.4 | (-3.5%)* | 0.7 | (1%)* |
| | s=2.61 | P=0.035 | s=11.07 | P=0.869 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

*Table 5-8: Velocity of Crank*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Velocity (m/s) | | | | |
| Average minimum | 0.31 | 0.32 | 0.272 | 0.27 |
| | s=0.045 | s=0.037 | s=0.025 | s=0.027 |
| Average maximum | 0.357 | 0.36 | 0.55 | 0.547 |
| | s=0.018 | s=0.017 | s=0.01 | s=0.011 |
| Add range | 0.046 | 0.038 | 0.274 | 0.277 |
| | s=0.03 | s=0.02 | s=0.023 | s=0.024 |
| Mean velocity | 0.36 | 0.36 | 0.366 | 0.36 |
| | s=0.01 | s=0.007 | s=0.012 | s=0.023 |

| **Hardtail subtract (-) Full Suspension** | | |
|---|---|---|
| Difference in avg Min | -0.01 (-3.1%)* | 0.002 (0.7%)* |
| | s=0.044 P=0.553 | s=0.04 P=0.89 |
| Difference in avg Max | -0.002 (-0.5%)* | -0.001 (-0.2%)* |
| | s=0.024 P=0.839 | s=0.011 P=0.76 |
| Difference in avg Range | 0.008 (17.3%)* | -0.003 (-1.15%)* |
| | s=0.02 P=0.376 | s=0.035 P=0.808 |
| Diff in mean velocity | 0.001 (0.3%)* | 0.008 (2.2%)* |
| | s=0.007 P=0.699 | s=0.024 P=0.38 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

The results for the velocity of the cranks of both the hardtail and fully suspended bikes are displayed in Table 5-8. As the p values for all of the results are greater than 0.05, this signifies that none of the results are statistically significant.

Table 5-9 displays the results for the average maximum and minimum force exerted on the crank; the range between these average values; the average velocity of the crank force; and the differences between these values for the hardtail and fully suspended bike on both surface types. The findings illustrate that whilst cycling on the smooth surface, the hardtail bike presents a slight advantage to the rider over the fully suspended bike: the average difference in minimum, maximum and mean force is 3.5 %, 2.9 % and 3.9 % less (respectively) when cycling on the hardtail bike, compared to the fully suspended bike, on the smooth surface. These results have p values less than 0.05, and are consequently rendered statistically significant. The results for the magnitude of force exerted on the crank for the tests on the surface with bumps do not follow the same trend; the hardtail bike produces a lower average mean and average minimum force. However, the results for the difference in the average maximum force and the difference in the average force range exerted on the crank (producing higher values for the hardtail bike of 4.1 %; 7.4 % respectively) suggest that there is no benefit to using either suspension system as all of the results are deemed statistically insignificant due to the high p values obtained from the results. It would be expected that the average force would be less on the smooth surface compared to the rough road, however this is not the case in these results.

*Table 5-9: Force exerted the Crank*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | 151.1 | 156.4 | 144.8 | 148.1 |
| | s=17.98 | s=18.68 | s=24.07 | s=16.61 |
| Average maximum | 221.5 | 228 | 236.2 | 232.1 |
| | s=13.04 | s=15.79 | s=13.33 | s=8.03 |
| Total avg force Range | 70.4 | 71.6 | 91.4 | 84 |
| | s=12.73 | s=15.58 | s=16.52 | s=16.59 |
| Mean Force | 188.4 | 195.7 | 187.6 | 189.5 |
| | s=13.41 | s=14.75 | s=17.89 | s=13.37 |

**Hardtail subtract (-) Full Suspension**

| | | | | |
|---|---|---|---|---|
| Difference in avg Min | -5.3 | (-3.5%)* | -3.3 | (-2.3%)* |
| | s=4.56 | P=0.014 | s=36.69 | P=0.806 |
| Difference in avg Max | -6.5 | (-2.9%) | 4.1 | (1.7%)* |
| | s=6.25 | P=0.022 | s=19.62 | P=0.577 |
| Diff in avg force range | -1.2 | (-1.7%) * | 7.4 | (8%)* |
| | s=4.78 | P=0.491 | s=26.23 | P=0.453 |
| Diff in mean force | -7.3 | (-3.9%)* | -1.9 | (-1%)* |
| | s=4.74 | P=0.004 | s=28.15 | P=0.857 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

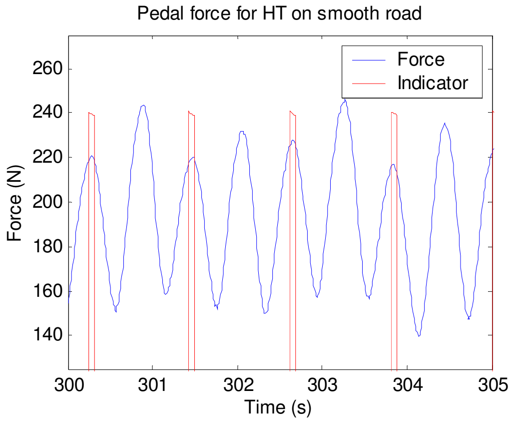


*Figure 5-21: Pedal force for the hardtail bike on the rolling road rig on a smooth surface.*

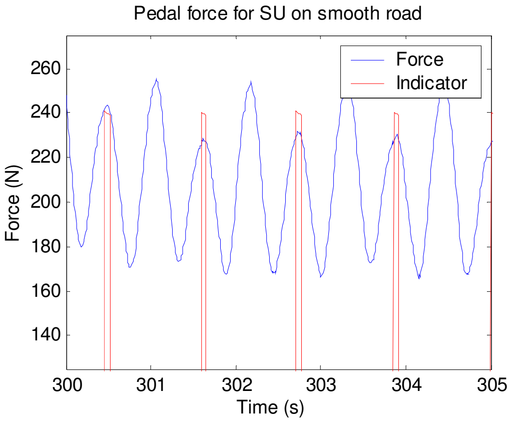


*Figure 5-22: Pedal force for the fully suspended bike on the rolling road rig on a smooth surface.*

The amount of force exerted on the pedals of the hardtail and fully suspended bike (on a smooth surface) by one subject is illustrated in Figures 5-21 and 5-22. The red line indicates the output from the pedal indicator which is placed at the base of the pedal stroke, as illustrated in Figure 5-23. The maximum force is applied to the pedals at this pedal position. Following this pedal position, the amount of force that is applied to the pedals is reduced until the pedals once again reach a horizontal position - where the rider exerts the minimum force.

From the horizontal position the force is gradually increased until another maximum peak is reached when the opposite pedals again reach a vertical position. Figures 5-21 and 5-22 demonstrate the variation in pedal stroke for the subject; a more even pedal stroke would consequently present less variation between the maximum and minimum force which could potentially reduce the bobbing effect on a fully suspended bike. The use of Shimano Pedalling Dynamics (SPD) pedals could aid in levelling the pedal stroke to some extent as the rider can pull up and push down on the pedal. However, these pedals were not used for the experiments on the rolling road rig as specialised footwear was required in order to attach the pedals; subsequently, subjects used toe grips for all experiments.

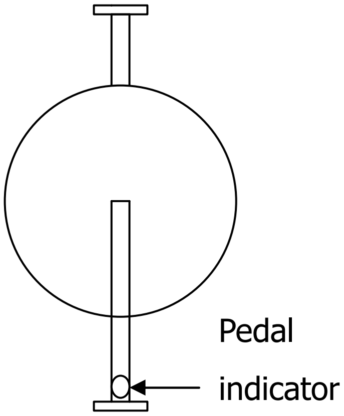


*Figure 5-23: Pedal Indicator*

Figures 5-24 and 5-25 illustrate the amount of force exerted on the pedals by one individual subject on the rolling road rig with a rough surface.

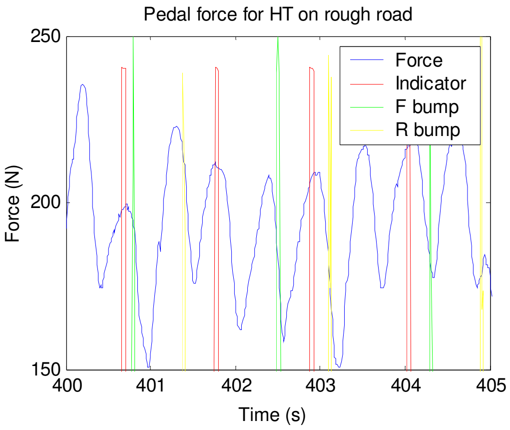


*Figure 5-24: Pedal force for the hardtail bike on the rolling road rig on a rough surface.*

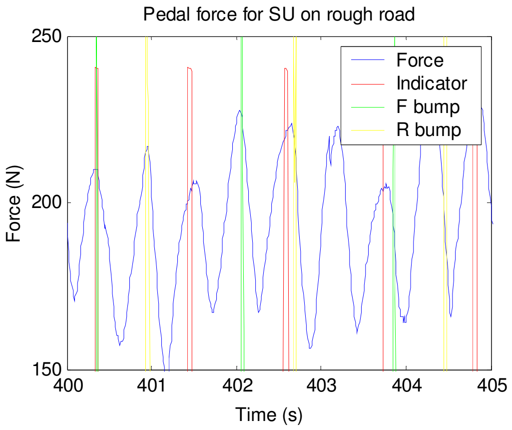


*Figure 5-25: Pedal force for the fully suspended bike on the rolling road rig on a rough surface.*

From a comparison of Figures 5-24 and 5-25 it is evident that the amount of force exerted on the crank for the subject cycling on the fully suspended bike is less than when cycling on the hardtail bike. For the subject to maintain a constant speed on the hardtail bike, the amount of force applied to the crank must be continually adjusted due to the effect of cycling over the bumps. In contrast, the rear suspension of the fully suspended bike aids in absorbing some of the bump impact so that the rider can maintain a more constant pedal stroke. This finding may be a contributing factor to the subjects citing higher RPE ratings for cycling on the fully suspended bike compared to the hardtail bike on the rolling road rig with bumps. In comparing these findings to those from the roller rig, it is apparent that a cyclist is able to maintain a smoother pedal stroke on the rolling road rig compared to the roller rig. This is due to the smaller, more realistic bumps on the rolling road rig compared to those on the roller rig.

*Table 5-10: Vertical force exerted on the Saddle*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | 237.6 | 169.4 | -111.1 | -3.5 |
| | s=115.61 | s=104.1 | s=78.91 | s=111.78 |
| Average maximum | 371.5 | 443.2 | 750 | 610.6 |
| | s=120.1 | s=183.4 | s=184.64 | s=197.28 |
| Total avg force Range | 133.8 | 273.8 | 861.4 | 614.1 |
| | s=49.11 | s=120.7 | s=178.77 | s=203.57 |
| Mean Force | 288.8 | 296.8 | 285.1 | 321.1 |
| | s=120.55 | s=127.79 | s=101.1 | s=112.05 |

| **Hardtail subtract (-) Full Suspension** | | |
|---|---|---|
| Difference in avg Min | 68.2 (28.7%)* | -107.6 (-96.8%)* |
| | s=49.63 P=0.006 | s=112.6 P=0.031 |
| Difference in avg Max | -71.7 (-19.3%)* | 139.7 (18.6%)* |
| | s=73.48 P=0.028 | s=311.96 P=0.246 |
| Diff in avg force range | -140 (-104.6%)* | 247.2 (28.7%)* |
| | s=98.28 P=0.005 | s=104.9 P=0.001 |
| Diff in mean force | -8 (-2.8%)* | -36 (-12.6%)* |
| | s=23.54 P=0.368 | s=161.74 P=0.216 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

The results for the vertical force exerted on the saddle of both bikes on the smooth and bumpy surface of the rolling road rig are displayed in Table 5-10. The significant results from table 5-10 indicate that on the smooth surface, the minimum force exerted on the saddle is 28.7 % less for subjects cycling on the fully suspended bike.  Also the findings indicate that the maximum force exerted on the saddle is 19.3 % less for subjects cycling on the hardtail bike on the rolling road rig with the smooth surface.  Similarly, the force range exerted on the saddle is considerably less (by 130.1 %) whilst cycling on the hardtail bike on the smooth surface, thus suggesting that the hardtail bike presents an advantage to the cyclist whilst riding on the rolling road rig on the smooth surface.  For the results pertaining to the tests undertaken on the rolling road rig with bumps attached, the significant findings indicate that considerably less minimum force – 128 N - is exerted on the saddle whilst cycling on the hardtail bike.  The findings from Table 5-10 also highlight that the force range exerted on the saddle is 33.6 % less whilst cycling on the fully suspended bike on the bumpy surface.

The average range in the amount of force exerted on the saddle highlights a considerable variation between the hardtail and fully suspended bike on the smooth surface (Table 5-10).  This could be a result of the bobbing effect experienced when pedalling.

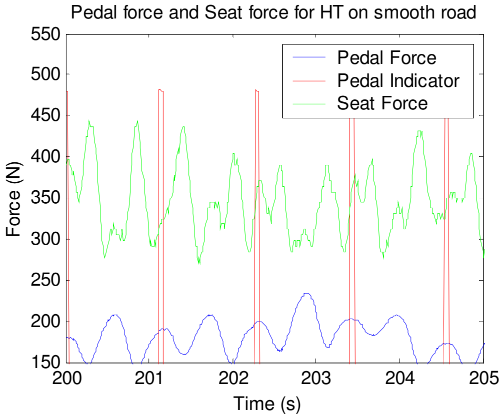


*Figure 5-27: Pedal force and seat force for the hardtail bike on the rolling road rig on a smooth surface.*

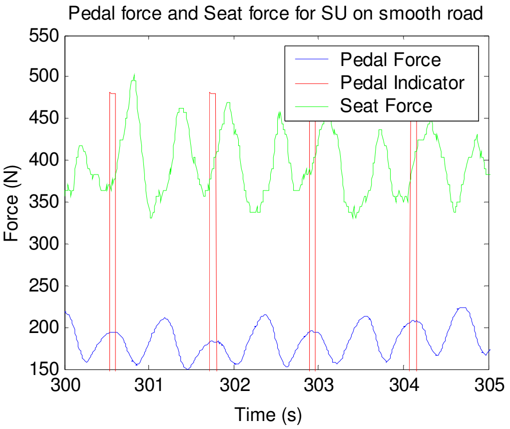


*Figure 5-26: Pedal force and seat force for the fully suspended bike on the rolling road rig on a smooth surface.*

Figures 5-26 and 5-27 illustrate how the rider's weight shifts while pedalling. The greatest amount of force exerted on the saddle coincides with the least amount of force exerted on the pedals. This indicates that the maximum seat force occurs when the pedals are in a horizontal position. Figure 5-26 illustrates that a greater amount of force is exerted on the saddle of the fully suspended bike compared to the hardtail bike on the smooth surface.

The analysis of the results for the amount of force exerted on the saddle, from the experiments on the rough track of the rolling road rig, shows that the average minimum force exerted on the saddle of the fully suspended bike is 17.1 N, and the average minimum force is -111.1 N for the hardtail bike. Although a negative force is not possible this indicates that when the rider leaves the seat after contact with a bump, the force causes the seat post to extend, thus resulting in a negative force. From analysis of the results obtained for each individual subject for the experiments on the rolling road rig with bumps, it was found that six of the eight subjects applied a greater amount of force on the saddle of the hardtail bike compared to the fully suspended bike. For the two remaining subjects, the opposite was true. This finding highlights the difference in riding styles adopted by cyclists - even in this small sample. The range in average force exerted on the saddle also highlighted interesting results: all subjects, with the exception of one, experienced a lower force range (approximately 40 % lower) when cycling on the fully suspended bike. The subject, whose results did not follow this pattern, experienced a greater average force range on the fully suspended system (908.15 N) compared to the hardtail bike (658.55 N). This subject was the heaviest cyclist to undertake testing, and through studying video footage, seemed to experience more bobbing than the other subjects, which once again highlights the difference in the riding styles between subjects.

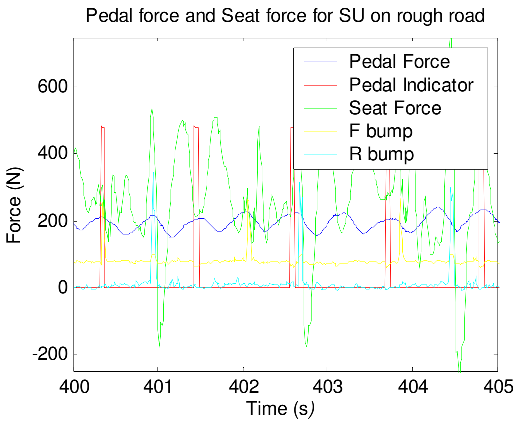


*Figure 5-28: Pedal force and seat force for the fully suspended bike on the rolling road rig on a rough surface.*

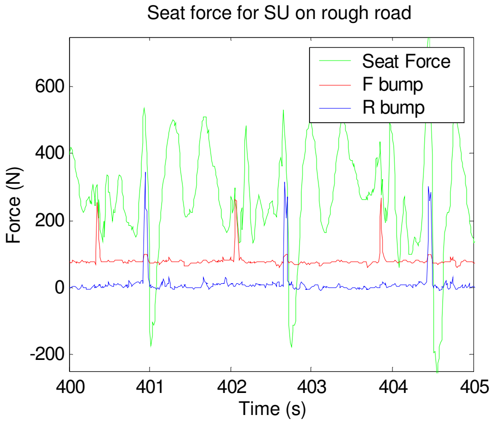


*Figure 5-29: Seat force for the fully suspended bike on the rolling road rig on a rough surface.*

From analysis of Figures 5-28 and 5-29, which display the force exerted on the pedals and saddle of the fully suspended bike on the rough road, it is evident that the wheel impacting with the bumps results in the majority of the changes in the amount of force exerted on the saddle. When the front wheel impacts with a bump (F bump) a number of small positive and negative vibrations occur as a result of the rear suspension moving slightly. It is also evident that when the rear wheel impacts with a bump (R bump), the greatest amount of force is exerted on the seat; a negative force occurs directly after this - a result of the seat post extending as the rider leaves the saddle.

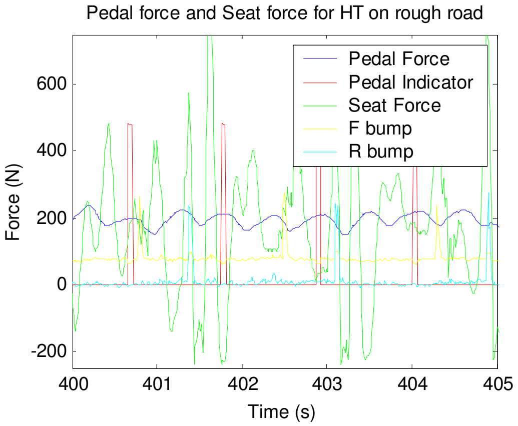


*Figure 5-30: Pedal force and seat force for the hardtail bike on the rolling road rig on a rough surface.*

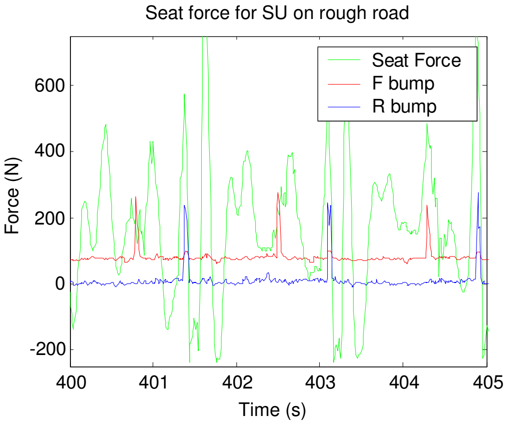


*Figure 5-31: Seat force for the hardtail bike on the rolling road rig on a rough surface.*

The force exerted on the pedals and saddle of the hardtail bike on the rough surfaced rolling road rig is illustrated in Figures 5-30 and 5-31. The graphs demonstrate that when the front wheel impacts with a bump, the cyclist raises slightly from the saddle before returning to the seated position. When the rear wheel impacts with a bump, a large negative value of almost -250 N is displayed on the graph which represents the force exerted on the saddle as the cyclist leaves the seat. Following this, the cyclist returns to the seated position before once again rising slightly from the saddle. Figures 5-30 and 5-31 highlight that a greater amount of force is exerted on the saddle and pedals of the hardtail bike compared to the fully suspended bike. This specifies the reason subjects experienced more discomfort when cycling on the hardtail bike compared to the fully suspended bike.

Tables 5-11 and 5-12 display the findings for the vertical force applied to the left and right handlebars respectively; that is the amount of force the cyclists exerts on the handlebars. The three significant findings (with p values greater than 0.05) relating to the left handlebar are concerned with the minimum vertical force; vertical force range; and mean vertical force applied to the left handlebar during tests on the rolling road rig with the smooth surface. Table 5-11 indicates that a lower minimum vertical force is exerted on the left handlebar of the hardtail bike, compared to the fully suspended bike by 17.3 N, whilst cycling on the smooth surface. Similarly, the range of vertical force applied to the left handlebar is 16.7 % less for subjects cycling on the hardtail bike. However, the results pertaining to the mean force highlight that twenty one percent less vertical force is exerted on the left handlebar whilst cycling on the fully suspended bike on the bumpy surface.

Tables 5-11 to 5-14 show the results relating to the force exerted on the handlebars. The recorded measurements were: the vertical force exerted on the right and left handlebar of both bikes; and the horizontal force exerted on the right and left handlebar of both bikes. All subjects were instructed to keep their hands placed on the handlebars for the duration of the tests - with the exception of when indicating RPE and comfort scale ratings- where the grip was released for a short time period only.

The amount of vertical force exerted on the handlebars was measured by strain gauges. The significant results from the tests indicate that 50.7 % less minimum and 11.7 % less mean vertical force is exerted on the right handlebar of the fully suspended bike whilst undertaking tests on the rolling road rig with the smooth surface. Conversely, 19.6 % less vertical force range is exerted on the right handlebar of the hardtail bike for tests conducted on the smooth surface.

*Table 5-11: Vertical force exerted on left Handlebar*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | -2.9 | -20.2 | -103.6 | -104.4 |
| | s=27.36 | s=24.42 | s=16.75 | s=15.68 |
| Average maximum | 110.6 | 112.4 | 171.4 | 174.6 |
| | s=25.48 | s=29.78 | s=33.92 | s=38.55 |
| Total avg force Range | 113.6 | 132.6 | 275 | 279 |
| | s=28.94 | s=33.57 | s=46.56 | s=47.46 |
| Mean force | 45 | 35.5 | 47.6 | 42.4 |
| | s=20.21 | s=21.36 | s=24.48 | s=18.53 |

**Hardtail subtract (-) Full Suspension**

| | | | | |
|---|---|---|---|---|
| Difference in avg Min | 17.3 | (-558.5%)* | -1.8 | (1.7%)* |
| | s=8.96 P=0.001 | | s=15.4 P=0.877 | |
| Difference in avg Max | -1.7 | (-1.6%)* | -0.9 | (-0.5%)* |
| | s=15.87 P=0.767 | | s=44.04 P=0.956 | |
| Diff in avg force range | -19 | (-16.8%)* | 0.9 | (0.33%)* |
| | s=21.64 P=0.042 | | s=44.06 P=0.955 | |
| Diff in mean force | 9.5 | (21.0%)* | 6.4 | (13.4%)* |
| | s=8.59 P=0.017 | | s=37.32 P=0.644 | |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

*Table 5-12: Vertical force exerted on the right Handlebar*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | 30.8 | 15.2 | -47.7 | -48 |
| | s=16.5 | s=21.64 | s=19.63 | s=13.73 |
| Average maximum | 137 | 142.1 | 193.2 | 170.8 |
| | s=17.08 | s=27.79 | s=35.75 | s=29.36 |
| Total avg force range | 106.1 | 126.9 | 240.9 | 218.8 |
| | s=18.09 | s=19.88 | s=36.15 | s=37.03 |
| Mean force | 82.9 | 73.2 | 79.8 | 68.8 |
| | s=16.22 | s=22.85 | s=23.54 | s=18.7 |

| **Hardtail subtract (-) Full Suspension** | | |
|---|---|---|
| Difference in avg Min | 15.6 (50.7%)* | 0.3 (0.6%)* |
| | s=13.83 P=0.015 | s=27.65 P=0.976 |
| Difference in avg Max | -5.2 (-3.8%) * | 22.4 (11.6%)* |
| | s=13.43 P=0.314 | s=46.1 P=0.211 |
| Diff in avg force range | -20.8 (-19.6%)* | 22.1 (9.17%)* |
| | s=12.39 P=0.002 | s=49.09 P=0.244 |
| Diff in mean force | 9.7 (11.7%)* | 10.9 (13.7%)* |
| | s=10.74 P=0.038 | s=38.23P =0.445 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

The results obtained for the amount of vertical force exerted on the left handlebar demonstrates that, on average, 9.5 N more force is exerted on the left handlebar of the hardtail bike compared to the fully suspended bike on the smooth track (Table 5-11). The results obtained from each individual subject signified that a greater average force is exerted on the left handlebar of the hardtail bike, ranging from 0.66 N to 27.89 N.

Furthermore, the subjects' individual results for the force exerted on the left handlebar indicate that, although the majority of subjects experienced a significantly higher average force range whilst cycling on the fully suspended bike on the smooth surface, two of the subjects experienced a higher force range whilst cycling on the fully suspended system; one by a difference of 20.78 N, and the other by a difference of 0.58 N. Interestingly, the same two subjects were also recorded as exerting less force on the saddle than the other subjects.

In comparing the results for the amount of force exerted on the right handlebar of the bikes to the amount of force exerted on the left handlebar of the bikes on the smooth surface, it was found that the amount of force exerted on the right handlebars of both bikes was an average 30 N greater than the force exerted on the left handlebars of both bikes. An explanation for this could be that the subjects are all right-handed, or that the design of the rig encourages a subject to lean to one side more than the other. On average, the amount of force exerted on the right handlebar of the hardtail bike is 9.7 N greater than that amount exerted on the right handlebar of the fully suspended bike whilst cycling on the smooth surface. Similarly, on average, the amount of force exerted on the left handlebar of the hardtail bike is 9.5 N greater than that amount exerted on the left handlebar of the fully suspended bike whilst cycling on the smooth surface.

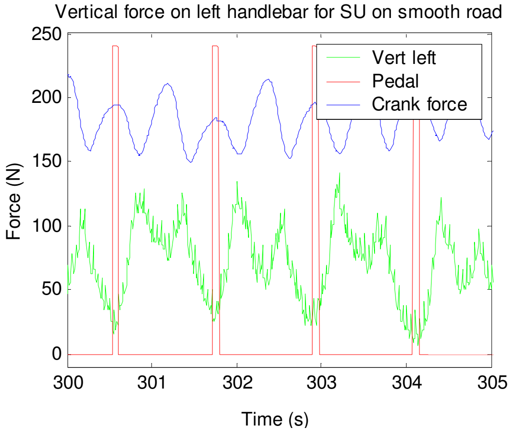


*Figure 5-32: Vertical force on the left handlebar for the fully suspended bike on the rolling road rig on a smooth surface.*

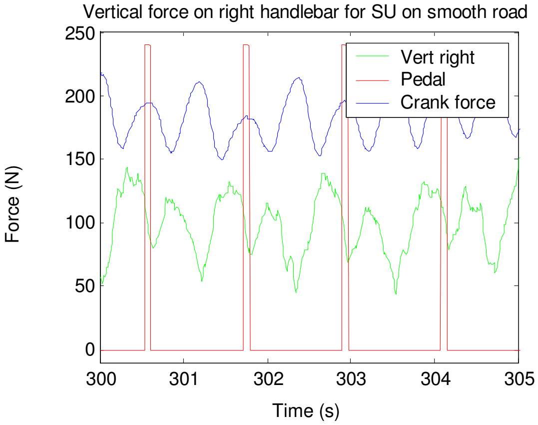


*Figure 5-33: Vertical force on the right handlebar for the fully suspended bike on the rolling road rig on a smooth surface.*

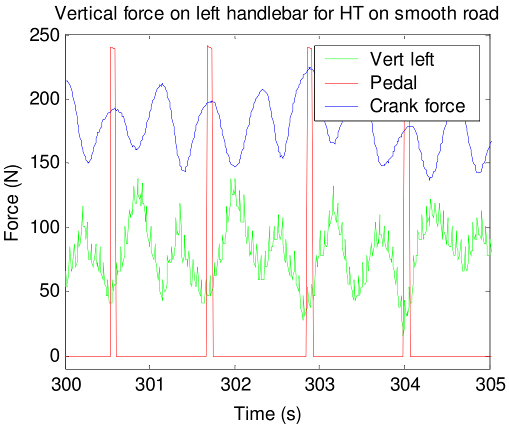


*Figure 5-34: Vertical force on the left handlebar for the hardtail bike on the rolling road rig on a smooth surface.*

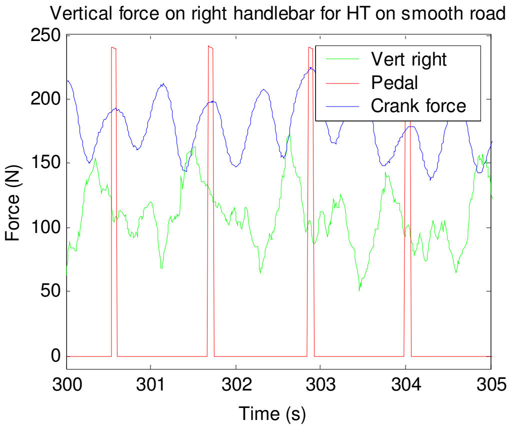
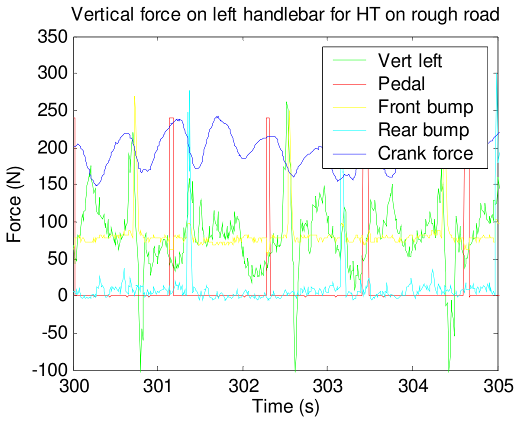


*Figure 5-35: Vertical force on the right handlebar for the hardtail bike on the rolling road rig on a smooth surface.*

Figures 5-32 to 5-33 display the force exerted on the left and right handlebars of the hardtail and fully suspended bike. The figures illustrate that the force exerted on the handlebars is directly proportional to the force applied to the pedals. This is similar to the results obtained for the amount of force exerted on the saddle of the bikes which is also directly proportional to the force exerted on the crank. As more force is applied to the pedals, the amount of force exerted on the handlebars is reduced; the reverse of this is also true. Figures 5-32 to 5-33 indicate that the subject leans from side to side when pedalling - illustrated by the maximum and minimum turning points of the graphs which occur at different time intervals.



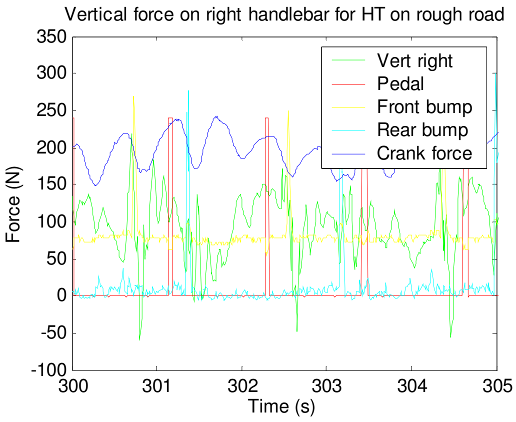
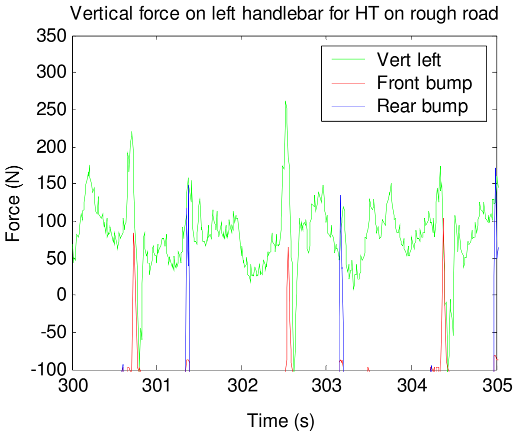


*Figure 5-36: Vertical force on the left handlebar for the hardtail bike on the rolling road rig on a rough surface.*

*Figure 5-37: Vertical force on the right handlebar for the hardtail bike on the rolling road rig on a rough surface.*



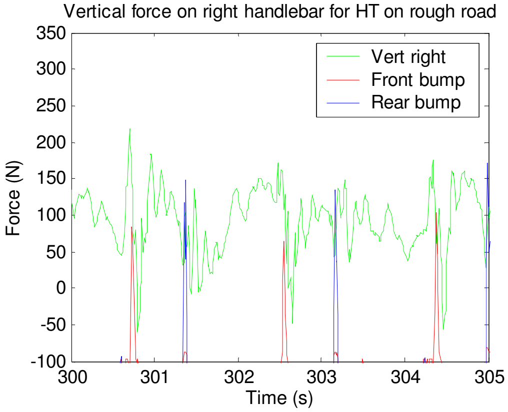


*Figure 5-38: Vertical force on the left handlebar for the hardtail bike on the rolling road rig on a rough surface.*

*Figure 5-39: Vertical force on the right handlebar for the hardtail bike on the rolling road rig on a rough surface.*

Figures 5-36 to 5-37 display the results for the amount of vertical force exerted on the left and right handlebars of the hardtail bike on the rough surface. They demonstrate that the maximum and minimum turning points displayed in the graphs are a result of the front wheel impacting with the bump; an expected result as the handlebars are positioned at the front of the bike. The minimum turning point results in a negative force for both the fully suspended and hardtail bike as the handlebars are lifted slightly when leaving the crest of the bump. On average, the amount of force exerted on the right handlebar is greater than the amount of force exerted on the left handlebar of the hardtail bike, due to the subject being right handed. The amount of force exerted on the handlebars of the hardtail bike is much less when the rear wheel impacts with the bump.

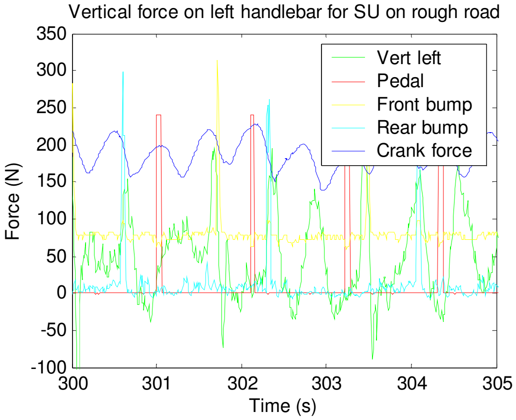


*Figure 5-40: Vertical force on the left handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

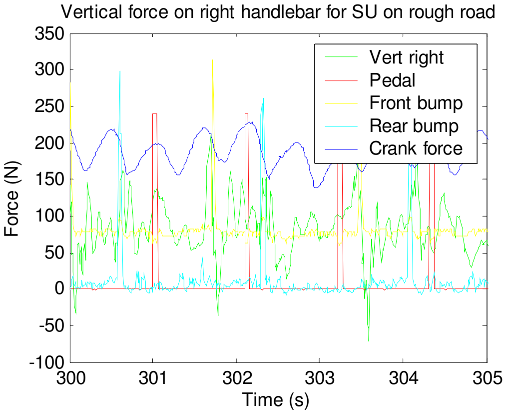


*Figure 5-41: Vertical force on the right handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

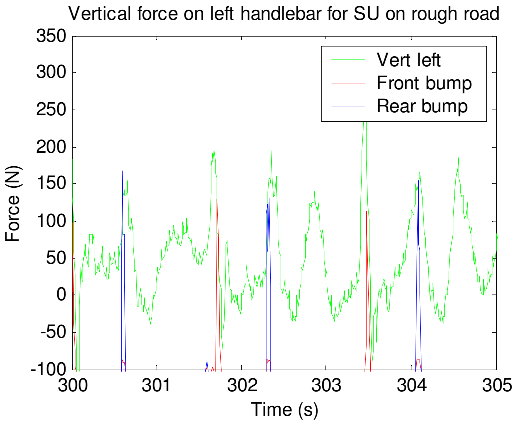


*Figure 5-42: Vertical force on the left handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

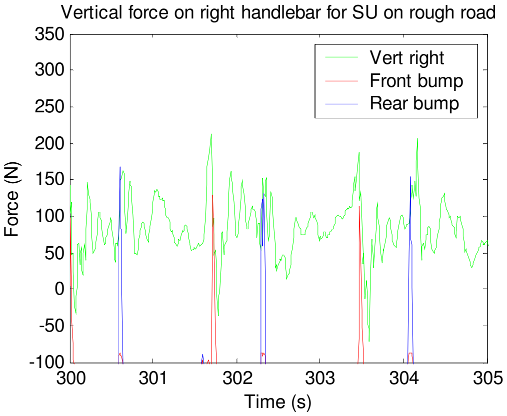


*Figure 5-43: Vertical force on the right handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-40 to 5-43 display the results for the amount of vertical force exerted on the left and right handlebars of the fully suspended bike on the rough surface. The graphs show that the rear suspension absorbs some of the impact of the bump; this is particularly evident for the right handlebar.

The horizontal force exerted on the left handlebar of the hardtail and fully suspended bike on the rolling road rig on the smooth surface and the surface with bumps is presented in Table 5-13. The significant findings indicate that for tests on the smooth surface, 8.7 % less maximum horizontal force is exerted on the left handlebar of the hardtail bike in comparison to the fully suspended bike. The results for the mean horizontal force exerted on the left handlebar also indicates that less horizontal force (35.7 %) is applied to the left handlebar whilst cycling on the hardtail bike. However, the results pertaining to the tests on the surface with bumps highlight that the fully suspended bike presents an advantage to the rider in terms of the minimum, maximum, and mean range of horizontal force that is exerted on the left handlebar. 15.2 %; 18 %; and 16.82 % less horizontal force is exerted on the left handlebar of the fully suspended bike for these results respectively.

*Table 5-13: Horizontal force exerted on the left Handlebar*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | -192.6 | -179.5 | -720 | -610.7 |
| | s=91.06 | s=90.26 | s=20.63 | s=78.22 |
| Average maximum | 406.9 | 442.3 | 1034.6 | 848.9 |
| | s=68.14 | s=75.7 | s=56.65 | s=22.76 |
| Total avg force range | 599.6 | 621.9 | 1754.7 | 1459.6 |
| | s=71.08 | s=108.11 | s=56.58 | s=67.77 |
| Mean force | 90.9 | 123.3 | 100.4 | 127 |
| | s=73.97 | s=70.6 | s=53.96 | s=35.11 |

**Hardtail subtract (-) Full Suspension**

| | | |
|---|---|---|
| Difference in avg Min | -13.1 (6.8%)* | -109.3 (15.2%)* |
| | s=19.94 P=0.106 | s=68.87 P=0.003 |
| Difference in avg Max | -35.4 (-8.7%)* | 185.8 (18%)* |
| | s=37.79 P=0.033 | s=59.7 P=0.000 |
| Diff in avg force range | -22.3 (-3.7%)* | 295.1 (16.82%)* |
| | s=50.02 P=0.25 | s=84.28 P=0.000 |
| Diff in mean force | -32.4 (-35.7%)* | -26.6 (-26.6%)* |
| | s=13.68 P=0.000 | s=70.84 P=0.032 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Table 5-14 displays the results relating to the horizontal force exerted on the right handlebar of both the hardtail and fully suspended bikes on the rolling road rig on the smooth and bumpy surface. The significant findings from the experiments on the smooth surface relate to the maximum and range of horizontal force: 8.8 % less maximum force and 15.9 % less mean force is exerted on the right handlebar of the hardtail bike compared to the fully suspended bike. Conversely, the experiments undertaken on the rolling road rig with bumps attached illustrate that the fully suspended bike provides an advantage to subjects. 18.7 % less minimum horizontal force, 19.7 % less maximum horizontal force and 19.34 % less range of horizontal force is recorded for the right handlebar of the fully suspended bike on the rough surface.

*Table 5-14: Horizontal force exerted on the right Handlebar*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Force (N) | | | | |
| Average minimum | -128.5 | -120.5 | -580.3 | -471.6 |
| | s=37.75 | s=46.97 | s=26.11 | s=35.46 |
| Average maximum | 384.2 | 418.2 | 954.6 | 766.4 |
| | s=44.51 | s=69.05 | s=58.96 | s=19.43 |
| Total avg force Range | 512.7 | 538.7 | 1534.9 | 1238 |
| | s=59.32 | s=90.37 | s=67.15 | s=35.42 |
| Mean force | 129.3 | 149.9 | 144.5 | 151.3 |
| | s=25.2 | s=24.15 | s=23.21 | s=22.63 |

| **Hardtail subtract (-) Full Sus** | | | | |
|---|---|---|---|---|
| Difference in avg Min | -8 | (6.2%)* | -108.7 | (18.7%)* |
| | s=22.92 | P=0.355 | s=11.22 | P=0.000 |
| Difference in avg Max | -33.9 | (-8.8%)* | 188.2 | (19.7%)* |
| | s=33.37 | P=0.024 | s=59.43 | P=0.000 |
| Diff in avg force range | -25.9 | (-5.1%)* | 296.9 | (19.34%)* |
| | s=47.97 | P=0.170 | s=81.26 | P=0.000 |
| Diff in mean force | -20.6 | (-15.9%)* | -6.8 | (-4.7%)* |
| | s=10.47 | P=0.000 | s=32.37 | P=0.57 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Further analysis of the individual subjects' results obtained for the amount of horizontal force exerted on the left handlebars of both bikes on a smooth surface indicate that the average range of horizontal force was found to be greater when cycling on the hardtail bike for two of the subjects, and greater when cycling on the fully suspended bike for the other eight subjects. The amount of horizontal force exerted on the right handlebar was measured to be, on average, 30 N greater than the amount of horizontal force exerted on the left handlebar for both bikes; a result of all subjects being right handed.

The results obtained from the amount of horizontal force applied to the right handlebar of the hardtail and fully suspended bike follow a similar pattern to those obtained from measuring the amount of force applied to the left handlebar of both of the bikes. For subjects undertaking testing on the rolling road rig with a smooth surface, the significant results illustrate that less maximum and average horizontal force is exerted on the right handlebar of the hardtail bike compared to the fully suspended bike. This is similar to the results relating to the force exerted on the left handlebar of the bikes: for these results only the maximum and average force measurements were statistically significant. Although a large difference is apparent between the mean horizontal force value obtained from the right handlebar of the hardtail, and right handlebar of the fully suspended bike whilst cycling on the smooth road, the difference is more evident in the results obtained from the horizontal force exerted on the left handlebar.

*Figure 5-44: Horizontal force on the both handlebars for the hardtail bike on the rolling road rig on a smooth surface.*

*Figure 5-45: Horizontal force on the both handlebars for the fully suspended bike on the rolling road rig on a smooth surface.*

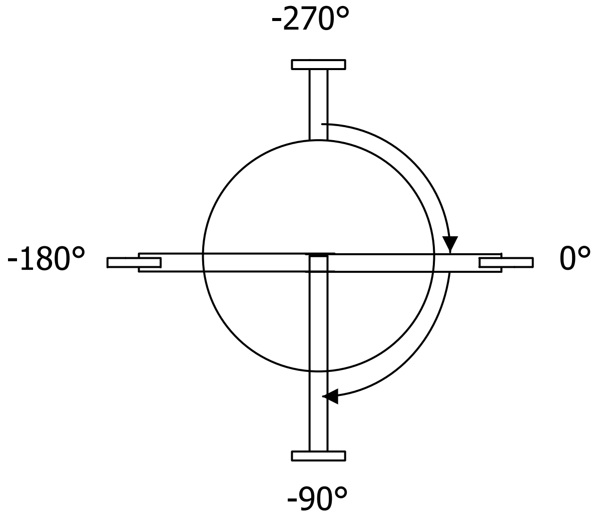
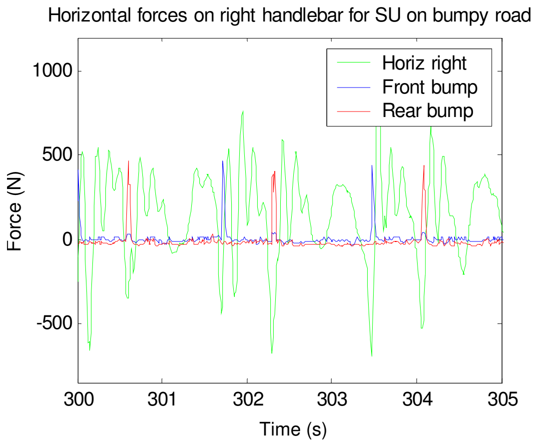


*Figure 5-46: Pedal positions of the crank*

Figures 5-44 and 5-45 display graphs which illustrate that the maximum horizontal force exerted on the handlebars of both bikes results predominantly from the force exerted on the pedals by the cyclist. The maximum amount of force exerted on the handlebars occurs when the pedals are between the horizontal and vertical position (0° to -90°), and the minimum amount of force exerted on the handlebars occurs when the pedals are between - 270° and 0°. These pedal positions are illustrated in figure 5-46. Figure 5-46 highlights the crank positions where the majority of the forward momentum is produced.



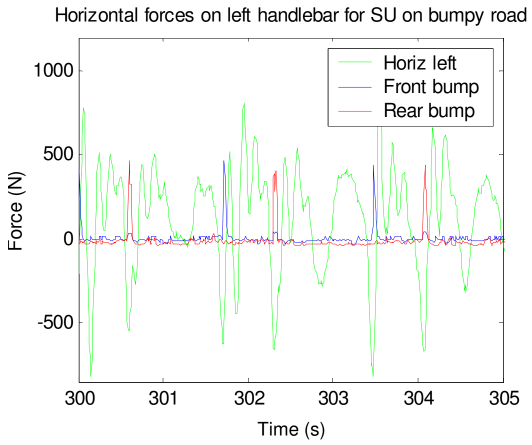


*Figure 5-47: Horizontal force on the right handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

*Figure 5-48: Horizontal force on the left handlebar for the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-47 and 5-48 illustrate graphs displaying the amount of horizontal force exerted on both the right and left handlebars of the fully suspended bike whilst cycling on the rolling road rig with a rough surface. The amount of force exerted on the right and left handlebars of the fully suspended bike is similar: the most prominent negative values occur when the wheel impacts with a bump and creates a bending force between the handlebars and the frame of the rig.

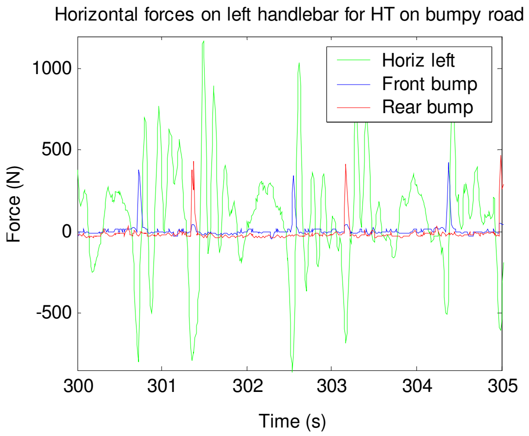


*Figure 5-49: Horizontal force on the left handlebar for the hardtail bike on the rolling road rig on a rough surface.*

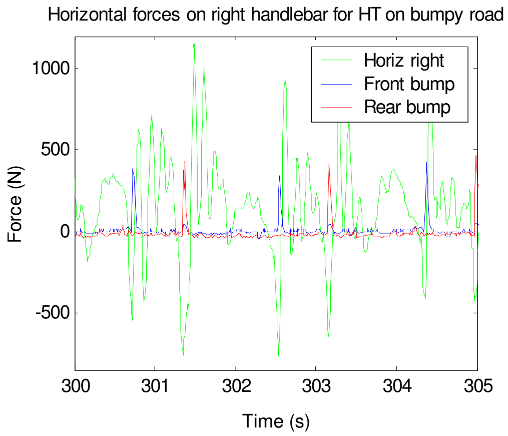


*Figure 5-50: Horizontal force on the right handlebar for the hardtail bike on the rolling road rig on a rough surface.*

Figures 5-49 and 5-50 display graphs illustrating the amount of horizontal force exerted on both the right and left handlebar of the hardtail bike whilst cycling on the rough road. From analysis of Figures 5-47 to 5-50, it is evident that the horizontal force which is exerted on the handlebars of both bikes is a direct result of bump impact. In comparison to Figures 5-47 and 5-48, Figures 5-49 and 5-50 highlight that the hardtail bike exerts a greater amount of horizontal force on the handlebars following contact of the front and rear wheel with the bump. This is particularly evident when the rear wheel of the hardtail bike hits the bump.

The findings relating to the handlebar and saddle accelerations; the handlebar and saddle velocities; and the handlebar and saddle displacements of the hardtail and fully suspended bikes on the rolling road rig on both the smooth surface and surface with bumps are displayed in Tables 5-15 to 5-19. In replace of the average mean values (which would equate to approximately zero for the velocity, acceleration and displacement of the seat and handlebars due to the positive and negative values that are obtained when calculating the results), the average root mean squared (RMS) value is given in each table to provide a representation of the average acceleration, velocity and displacement. As with the results displayed in Tables 5-7 to 5-14, the lower sections of the results displayed in Tables 5-15 to 5-19 compare the findings from the fully suspended and hardtail bikes on both surface types.

*Table 5-15: Handlebar Acceleration*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Handlebar Acceleration (m/s^2) | | | | |
| Average minimum | -0.7 | -0.5 | -4.0 | -2.1 |
| | s=0.05 | s=0.08 | s=0.49 | s=0.21 |
| Average maximum | 0.6 | 0.5 | 2.5 | 1.8 |
| | s=0.05 | s=0.08 | s=0.17 | s=0.11 |
| Total avg range | 1.3 | 0.9 | 6.5 | 3.9 |
| | s=0.11 | s=0.15 | s=0.36 | s=0.3 |
| RMS | 0.2587 | 0.1594 | 0.6375 | 0.4089 |
| | s=0.01 | s=0.02 | s=0.03 | s=0.02 |

**Hardtail subtract (-) Full Suspension**

| | | |
|---|---|---|
| Difference in avg Min | -0.2 (31.5%)* | -1.9 (48%)* |
| | s=0.07 P=0.000 | s=0.58 P=0.000 |
| Difference in avg Max | 0.2 (29.6%)* | 0.7 (27.9%)* |
| | s=0.06 P=0.000 | s=0.18 P=0.000 |
| Diff in total avg range | 0.4 (30.5%)* | 2.6 (40.18%)* |
| | s=0.13 P=0.000 | s=0.39 P=0.000 |
| Difference in RMS | 0.0993 (38.4%)* | 0.2286 (35.9%)* |
| | s=0.021 P=0.046 | s=0.035 P=0.042 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Table 5-15 displays the results obtained from the accelerometer placed at the handlebars of the hardtail and full suspension system. The results obtained from the tests on the rolling road rig on the smooth surface indicate that there is 31.5 %; 29.6 %; 30.5 %; and 38.4 % less minimum, maximum, range, and RMS acceleration of the handlebars respectively, for subjects cycling on the fully suspended bike compared to the hardtail bike. The findings obtained from the tests on the rolling road rig with bumps attached display a similar trend: 48 % less minimum handlebar acceleration; 27.9 % less maximum handlebar acceleration; 40.18 % less range; and a 35.9 % lower RMS value for handlebar acceleration occurs whilst cycling on the fully suspended bike. As all the results pertaining to the handlebar accelerations of both the hardtail and fully suspended bikes have p values of less than 0.05, these results are rendered significant.

Figures 5-51 and 5-52 show that less acceleration occurs at the handlebars of the fully suspended bike, compared to the hardtail bike, whilst cycling on a smooth road. This is an unexpected result: as there are no bumps on the smooth surface, it is hypothesised that both bikes would obtain a similar value for the acceleration at the handlebars, as a result of both bikes possessing front suspension. Indeed, if a greater acceleration was to occur at the handlebars of either of the two bikes, it would be justifiable to presume that it be the handlebars of the fully suspended bike - due to the bobbing effect occurring at the rear suspension. In supporting this hypothesis, higher $VO_2$ and heart rate levels were recorded for subjects cycling on the fully suspended bike on the smooth surface. Although these results were not statistically significant, they would nevertheless suggest that the fully suspended bike would also record a greater acceleration at the handlebars compared to the hardtail bike.

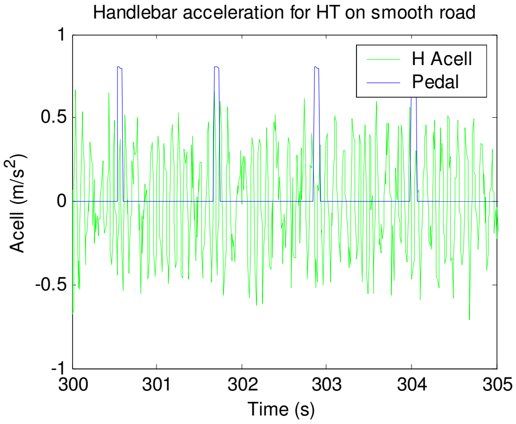


*Figure 5-51: Acceleration of the handlebars of the hardtail bike on the rolling road rig on a smooth surface.*

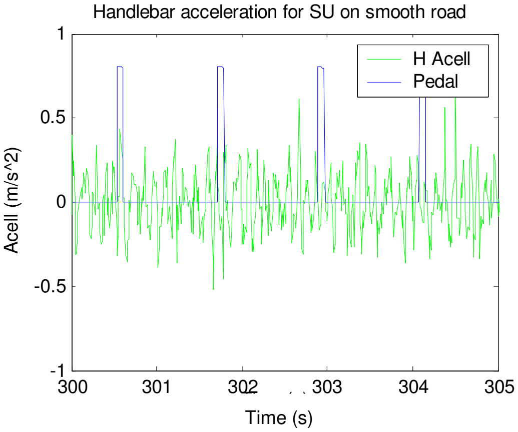


*Figure 5-52: Acceleration of the handlebars of the fully suspended bike on the rolling road rig on a smooth surface.*

The results for the acceleration of the handlebars of both bikes on the surface with bumps demonstrate similar results to the tests conducted on the smooth surface rolling road rig. All of the results are statistically significant and indicate that less acceleration occurs at the handlebars of the fully suspended bike compared to the hardtail bike whilst cycling on the surface with bumps. The eight individual results pertaining to handlebar acceleration present similar results to those obtained from cycling on the smooth surface, indicating that more acceleration occurs at the handlebars of the hardtail bike compared to the fully suspended bike whilst cycling on a surface with bumps.

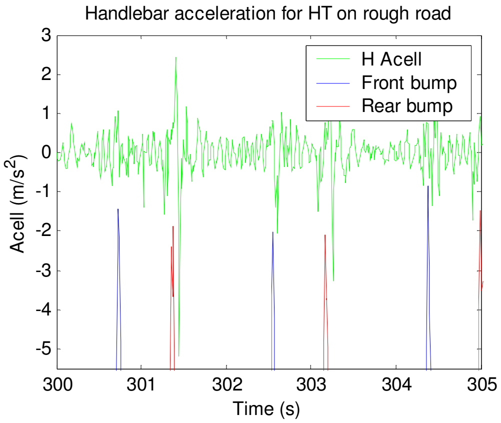


*Figure 5-53: Acceleration of the handlebars of the hardtail bike on the rolling road rig on a rough surface.*

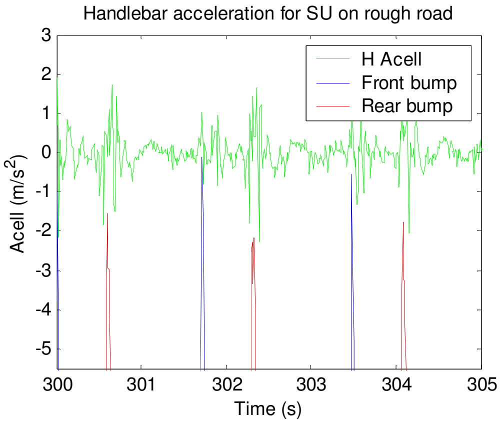


*Figure 5-54: Acceleration of the handlebars of the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-53 and 5-54 show that less acceleration occurs at the handlebars of the fully suspended bike, compared to the hardtail bike, whilst cycling on a rough road. The graphs illustrate that the maximum and minimum acceleration values are significantly lower for the fully suspended system. This signifies that less vibration is felt by the rider whilst cycling on the fully suspended bike; a result of the damper in the rear suspension reducing the amount of vibrations felt as the bike impacts with the bump. This finding corresponds with the results obtained from the roller rig which also found that the acceleration of the handlebars of the fully suspended bike was lower than that of the hardtail bike (Table 4-9; Chapter

4). As the hardtail bike has no rear suspension system to absorb bump impact, the rider's weight is forced forward towards the front of the bike, thus accounting for the higher handlebar acceleration results obtained for the hardtail bike. When considering the results pertaining to the acceleration of the saddle of the hardtail and fully suspended bikes on the smooth and rough surface, the only significant results relate to the RMS values for saddle acceleration on both the smooth and rough track. Both sets of results for cycling on the smooth and rough surface demonstrate that greater acceleration occurs at the seat of the hardtail bike compared to the fully suspended bike. All of the eight subjects obtained a greater RMS seat acceleration value whilst cycling on the hardtail bike compared to the fully suspended bike on the smooth track. The average range of seat acceleration for each subject illustrated that four subjects experienced a lower range whilst cycling on the fully suspended bike; and four subjects experienced a lower range whilst cycling on the hardtail bike on the smooth track.

The results obtained from the accelerometers placed under the saddle of the hardtail and full suspension system (Table 5-16) all - with the exception of the difference in RMS values - produce p values greater than 0.05, thus rendering these results statistically insignificant. The statistically significant RMS values indicate that the average mean acceleration of the saddle of the hardtail bike is a 38.3 % and 35.9 % greater (on the smooth and bumpy surface respectively) than that of the fully suspended bike.

*Table 5-16: Saddle Acceleration*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Seat Acceleration (m/s^2) | | | | |
| Average minimum | -1.3 | -1.3 | -6.9 | -6.7 |
| | s=0.1 | s=0.09 | s=0.22 | s=0.2 |
| Average maximum | 1.4 | 1.3 | 10.3 | 10.1 |
| | s=0.09 | s=0.15 | s=1.19 | s=1.62 |
| Total avg Range | 2.7 | 2.6 | 17.3 | 17.2 |
| | s=0.17 | s=0.24 | s=1.25 | s=1.35 |
| RMS | 0.8768 | 0.5408 | 2.17282 | 1.3931 |
| | s=0.211 | s=0.131 | s=0.25 | s=0.21 |

**Hardtail subtract (-) Full Suspension**

| | | | | |
|---|---|---|---|---|
| Difference in avg Min | -0.01 | (0.5%)* | -0.3 | (3.7%)* |
| | s=0.14 | P=0.893 | s=0.41 | P=0.117 |
| Difference in avg Max | 0.1 | (5%)* | 0.2 | (2.1%)* |
| | s=0.2 | P=0.374 | s=2.12 | P=0.784 |
| Diff in total avg Range | 0.1 | (2.8%)* | 2.2 | (12.77%)* |
| | s=0.33 | P=0.536 | s=5.48 | P=0.293 |
| Difference in RMS | 0.336 | (38.3%)* | 0.7797 | (35.9%)* |
| | s=0.018 | P=0.046 | s=0.23 | P=0.042 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Figures 5-55 and 5-56 are graphs illustrating the acceleration of the seats of both the hardtail and fully suspended bike whilst cycling on the smooth road of the rolling road rig. It is evident from Figures 5-55 and 5-56 that the seat of the fully suspended bike accelerates less than the seat of the hardtail bike whilst cycling on the smooth road. This finding correlates with the results obtained for the acceleration at the handlebars, and is again a somewhat surprising result: the simulation analysis suggest that a bobbing motion occurs when cycling on the fully suspended bike on a smooth surface, which would in turn suggests that the seat of the fully suspended bike would accelerate more than that of the hardtail bike.

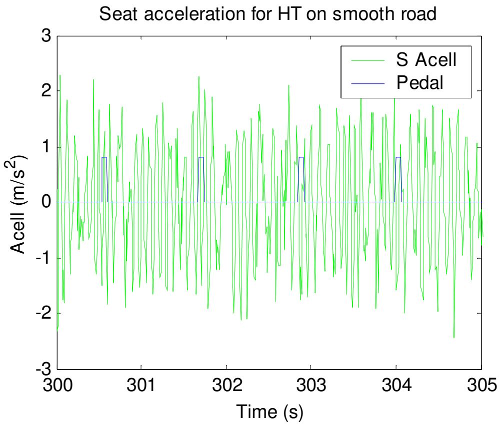


*Figure 5-55: Acceleration of the seat of the hardtail bike on the rolling road rig on a smooth surface.*

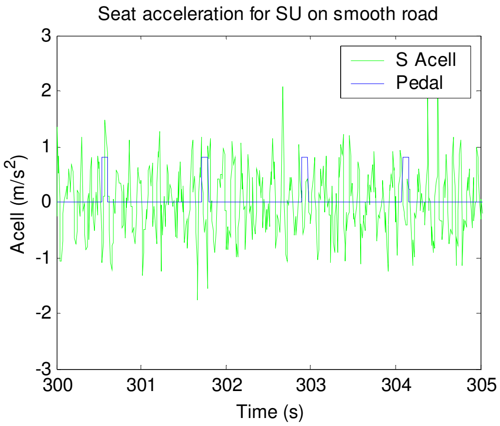


*Figure 5-56: Acceleration of the seat of the fully suspended bike on the rolling road rig on a smooth surface.*

The results obtained from measuring the saddle acceleration of both the hardtail and fully suspended bike on the rough surface of the rolling road rig (Table 5-16) illustrate that greater acceleration occurs at the seat of the hardtail bike compared to the fully suspended bike. Analysis of the individual subjects' saddle acceleration results indicate that every subject obtained a higher RMS value when cycling on the hardtail bike on the rolling road rig. Two subjects obtained a higher average seat acceleration range on the fully suspended bike, and six subjects obtained a higher range on the hardtail bike. This again highlights the different techniques used by riders even amongst this small group of individuals. The RMS results for saddle acceleration on the rough track of the roller rig agree with those obtained from the rolling road rig with a rough surface: both rigs indicate that a greater acceleration occurs at the seat of the hardtail bike compared to the fully suspended bike. This is attributed to the omission of a rear suspension on the hardtail bike which results in greater vibrations being felt whilst cycling over the bumps and consequently, a greater acceleration of the saddle.

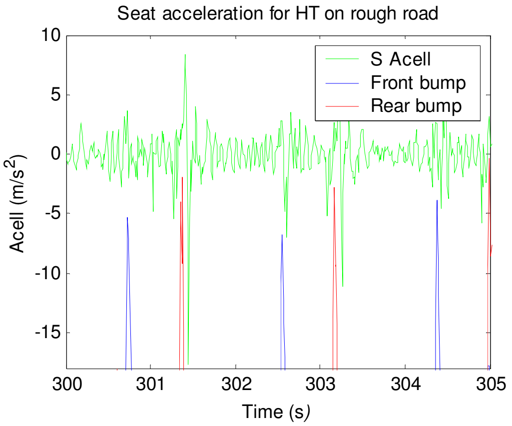


*Figure 5-57: Acceleration of the seat of the hardtail bike on the rolling road rig on a rough surface.*

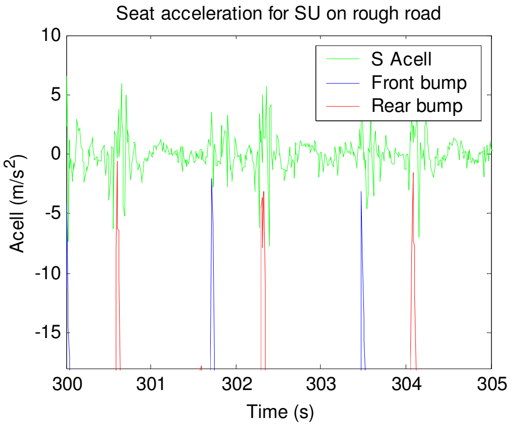


*Figure 5-58: Acceleration of the seat of the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-57 and 5-58 are graphs illustrating the acceleration of the seats of both the hardtail and fully suspended bikes whilst cycling on the road with bumps. From examining the graphs it is apparent that the seat of the fully suspended bike accelerates less than the seat of the hardtail bike whilst cycling on the road with bumps.

Through integrating the acceleration results obtained from the accelerometers placed under the saddle and on the handlebars of the bike, the resulting saddle and handlebar velocities were calculated: the results of which are displayed in Table 5-18 and 5-17. Table 5-17 displays the results of the handlebar velocities, calculated through integrating the accelerations recorded for the handlebars. The significant results indicate that the minimum handlebar velocity is 24.2 % lower; the maximum handlebar velocity is 23.7 % lower; and the range in handlebar velocity is 23.9 % lower when cycling on the fully suspended bike on the smooth surface compared to the hardtail bike on the smooth surface. The significant results obtained for the handlebar velocities for the tests on the surface with bumps attached show that a lower maximum handlebar velocity (by

43.6 %) and a lower range in handlebar velocity (by 32.2 %) is recorded for cyclists riding on the fully suspended bike.

*Table 5-17: Handlebar Velocity*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Handlebar Velocity (m/s) | | | | |
| Average minimum | -0.1225 | -0.0929 | -0.2780 | -0.259 |
| | s=0.0272 | s=0.0252 | s=0.0144 | s=0.0108 |
| Average maximum | 0.1230 | 0.0939 | 0.6562 | 0.37 |
| | s=0.0258 | s=0.0231 | s=0.0438 | s=0.0220 |
| Total avg range | 0.2455 | 0.186817 | 0.927 | 0.62898 |
| | s=0.05297 | s=0.0482 | s=05686 | s=0.02798 |
| RMS | 0.05 | 0.0381 | 0.126586 | 0.1082 |
| | s=0.018 | s=0.0117 | s=0.0104 | s=0.052 |

| **Hardtail subtract (-) Full Suspension** | | |
|---|---|---|
| Difference in avg Min | -0.0296 (24.16%)* | -0.0118 (4.4%)* |
| | s=0.0203 P=0.005 | s=0.023 P=0.197 |
| Difference in avg Max | 0.0291 (23.66%)* | 0.2862 (43.62%)* |
| | s=0.0189 P=0.003 | s=0.038 P=0.000 |
| Diff in total avg Range | 0.0587 (23.9%)* | 0.298 (32.15%)* |
| | s=0.0153 P=0.004 | s=0.051 P=0.000 |
| Difference in RMS | 0.0142 (28.4%)* | 0.32 (14.5%)* |
| | s=0.0173 P=0.053 | s=0.0238 P=0.065 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Figures 5-59 and 5-60 illustrate one subject's handlebar velocity for the hardtail and fully suspended bike whilst cycling on the smooth road on the rolling road rig. The graphs show that the velocity of the handlebars does not follow the same pattern as the rider's pedalling motion and that less velocity occurs at the handlebars of the fully suspended bike compared to the hardtail on a smooth road. This again indicates that no bobbing effect occurs at the front of the bike due to the rider's pedalling motion.

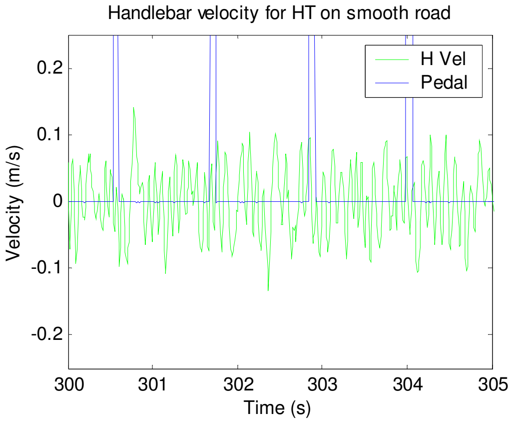


*Figure 5-59: Handlebar velocity of the hardtail bike on the rolling road rig on a smooth surface.*

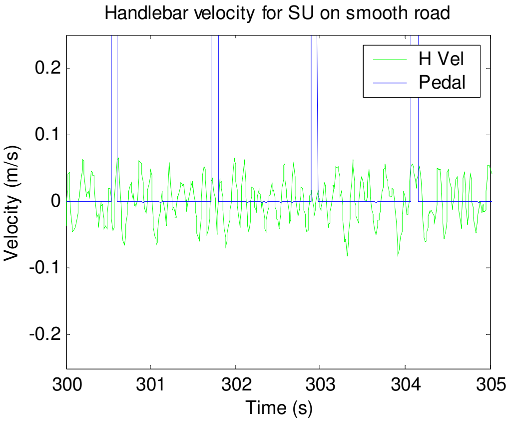


*Figure 5-60: Handlebar velocity of the fully suspended bike on the rolling road rig on a smooth surface.*

The results obtained from recording the velocity at the handlebars of both bikes whilst cycling on the rough road (Table 5-17), all indicate that the velocity of the handlebars of the fully suspended bike is less than that of the hardtail bike. However, only the results pertaining to the difference in average maximum handlebar velocity and the difference in total average range are statistically significant, suggesting that these results do not highlight as significant a difference as those relating to the acceleration of the handlebars. This is also true for the results relating to handlebar velocity obtained from the experiments on the roller rig: the results for the average handlebar velocity indicate a significant difference between both bikes when cycling on rough terrain on the roller rig (Table 4-10; Chapter 4). However, this is the only statistically significant result pertaining to handlebar velocity on the roller rig, which suggests that it does not highlight as significant a difference as other results obtained on the roller rig.

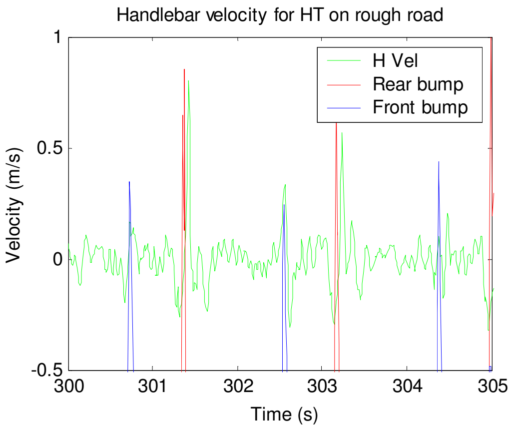


*Figure 5-61: Handlebar velocity of the hardtail bike on the rolling road rig on a rough surface.*

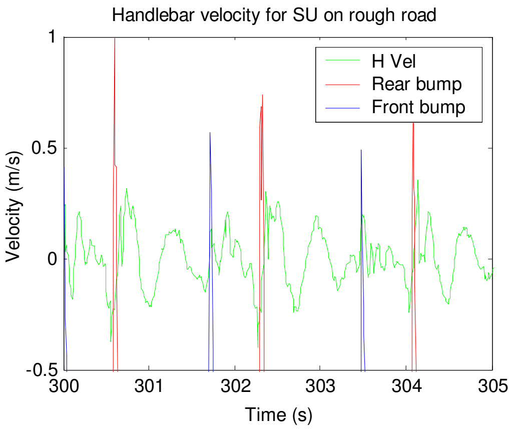


*Figure 5-62: Handlebar velocity of the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-61 and 5-62 are graphs displaying the velocity of the handlebars for one subject cycling on the hardtail and fully suspended bike on the rough road. The graphs illustrate that more vibrations are felt by the rider when cycling on the hardtail bike due to the greater velocity of the handlebars experienced when cycling on this bike type. Figures 5-61 and 5-62 also illustrate that, for both bikes, the maximum and minimum velocity values occur immediately after the rear wheel impacts with the bump. Figure 5-62 clearly illustrates the way in which the rear suspension causes the front of the bike to oscillate following contact between the rear wheel and bump. Consequently, although the velocity of the handlebars is lower whilst cycling on the fully suspended bike when the rear wheel impacts with the bump, it takes considerably longer for the fully suspended bike - compared to the hardtail bike - to stabilise following this impact.

The significant results (with p values of less than 0.05) pertaining to the saddle velocities indicate that a 27.8 % lower minimum velocity; 26.6 % lower maximum velocity; and 27.1 % lower range in velocity occurs whilst cycling on the fully suspended bike on the smooth surface, compared to the hardtail bike on the same smooth surface. Similarly, the statistically significant results highlight that for the tests on the surface with bumps, the velocity of the saddle of the fully suspended bike is forty four percent (maximum velocity) and 32.3 % (range in velocity) lower than whilst cycling on the hardtail bike.

*Table 5-18: Saddle Velocity*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Saddle Velocity (m/s) | | | | |
| Average minimum | -0.4177 | -0.3014 | -0.9398 | -0.8963 |
| | s=0.0893 | s=0.0800 | s=0.05 | s=0.0371 |
| Average maximum | 0.4147 | 0.3055 | 2.2333 | 1.2508 |
| | s=0.0901 | s=0.0762 | s=0.1471 | s=0.0779 |
| Total avg range | 0.8325 | 0.6069 | 3.1731 | 2.1471 |
| | s=0.1792 | s=0.155 | s=0.193 | s=0.0932 |
| RMS | 0.17 | 0.1301 | 0.43224 | 0.369523 |
| | s=0.062 | s=0.04 | s=0.036 | s=0.0546 |

**Hardtail subtract (-) Full Suspension**

| | | |
|---|---|---|
| Difference in avg Min | -0.1163 (27.84%)* | -0.0434 (4.6%) * |
| | s=0.0695 P=0.002 | s=0.0788 P=0.016 |
| Difference in avg Max | 0.1092 (26.63%)* | 0.9826 (44%)* |
| | s=0.0506 P=0.0001 | s=0.1257 P=0.000 |
| Diff in total avg range | 0.2255 (27.08%)* | 1.026 (32.33%)* |
| | s=0.009 P=0.001 | s=0.321 P=0.000 |
| Difference in RMS | 0.0486 (28.6%)* | 0.0627 (14.5%)* |
| | s=0.0591 P=0.053 | s=0.0813 P=0.065 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Figures 5-63 and 5-64 present the velocity of the seat of the hardtail and fully suspended bikes when cycling on the smooth road. The shape of both graphs is similar to those graphs displaying the velocity of the handlebars (Figures 5-59 and 5-60). However, the velocity of the saddle is three times the magnitude of the handlebar velocity for both the hardtail and fully suspended bike.

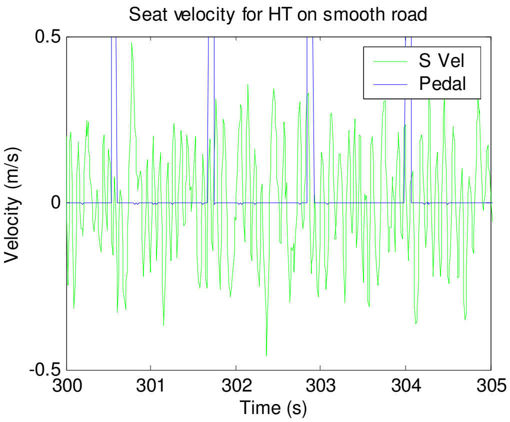


*Figure 5-63: Seat velocity of the hardtail bike on the rolling road rig on a smooth surface.*

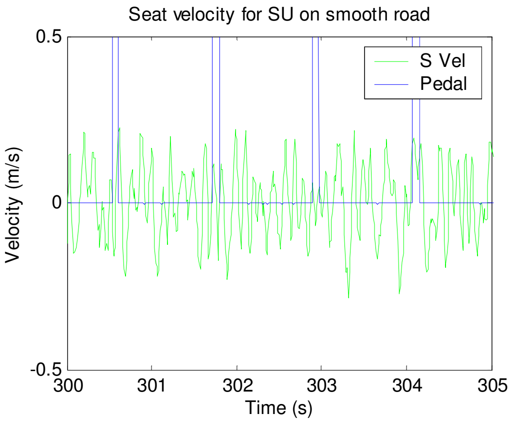


*Figure 5-64: Seat velocity of the fully suspended bike on the rolling road rig on a smooth surface.*

The results pertaining to the velocity of the saddle of the hardtail and fully suspended bike when cycling on the surface with bumps on the rolling road rig (Table 5-1) highlight that the fully suspended bike presents an advantage to the rider over the hardtail bike. This finding agrees with the results relating to saddle velocity on the roller rig, which also highlights a significant advantage for cyclists on the fully suspended bike, compared the hardtail bike when cycling on rough terrain (Table 4-7; Chapter 4).

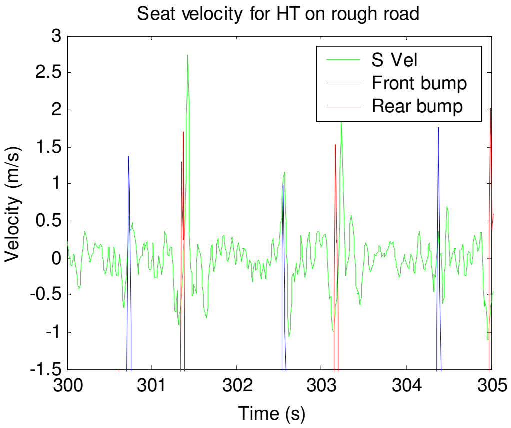


*Figure 5-65: Seat velocity of the hardtail bike on the rolling road rig on a rough surface.*

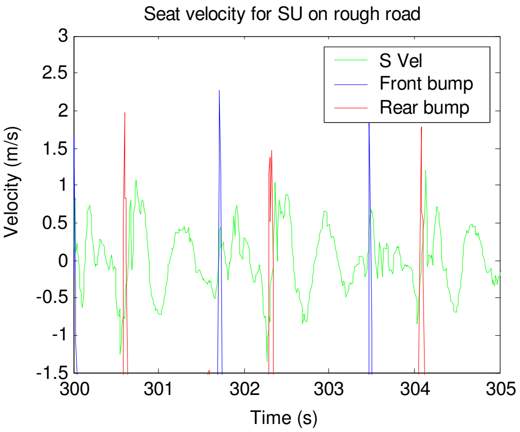


*Figure 5-66: Seat velocity of the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-65 and 5-66 show the velocity of the seat of the hardtail and fully suspended bikes when cycling on the surface with bumps on the rolling road rig. The point at which the velocity of the saddle is at its lowest is similar for both bikes: when the rear and front wheel impact with the bump. Further analysis demonstrates that the seat of the hardtail bike has a greater velocity than the fully suspended bike. Following impact with the bump, a bobbing effect occurs whilst cycling on the fully suspended bike, yet the vibrations felt on the fully suspended bike are less than those felt when cycling on the hardtail bike due to the rear suspension reducing the smaller oscillations that are apparent when cycling on the hardtail system.

The results for the displacement of the handlebars and saddle are displayed in Tables 5-19 and 5-20 respectively: these were calculated through integrating the velocity results. The results concerning the handlebar displacements were found to be statistically insignificant: all p values for the minimum, maximum and displacement range were recorded as greater than 0.05 for both the hardtail and fully suspended bikes on the smooth surface and on the surface with bumps.

*Table 5-19: Handlebar Displacement*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Handlebar Displacement (m) | | | | |
| Minimum Disp | -0.0051 | -0.0045 | -0.0175 | -0.0145 |
| | s=0.0021 | s=0.0015 | s=0.013 | s=0.0017 |
| Maximum Disp | 0.0051 | 0.0044 | 0.0127 | 0.0142 |
| | s=0.0019 | s=0.0016 | s=0.0008 | s=0.0016 |
| Total avg range | 0.0102 | 0.0089 | 0.0302 | 0.0286 |
| | s=0.004 | s=0.0031 | s=0.002 | s=0.0032 |
| RMS | 0.0023 | 0.0021 | 0.0055 | 0.00698 |
| | s=0.0012 | s=0.001 | s=0.0005 | s=0.02 |

| **Hardtail subtract (-) Full Suspension** | | |
|---|---|---|
| Difference in avg Min | -0.0006 (10.8%)* | -0.003 (17.14%)* |
| | s=0.002 P=0.473 | s=0.0025 P=0.98 |
| Difference in avg Max | 0.0007 (12.7%)* | -0.0012 (11.9%)* |
| | s=0.002 P=0.401 | s=0.0019 P=0.061 |
| Difference in avg Range | 0.0013 (11.7%)* | 0.0016 (5.2%)* |
| | s=0.061 P=0.432 | s=0.2997 P=0.346 |
| Difference in RMS | 0.0002 (8.7%)* | -0.0015 (27.3%)* |
| | s=0.0013 P=0.648 | s=0.0022 P=0.01 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Figures 5-67 and 5-68 illustrate the handlebar displacement of the hardtail and fully suspended bikes when cycling on the smooth surface. From comparing the graphs it is evident that the displacement of the handlebars of the hardtail bike is greater than that of the fully suspended bike whilst cycling on the smooth road. In turn, this would indicate that the front suspension of the hardtail bike is utilised more than the front suspension of the fully suspended bike, despite the fact that suspension is not required when cycling on a smooth road.

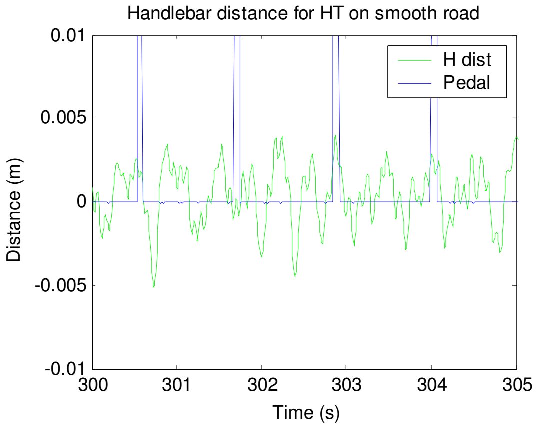


*Figure 5-67: Handlebar displacement of the hardtail bike on the rolling road rig on a smooth surface.*

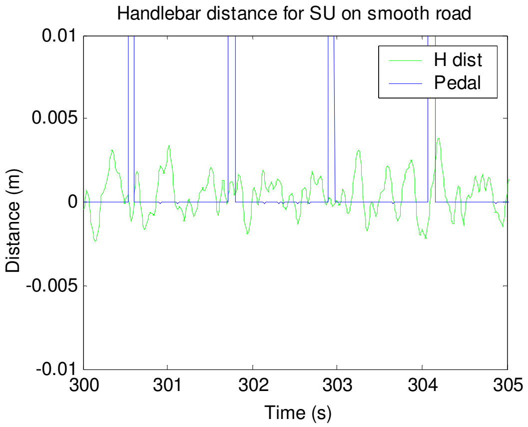


*Figure 5-68: Handlebar displacement of the fully suspended bike on the rolling road rig on a smooth surface.*

*Figure 5-69: Handlebar displacement of the hardtail bike on the rolling road rig on a rough surface.*

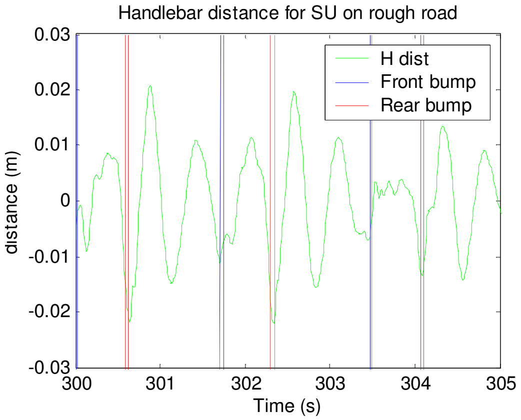


*Figure 5-70: Handlebar displacement of the fully suspended bike on the rolling road rig on a rough surface.*

Figures 5-69 and 5-70 display the results for the handlebar displacement of the hardtail and fully suspended bikes when cycling on the rough surface of the rolling road rig. The graphs indicate that the displacement of the handlebars of the fully suspended bike is greater, compared to the hardtail bike, when the rear wheel impacts with the bump. This is a result of the rear suspension causing the front of the bike to oscillate considerably prior to contact with the bump. Conversely, when the front wheel comes into contact with the bump, the displacement of the handlebars of the hardtail bike is greater than the fully suspended bike. From observing the graphs it can be noted that the rate at which the maximum handlebar displacement is achieved is also noticeably different for both bikes. The maximum handlebar displacement of the hardtail bike occurs immediately after the wheels impact with the bump, whereas the maximum handlebar displacement of the fully suspended bike occurs after the rear wheel impacts with the bump. A bobbing effect is also particularly noticeable after the rear wheel of the fully suspended bike impacts with the bump (Figure 5-70); the handlebars oscillate until impact with the next bump occurs.

The results relating to the displacement of the saddle (Table 5-20) present only one statistically significant result: 15 % less saddle displacement occurs whilst cycling on the fully suspended bike, compared to the hardtail bike, on the surface with bumps. All other findings concerning the displacement of the saddle produced results with p values of greater than 0.05, and thus these results were statistically insignificant.

*Table 5-20: Saddle Displacement*

| **Track type:** | **Smooth** | | **Bumps** | |
|---|---|---|---|---|
| **Suspension:** | **Hardtail** | **Full Suspension** | **Hardtail** | **Full Suspension** |
| Saddle Displacement (m) | | | | |
| Average minimum | -0.0177 | -0.0167 | -0.056 | -0.0483 |
| | s=0.0075 | s=0.0053 | s=0.0044 | s=0.0054 |
| Average maximum | 0.0162 | 0.0154 | 0.0399 | 0.0433 |
| | s=0.0063 | s=0.0052 | s=0.0025 | s=0.0095 |
| Total avg range | 0.0339 | 0.0321 | 0.0959 | 0.0915 |
| | s=0.0138 | s=0.0105 | s=0.0069 | s=0.0121 |
| RMS | 0.0079 | 0.0076 | 0.018875 | 0.0238 |
| | s=0.04 | s=0.035 | s=0.0017 | s=0.0062 |

**Hardtail subtract (-) Full Suspension**

| | | |
|---|---|---|
| Difference in avg Min | -0.0011 (6%)* | -0.0084 (15%)* |
| | s=0.0075 P=0.698 | s=0.0083 P=0.024 |
| Difference in avg Max | 0.0008 (4.9%)* | -0.0033 (8.27%)* |
| | s=0.0072 P=0.765 | s=0.0095 P=0.353 |
| Difference in avg Range | 0.0019 (5.5%)* | -0.0051 (5.2%)* |
| | s=0.06 P=0.729 | s=0.257 P=0.369 |
| Difference in RMS | 0.0008 (10.1%)* | 0.005 (26.5%)* |
| | s=0.0046 P=0.648 | s=0.0074 P=0.099 |

*** : % Improvement by fitting suspension = 100* (average diff. / HT mean)**

Figures 5-71 and 5-72 display the results for saddle displacement of both the fully suspended and hardtail bike on the smooth surfaced rolling road rig. The graphs highlight that there is less displacement of the saddle of the fully suspended bike when travelling at the constant velocity of 8 km/h on the rolling road rig. This result disproves the theory that a bobbing effect exists when cycling on a flat surface on a fully suspended bike.

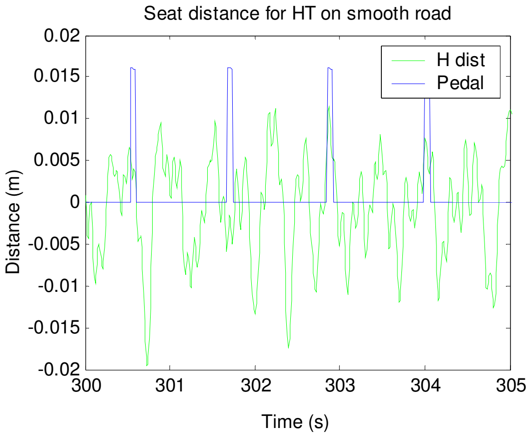


*Figure 5-71: Seat displacement of the hardtail bike on the rolling road rig on a smooth surface.*

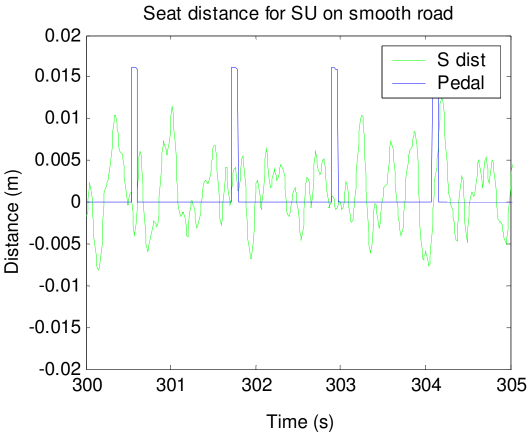


*Figure 5-72: Seat displacement of the fully suspended bike on the rolling road rig on a smooth surface.*

The average results obtained for saddle displacement whilst cycling on the rough road of the rolling road rig demonstrate that the average maximum, range and RMS seat displacement values are greater for the fully suspended bike compared to the hardtail bike (Table 5-20). Figures 5-73 and 5-74 demonstrate the results for one subject's saddle displacement on the hardtail and fully suspended bikes when cycling on the rough surface. The graphs show that the displacement of the saddle is greater whilst cycling on the fully suspended bike compared to the hardtail bike; these results concur with the average results (Table 5-20; Chapter 5). Figure 5-74 also demonstrates that a significant bobbing effect occurs on the fully suspended bike prior to impact with the bump. These results conflict with the results for saddle displacement recorded on the roller rig on a rough surface (Table 4-8; Chapter 4). The results obtained from the roller rig indicate that the saddle of the fully suspended bike moves to a lesser degree than that of the hardtail bike. A reason for the discrepancy in rig results may be attributed to the magnitude and frequency of the bumps used during the experimentations: the spacing of the bumps is greater on the rolling road rig; therefore the fully suspended bike can oscillate to a greater degree on this rig than on the roller rig.

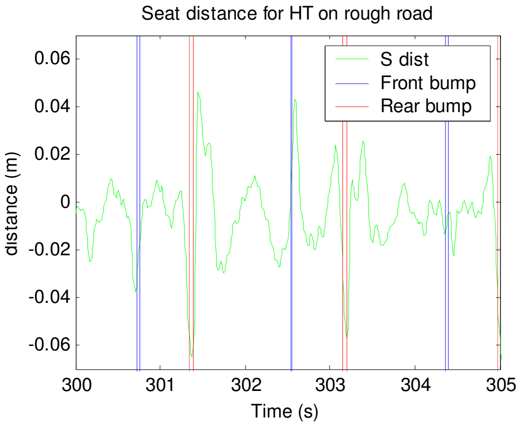


*Figure 5-73: Seat displacement of the hardtail bike on the rolling road rig on a rough surface.*

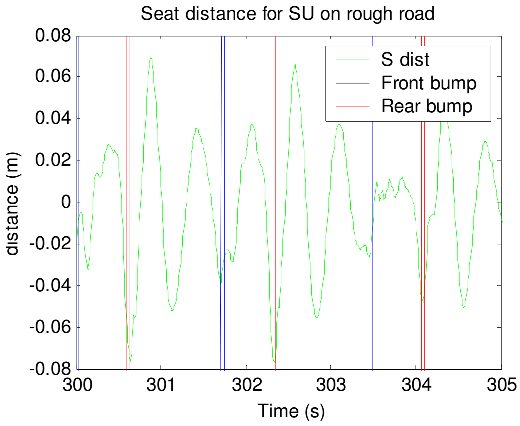


*Figure 5-74: Seat displacement of the fully suspended bike on the rolling road rig on a rough surface.*

# 6. Indoor Track

## 6.1. Objectives

The main objective of the indoor track tests was to conduct controlled experiments to validate the results obtained from the roller rig and rolling road rig laboratory tests and to provide further evidence from which to draw conclusions. The results of the roller rig tests indicated that a reduction in a subject's heart rate and oxygen consumption is achieved when cycling on a fully suspended bike on a rough surface. Conversely, the rolling road rig experiments highlighted no significant differences between riding a fully suspended and hardtail bike (on either the rough or smooth surface) for any of the physiological measurements. Both sets of laboratory tests on the roller rig and rolling road rig produced relevant findings to the current study, yet (as discussed in Chapter 2) laboratory tests often present limitations to testing. With this mind, the key rationale was to develop a new form of testing. It was decided that outdoor testing would present a vast number of variables which would affect the repeatability of tests. Therefore, it was hypothesised that an indoor track test would present less restrictions than a laboratory rig, yet still allow for repeatable tests with a reduced number of variables.

A further objective was to design the indoor track to be as comparative as possible with the previously designed rigs. As the rolling road rig was deemed to be more representative of outdoor cross-country cycling, the indoor track was designed so as to present as close a direct comparison as possible to this rig.

## 6.2. Track Design

The purpose of designing the indoor track and subsequent set of experiments was to simulate a rough track equivalent to that used for the rolling road rig tests.

As with the design of the rolling road rig, a morphological chart (Table 6-1) was generated to aid in the development of conceptual designs (Appendix I). The weighted objectives method (Table 6-2) was then applied to determine the most suitable design for the indoor track. The weighted objectives method for the rig indicated that Concept A (Figure 6-1) was the most appropriate concept to satisfy all of the criteria for the indoor track.

*Table 6-1: Morphological Chart*

| Solutions<br>Sub-functions | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Bump | Wooden slats | Rubber | Metal | None | | |
| Track surface | Wooden | Concrete | Dirt | Chipboard | Metal | Carpet |
| Track fastening | Staples | Screwed | Bolted | Adhesive | Click fit | |
| Corners | Banked | Flat | | | | |
| Number of bumps | Every 3 m | Varied | Every 1 m | None | | |
| How bumps are attached | Adhesive | Bolts | clips | Welding | | |
| Bump shape | Triangle | Round | Rounded edges | Chamfered edges | Square | Rectangle |
| Track Gradient | Flat | Uphill and downhill section | 2 Uphill and downhill sections | | | |
| Track design | Circular | Oval | Straight | Varied | | |
| Ensure Constant Speed of bike | Monitor speed | Bleep test | Timed laps | Subject Monitors speed | | |

*Table 6-2: Weighted Objectives Method*

| | **Concepts rated 1-5 ( 5 being the highest )** | | | | |
|---|---|---|---|---|---|
| Criteria | Concept A | Concept B | Concept C | Concept D | Concept E |
| Safety | 4 | 2 | 4 | 5 | 1 |
| Repeatable | 5 | 3 | 4 | 3 | 3 |
| Able to maintain constant speed | 4 | 3 | 3 | 3 | 2 |
| Ease of production | 4 | 3 | 3 | 5 | 2 |
| Irregular bumps | 2 | 2 | 2 | 3 | 3 |
| Feels natural | 4 | 3 | 2 | 2 | 2 |
| Riders movement can be examined | 4 | 4 | 4 | 4 | 2 |
| Forces applied to the bikes can be studied easily | 1 | 1 | 1 | 1 | 1 |
| Physiology of rider can be recorded | 5 | 4 | 4 | 4 | 3 |
| Bump frequency and height changing | 3 | 4 | 3 | 3 | 5 |
| Movement of suspension can be studied | 3 | 4 | 3 | 3 | 4 |
| Cost | 4 | 3 | 3 | 5 | 2 |
| **Total** | 43 | 36 | 33 | 36 | 30 |

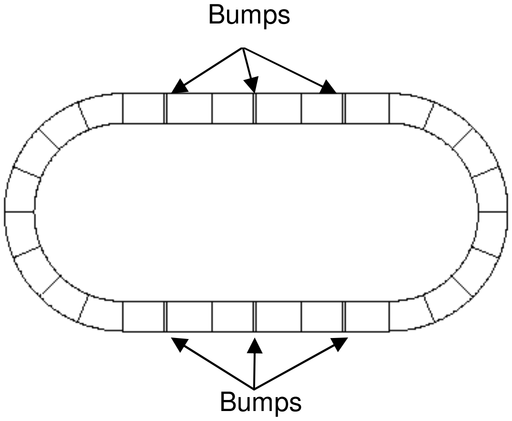


*Figure 6-1: Concept A*

The bumps placed on the indoor track were designed to emulate the identical shape, magnitude and frequency as those on the rolling road rig. Due to safety concerns it was decided that no bumps were to be placed on the corners of the track as it was felt that these may cause subjects to lose balance when cycling. As the tests on the indoor track were to be sub-maximal, banked corners (as usually appear in a velodrome design) were omitted from this track design. The indoor track was assembled in an equine centre as this provided adequate space from an indoor track which would be sheltered from the elements. As the subjects would be unable to cycle directly on the equine centre surface due to its softness a track was developed for the bikes to run on. The track was created from textured hardboard which was durable; provided traction between the tyre and the track; and ensured repeatable results for comparison.

### 6.2.1. Track Construction

Each double layer of hardboard used for the construction of the track was 2.44 m in length; 1.22 m wide; and 3 mm thick. The track comprised of two straight sections, each 10.5 m long with an 18 m radius bend at each end. 6 bumps in total were placed along the track: 3 bumps - each 3 m apart - on each of the two straight sections. 3 m spacing’s were used as this was equivalent to the spacing used for the bumps on the rolling road rig. The indoor track with bumps and equipment is illustrated in Figure 6-2.

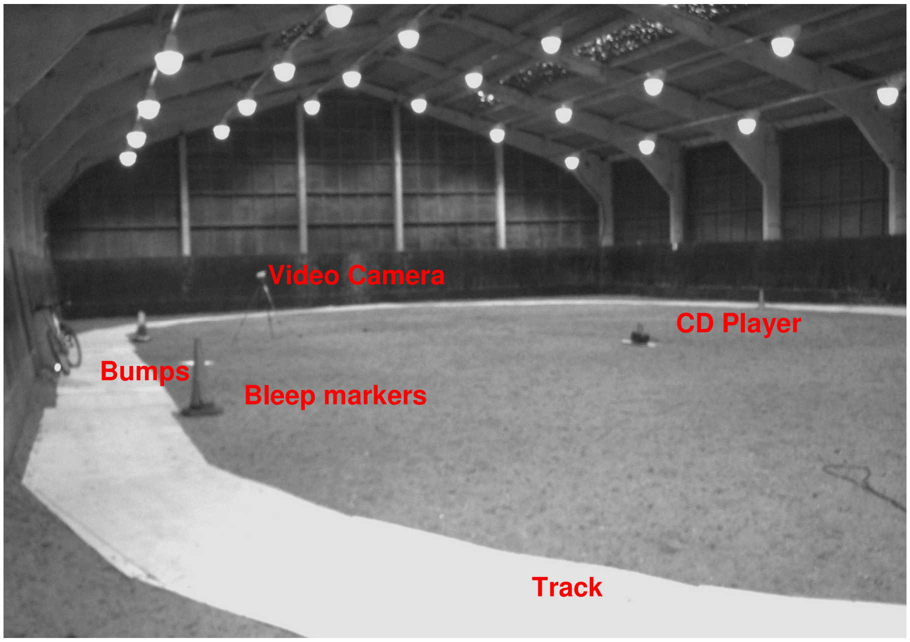


*Figure 6-2: Indoor Track*

## 6.3. Equipment

To pose fewer restrictions on the rider it was proposed that for the purpose of the experiments on the indoor track that no mechanical equipment would be attached to the bike as it was felt that the added equipment would impede the subjects' performance. The only apparatus attached to the bike was a downloadable cyclometer which allowed the speed of each subject to be recorded. This was a vital piece of electronic equipment as it verified that each subject cycled at a constant speed throughout testing. Although the subjects were able to view the cyclometer on the bikes, there had to be a means of ensuring that the subjects maintained this speed on both bikes to ensure that the tests were repeatable and comparable. For this reason a bleep test was developed in which subjects were instructed to pass certain markers (cones) on the track at the same time as a bleep was heard. The bleeps were transmitted via a CD recording placed in the centre of the equine centre. The single other piece of electrical equipment used for the tests was a high-speed digital video camera which was used to observe the subjects' movement over the bumps and which allowed any differences between the two bikes to be detected visually.

### 6.3.1. Physiological Measurements

As it was still imperative to assess each rider's physiological measurements, a portable, downloadable $VO_2$ and heart rate monitor was used for this purpose. Heart rate was recorded through the use of a Polar heart rate system. The transmitter belt of the apparatus was placed around the subject's chest and data was recorded using a Polar S710 watch receiver. The subject wore this throughout testing and the results were available to download at the end of each test.

To evaluate each subject's $VO_{2,}$ a portable Breath by Breath monitor was strapped to the subject's chest; this cardiopulmonary exercise system was used to monitor the physiological responses of the subject. The system directly measures $O_2$ and $CO_2$ concentrations of the inspired/expired air through a facemask covering both the mouth and nose. The mask has a volume transducer (turbine with 2 % accuracy) fitted with gas sample lines. The gas analysers have an accuracy of 0.1 % and a response time of 100 ms. The system used for gas monitoring is via a MetaMax 3B Breath by Breath Gas Analyser (Cortex Biophysik GmbH, Germany).

### 6.3.2. Psychological Measurements

Rating of perceived exertion (RPE) was monitored at intervals using a standard Borg scale which gives an indication as to how hard a person feels they are exercising. As with the tests carried out on the roller rig and the rolling road rig, comfort rating was measured using a scale rated from one (very uncomfortable) to five (very comfortable) as described by Seifert et al. (1997). As the subjects were prevented from talking during the tests, as a result of wearing the facemask, the RPE and comfort rating numbers were held up one at a time and the subject was instructed to nod when the appropriate number was reached. A full explanation of RPE and comfort scale can be found in section 4.3.5 of the current research.

## 6.4. Test Protocol

### 6.4.1. Test Subjects

The experimental protocol was reviewed and approved by the ethics committee at Glasgow University. Each subject was informed of the purpose and risks of the study and signed a physical activity questionnaire and consent form. Ten subjects, with an average age of twenty-three and an average weight of 71 kg, took part in the study; all were in good health at the time of testing and carried out at least two aerobic training sessions per week. Ten subjects were chosen over the eight previously used in the rolling road rig tests so as to increase the sample size and number of results for analysis.

### 6.4.2. Bikes

Similar to the tests on the rolling road rig, only one bike was used for testing on the indoor track: a Marin Mount Vision. Once again, the hardtail bike was created by replacing the rear suspension spring and damper with a specifically designed steel spacer. This ensured that all aspects relative to the bikes were kept uniform throughout the tests.

### 6.4.3. Method

Tyre pressure was kept at 40 psi throughout all of the tests. The subject was asked to cycle passively over the bumps and to remain seated at all times so as to minimise variation in riding styles. All of the subjects were instructed to use the same gear throughout the test and were instructed not to use the brakes at any point. Subjects were instructed to cycle at a constant speed of 10.5 km/hr; this speed was chosen to ensure sub-maximal conditions were met for each of the tests in order to allow for comparisons to be made between the roller rig and rolling road rig test results.

Each subject visited the track on one occasion and carried out a total of four tests: a familiarisation test on the hardtail bike; a familiarisation test on the fully suspended bike; an indoor track test on the hardtail bike; and an indoor track test on the fully suspended bike. All subjects were asked to refrain from exercising twenty-four hours prior to testing and were instructed not to eat three hours prior to testing. Each rider performed a six-minute familiarisation phase using both the fully suspended and the hardtail bike; this ensured that the subjects were comfortable with the apparatus and surroundings. The order of testing was such: five subjects undertook their initial test on the fully suspended bike followed by the hardtail, and five carried out their initial test on the hardtail bike followed by the fully suspended. As all of the subjects were competent cyclists, each met the bleeps on each section of track by the third minute of the familiarisation test.

Following the familiarisation test, and after the subject's heart rate had returned to its 'at rest' rate, each subject was instructed to cycle at a constant speed of 10.5 km/h for twelve minutes. This was the same time period for the tests undertaken on the roller rig and rolling road rig experiments so as to allow for comparison between the physiological results from all three test series.

The measurements for heart rate and $VO_2$ were taken from the second to the eleventh minute of testing and averaged over that period, and the subjects' RPE and comfort scales were recorded in the fourth, sixth and ninth minute of each test.

## 6.5. Physiological and Psychological Results

As the tests on the indoor track presented fewer constraints to the subjects in comparison to the tests undertaken on the roller rig and the rolling road rig, it was hypothesised that the obtained results would present a closer representation to what would be experienced on an outdoor cross-country track. The statistical analysis of the results is based on the average of the ten subjects' physiological and psychological results.

### 6.5.1. Indoor Track Test Results

Figures 6-3 to 6-6 are scatter plot graphs which illustrate the subjects' average physiological and psychological results for heart rate, $VO_2$, RPE and comfort rating on both the fully suspended and hardtail mountain bikes whilst cycling on the indoor track. The full data set for each individual subject during the indoor track tests is given in Appendix B. Each point on the graph represents one participant: the values recorded on the vertical axis are for the hardtail bike, and those recorded on the horizontal axis are for the fully suspended bike. The points above the equality line on the scatter graphs indicate the higher readings obtained for the hardtail bike.

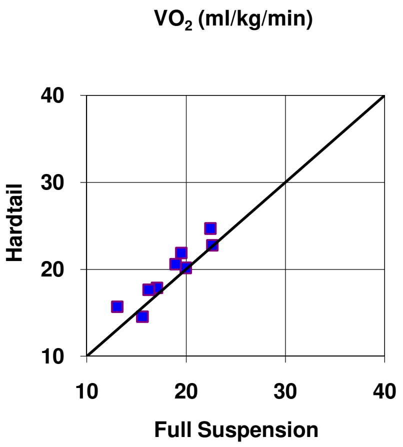


*Figure 6-3: Comparison of $VO_2$ results for the hardtail and fully suspended bike on the indoor track*

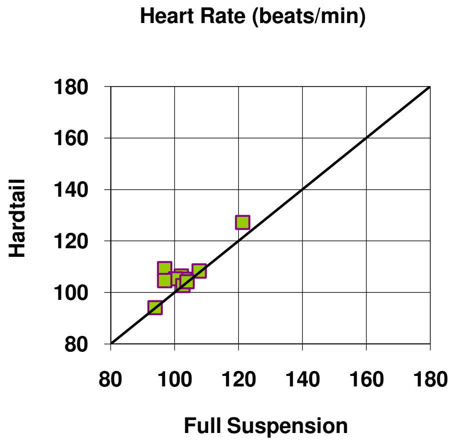


*Figure 6-4: Comparison of heart rate results for the hardtail and fully suspended bike on the indoor track.*

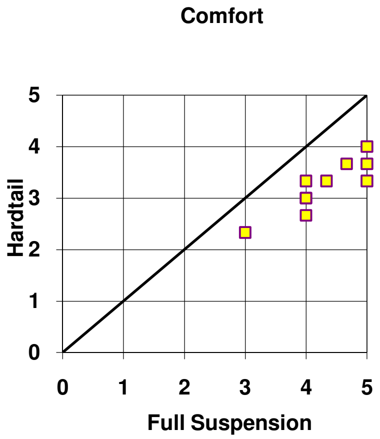


*Figure 6-5: Comparison of comfort results for the hardtail and fully suspended bike on the indoor track.*

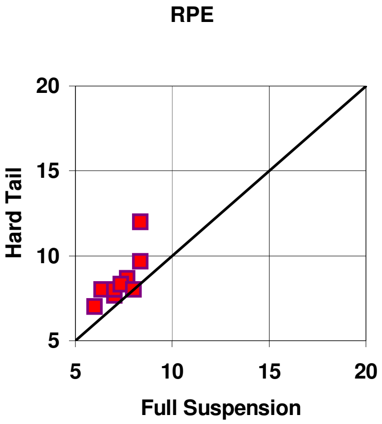


*Figure 6-6: Comparison of RPE results for the hardtail and fully suspended bike on the indoor track.*

Figures 6-3 to 6-6 clearly display each subject's physiological and psychological results and each display a similar pattern. Nine out of the ten subjects were found to have lower measurements of $VO_2$ whilst cycling on the fully suspended bike compared to the hardtail bike; a lower $VO_2$ was recorded for only one subject whilst cycling on the hardtail bike (Figure 6-3). The results for heart rate (Figure 6-4) highlight that each subject's heart rate was found to be lower whilst cycling on the fully suspended bike on the indoor track compared to the hardtail bike. Similarly, lower recordings of RPE were found for all subjects cycling on the fully suspended bike compared to the hardtail bike (Figure 6-6). Figure 6-5 illustrates that for the results pertaining to comfort rating, all subjects gave a higher comfort rating level whilst cycling on the fully suspended bike compared to the hardtail bike. These higher comfort ratings indicate that the fully suspended bike presents an advantage to the rider, in terms of comfort. Similarly, the findings for $VO_{2,}$ heart rate and RPE indicate that, for the tests on the indoor track, the fully suspended bike uses less of the rider's energy compared to the hardtail bike, and thus this suspension system presents an advantage to the rider over the hardtail bike. Table 6-3 and 6-4 also illustrate the average values obtained for each subject.

*Table 6-3: The mean values obtained for the subjects' $VO_2$, heart rate, RPE and comfort rating for the hardtail system on the indoor track tests.*

| **Track test** | **Hardtail** | | | |
|---|---|---|---|---|
| **Subject** | **$VO_2$ (ml/kg/min)** | **Heart Rate (beats/min)** | **Exertion** | **Comfort** |
| 1 | 21.89 | 106.4 | 7.7 | 3.3 |
| 2 | 17.87 | 127.2 | 12.0 | 3.0 |
| 3 | 20.17 | 105.1 | 8.0 | 4.0 |
| 4 | 17.64 | 109.3 | 8.0 | 3.7 |
| 5 | 20.58 | 105.3 | 8.7 | 3.0 |
| 6 | 24.69 | 108.4 | 8.0 | 3.3 |
| 7 | 15.70 | 94.1 | 7.0 | 3.3 |
| 8 | 22.76 | 104.6 | 9.7 | 2.7 |
| 9 | 17.65 | 102.7 | 8.3 | 3.7 |
| 10 | 14.56 | 104.2 | 8.0 | 2.3 |
| **Mean** | 19.4 | 106.7 | 8.5 | 3.2 |
| **SD** | 3.215443 | 8.299404 | 1.3984118 | 0.4981447 |

*Table 6-4 :The mean values obtained for the subjects' $VO_2$, heart rate, RPE and comfort rating for the full suspension system on the indoor track tests.*

| **Track test** | **Full Suspension** | | | |
|---|---|---|---|---|
| **Subject** | **$VO_2$ (ml/kg/min)** | **Heart Rate (beats/min)** | **Exertion** | **Comfort** |
| 1 | 19.517 | 102.1 | 7.0 | 5.0 |
| 2 | 17.07 | 121.3 | 8.3 | 4.0 |
| 3 | 19.96 | 103.1 | 6.3 | 5.0 |
| 4 | 16.23 | 96.9 | 7.0 | 5.0 |
| 5 | 18.93 | 100.3 | 7.7 | 4.0 |
| 6 | 22.45 | 107.7 | 7.0 | 4.3 |
| 7 | 13.06 | 93.9 | 6.0 | 4.0 |
| 8 | 22.63 | 96.9 | 8.3 | 4.0 |
| 9 | 16.24 | 102.6 | 7.3 | 4.7 |
| 10 | 15.6 | 103.9 | 8.0 | 3.0 |
| **Mean** | 18.2 | 102.9 | 7.3 | 4.3 |
| **SD** | 3.0771847 | 7.6239462 | 0.7927137 | 0.6373169 |

## 6.6. Statistical Analysis of Results

Similar to the tests conducted on the roller road rig and the rolling road rig, the null hypothesis two-tailed dependent t-test was applied to the results obtained from the indoor track tests to calculate the probability that the differences measured between the hardtail and fully suspended systems are purely the result of chance. Low probabilities ($p < 0.05$) indicate that the measured effect in the sample (ten subjects) is evidence of a real effect in the population. A full explanation of the null hypotheses two tailed dependent t-test can be found in section 4.7.3 of the current project.

*Table 6-5: The difference between the means of the subjects' $VO_2$, heart rate, RPE and comfort rating obtained by comparing the hardtail and fully suspended bikes on the indoor track tests.*

| **Indoor Track Test** | $VO_2$ (ml /kg/min) | Heart rate (beats/min) | RPE | Comfort |
|---|---|---|---|---|
| Sample size | 10 | 10 | 10 | 10 |
| Mean of differences | 1.2 | 3.9 | 1.2 | -1.1 |
| Standard deviation | 1.16 | 4.04 | 0.96 | 0.31 |
| P-value | 0.01 | 0.015 | 0.0027 | 0.0002 |
| Effect size | 0.4 | 0.5 | 1.1 | -1.9 |

N.B.: All differences are obtained through subtracting (-) the means obtained from cycling on the fully suspended bike from the means obtained from cycling on the hardtail bike.

Table 6-5 displays the differences between the means of the subjects' $VO_{2,}$ heart rate, RPE and comfort rating whilst cycling on the fully suspended compared to the hardtail bike during the indoor track tests. All of the differences between the means for the physiological and psychological measurements are greater for the hardtail bike, indicating that all of the subjects experienced a higher $VO_{2,}$ with the exception of one subject who had a slightly lower $VO_2$ by only 0.1 ml /kg/min, all of the subjects experienced a lower heart rate, RPE and higher level of comfort (6.1 %, 3.6% 14.14 %, and 33 % difference between the means respectively) whilst cycling on the fully suspended system on the indoor track. The lower comfort rating is represented through the negative value obtained through the difference in the means for the hardtail compared to the fully suspended bike, as all subjects indicated that they felt more comfortable whilst cycling on the fully suspended bike. As the p values for each of the difference in means are less than 0.05, this indicates that these differences are significant findings. The effect size of the difference in means, as illustrated in Table 6-5, varies from -1.9 to 1.1; supporting the claim that these results are meaningful. Similar to the data displayed in the scatter plot graphs (Figures 6-3 to 6-6), the findings from Table

6-5 indicate that the fully suspended bike, in comparison to the hardtail bike, presents an advantage to the subject when cycling on the indoor track.

# 7. Dynamic Simulation

## 7.1. Introduction

Previous researchers (Gonzalez et al., 2008; Good & McPhee, 1999; Wang & Hull, 1996) have developed dynamic simulation models to establish rider induced energy losses due to suspension systems, and consequently utilised these initial models to optimise the rear suspension geometry of a mountain bike in an attempt to reduce the amount of energy dissipated via the rear suspension. Other researchers (Bu et al., 2009; Wilczynski & Hull, 1994) have also developed simulation models to investigate energy losses due to suspension systems, yet these studies investigated the energy lost as a result of terrain-induced loads. Each of the studies investigating rider induced and terrain induced energy losses, and how these in turn affect the suspension system, were researched and analysed and consequently assisted in determining which line of investigating this current study should take. With this in mind, the main objectives of this dynamic simulation study were to develop simulations which could be used to quantify both the rider and terrain induced energy losses due to the suspension system.

The simulations were created to validate the experimental results and to establish if a simulation tool could be used to estimate the dynamic loads when using different suspension systems. The simulations were produced to emulate both the experimental roller rig and the rolling road rig tests in order to establish if any differences between the fully suspended and hardtail mountain bike were apparent. The simulations replicated all of the test scenarios for the roller rig: a seated cyclist travelling on a hardtail mountain bike on a smooth surface; a seated cyclist on a fully suspended mountain bike on a smooth surface; a seated cyclist travelling on a hardtail mountain bike on a surface with one bump and a seated cyclist on a fully suspended mountain bike on a surface with one bump.

Additionally, each of these four riding scenarios were simulated for the rolling road rig tests; thus a total of eight simulations were undertaken. In addition to using the simulations as a means of comparing the hardtail and fully suspended mountain bikes, the simulations were also used as a means of validating the experimental results of the roller rig and the rolling road rig tests.

A range of dynamic computer simulation models can be used to conceptualise mountain bikes and their suspension systems, with researchers opting to use different simulation programs in their studies: AUTOLEV (Wang and Hull, 1996); ADAMS (Bu et al., 2009); Matlab (Gonzalez et al., 2008); and DADS (Wilczynski and Hull, 1994). For the purpose of the current study, a dynamic model was developed with the aid of the Dynamic Analysis and Design Software (DADS) (CADSI Corp., Oakdale, IA) package - the package deemed most appropriate as it incorporates many features specifically designed to model vehicles. DADS is a mechanical computer aided engineering software package that enables the simulation and analysis of complex mechanisms and mechanical systems. This software package has the ability to perform static, kinematic and dynamic analysis to create two and three-dimensional models. Furthermore, DADS allows the user to model real-world behaviour; the equations of motion are automatically generated and the resultant differential-algebraic equations are then solved. Results can be interpreted through the use of plots, graphs, tables and animation.

## 7.2. Method

### 7.2.1. Model

#### 7.2.1.1. Rider Model

The literature review provided valuable information on how the current rider simulation model should be developed as it highlighted strengths, as well as any weaknesses, of the previously designed simulation models. In this respect, it was a useful tool in determining and developing an optimal model for the current study. Through researching and analysing previous dynamic simulation studies, it became apparent that the loads measured from laboratory experiments (used to represent the rider) were not required. A simulated rider placed on the mountain bike gives similar dynamic properties to that of riding outside, thus the need for specifying a number of rider-bike interface loads from laboratory tests are eliminated (Good & McPhee, 1999). Previous researchers (Wang & Hull, 1997; Wilczynski & Hull, 1994) recorded rider loads on the frame of the bike for each riding scenario - a cumbersome form of model development, which provides little benefit to the researcher. With this in mind, for the purpose of the current study, a rider was placed on the mountain bike and simulated using parameters obtained from previous literature (Wilczynski & Hull, 1994), as shown in Table 7-1.

*Table 7-1: Model parameters derived from the literature*

| **Element** | **Model Parameter** | **Value** | **Source** |
|---|---|---|---|
| Torso | Mass | 37.98 kg | Chandler et al. (1979) |
| | Moment of Inertia | 1.827 kg/m$^2$ | Chandler et al. (1979) |
| | Length | 0.51 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.31 m | Chandler et al. (1979) |
| Upper arm | Mass | 1.84 kg | Chandler et al. (1979) |
| | Moment of Inertia | 0.013 kg/m$^2$ | Chandler et al. (1979) |
| | Length | 0.32 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.14 m | Chandler et al. (1979) |
| Forearm | Mass | 1.49 kg | Chandler et al. (1979) |
| | Moment of Inertia | 0.0063 kg/m$^2$ | Chandler et al. (1979) |
| | Length | 0.32 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.16 m | Chandler et al. (1979) |
| Thigh | Mass | 6.52 kg | Chandler et al. (1979) |
| | Moment of Inertia | 0.116 kg/m$^2$ | Chandler et al. (1979) |
| | Length | 0.42 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.25 m | Chandler et al. (1979) |
| Lower leg | Mass | 3.52 kg | Chandler et al. (1979) |
| | Moment of Inertia | 0.039 kg/m$^2$ | Chandler et al. (1979) |
| | Length | 0.47 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.19 m | Chandler et al. (1979) |
| Front Fork | Mass | 5.05 kg | Wilczyinski & Hull (1994) |
| | Moment of Inertia | 0.488 kg/m$^2$ | Wilczyinski & Hull (1994) |
| | Length | 0.45 m | Wilczyinski & Hull (1994) |
| | Position of Mass Centre | 0.27 m | Wilczyinski & Hull (1994) |
| Arm | Stiffness | 14400 N/m | Wong M & Hull M L (1981) |
| | Damping | 202 Ns/m | Wong M & Hull M L (1981) |
| Tyre | Stiffness | 90000 N/m | Wilczyinski & Hull (1994) |
| Front Suspension | Stiffness | 73600 N/m | Wong M & Hull M L (1983) |
| | Damping | 975 Ns/m | Wong M & Hull M L (1983) |
| Rear Suspension | Stiffness | 73900 N/m | Good & McPhee (1999) |
| | Damping | 7776 Ns/m | Good & McPhee (1999) |

The rider model consisted of eight ridged bodies: the torso and head; the upper arm; the forearm; the right thigh; the left thigh; the lower right leg; lower left leg and hip. The details of each body part: its mass; length; the moment of inertia and the position of the mass centre, were all derived from the previous literature (Chandler et al., 1979; Good & McPhee, 1999; Wilczynski & Hull, 1994; Wong M & Hull M L, 1983): Table 7-1 highlights these details.

In order to emulate a seated rider (as all subjects participating in the roller rig and the rolling road rig experimental tests rode in this position) the base of the torso was connected to the seat; the forearm was connected to the handlebars and the lower legs to the pedals. Unlike previous simulation models, which did not consider the motion of the rider's body (Good & McPhee, 1999; Gonzalez et al., 2008; Wang & Hull, 1996; Bu et al., 2009), the current simulation model introduced improvements, which allowed the movement of the rider to be considered. Both legs were integrated into the simulation design and were connected using revolute joints to allow for the pedalling action; this emulated the rider's cycling movement in order to give similar dynamic and inertial properties to the experimental results.

#### 7.2.1.2. Bike Model

Both the simulated hardtail and fully suspended mountain bikes were modelled from the mountain bikes used in the roller rig and the rolling road rig experimental tests. The fully suspended bike was modelled on the Marin Mount Vision, and the hardtail mountain bike on the Marin Rocky Ridge. The hardtail bike and the fully suspended bike are illustrated in figure 4-3 and 4-4.

The mountain bike specifications were received from Marin and incorporated into the bike models' design, thus determining the specific length; moment of inertia and position of the mass centre for both the hardtail and fully suspended bikes. The simulated hardtail bike was designed as a model consisting of five bodies: the rig; the simulated rider; the rear wheel; the frame and the front fork. The front fork consisted of a linear steel coil spring in parallel with a viscous damper, which connected to the main frame via a telescopic bracket. Both the damping and spring stiffness values were obtained from previous research (Good & McPhee, 1999; Wong & Hull, 1983), which used a similar front suspension configuration.

Similar to the simulated hardtail mountain bike, the fully suspended bike was also designed as a five-body model. This model had the same front section of the frame as the hardtail bike; however, it also incorporated a rear suspension system, which was modelled on a single swing arm suspension design consisting of a linear steel coil spring in parallel with a fixed orifice damper.

The wheels of the bike model were connected to both the front and rear hubs of the simulated hardtail and fully suspended bikes using rotational joints. The tyres were developed using a complex tyre model incorporated in the DADS simulation package; the properties of which were taken from a previous study (Wilczynski & Hull, 1994). The form of tyre simulation used in this study differs from that of previous studies (Bu et al., 2009; Gonzalez et al., 2008; Good & McPhee, 1999; Wang & Hull, 1996). In these previous studies springs were used to represent the tyres. The use of springs presents a disadvantage to the simulation model as they do not present an adequate representation of a tyre's dynamic properties.

In order to ensure that the simulated bikes were as true a representation of a mountain bike as possible, several design parameters were established for the models. The bike models were developed so that the bikes were able to deviate from the road surface so as to give a truer representation of cycling conditions. This simulation model is unlike Bu et al's (2009) model where the simulated bikes were constrained to follow the road surface, thus presenting an unrealistic representation of cycling scenarios. Additionally, in order to ensure that a truer representation of cycling conditions was presented in the simulations, a belt drive was developed through the use of the DADS package to represent the chain of the bike, connecting the crank to the rear wheel cog. The driving force of the simulation was attached to this crank, giving the bike a forward momentum to equal that of the experimental tests. The same driver was developed for both the hardtail and fully suspended bike models, which consisted of a varying torque and giving both simulated bikes an average velocity of fifteen km/h. The decision to use a varying torque for the simulation came as a result of analysing the previous simulation studies of Bu et al., 2009; Gonzalez et al., 2008; Good & McPhee, 1999; Wang & Hull, 1996 and Wilczynski & Hull, 1994 - all of whom used a varying crank torque in order to represent the true uneven pedalling action of a cyclist.

## 7.3. The Simulations

As aforementioned, 4 tests were carried out on both the roller rig and the rolling road rig: a seated cyclist travelling on a hardtail mountain bike on a smooth surface; a seated cyclist on a fully suspended mountain bike on a smooth surface; a seated cyclist travelling on a hardtail mountain bike on a surface with one bump and a seated cyclist on a fully suspended mountain bike on a surface with one bump. All of the bike simulations were run for a total period of 6 s; a sufficient amount of time to establish how the suspension reacts when travelling over each surface type. The simulation results were then compared to establish which mountain bike type - the hardtail or fully suspended - was most effective on the smooth surface and on the surface with the bump, and to what degree it was most effective.

The effects of wind and aerodynamic drag were not considered in the simulations. These were excluded from the simulations so as to match the experimental roller rig and rolling road rig test environments. Both experimental rig tests were conducted indoors and the bikes held stationary, thus deeming the effect of wind and aerodynamic drag negligible (only a small amount of aerodynamic drag was found at the spokes of the wheels).

### 7.3.1. Roller Rig Simulation Model

The dynamic simulation of the roller rig emulated the experimental roller rig test; the model of which is illustrated in Figure 7-1. Similar to the roller rig experimental tests, both the hardtail and fully suspended simulated bikes were tested on both the smooth surface and on the surface with a bump and the results for each bike were compared.

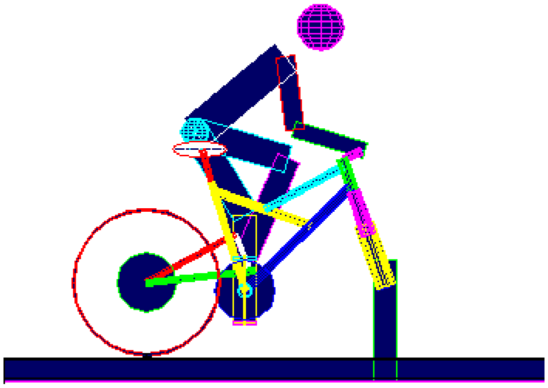


*Figure 7-1: Dynamic simulation model of the roller rig and rider*

In order to simulate the roller rig effectively, the bike model (as previously outlined in section 7.2.1.2) was adapted; no front wheel was incorporated into the model and the front axle was attached to the rig using a rotational joint. A simulated road running under the rear wheel represented the roller of the experimental tests.

The most significant results of the roller rig simulations were derived from the vertical and horizontal measurements of displacement, and the velocity and acceleration of both the rider and the front and rear accelerometers. In addition to these, significant results were also obtained from the measurements of displacement, velocity and force of the front and rear suspension.

### 7.3.2. Rolling Road Rig Simulation Model

The dynamic simulation of the rolling road rig emulated the experimental rolling road rig test; the model of which is illustrated in Figure 7-2.

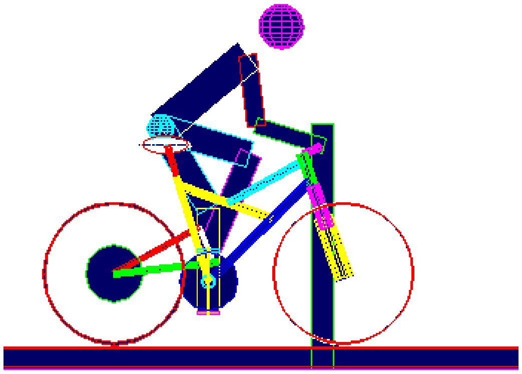


*Figure 7-2: Dynamic simulation model of the rolling road rig and rider*

As with the roller rig simulations, both the hardtail and fully suspended simulated bikes were tested on the simulated rolling road rig on both the smooth surface and on the surface with a bump, and the results for each bike compared. For this simulation, as was the case for the experimental rolling road rig test, the front wheel was incorporated into the bike design. For the rolling road rig simulation model, the hardtail bike was emulated by locking the rear suspension of the fully suspended bike, thus creating a rigid rear frame (in the experimental tests the rear suspension unit was replaced with a steel bar to create a hardtail bike).

Similar to the rolling road rig experimental tests, the simulated bike was attached to the rolling road rig at the handlebars with a rotational/translational joint. This allowed the handlebars to move freely in the vertical direction and rotate about its axis, thus giving a closer representation of truer cycling conditions. The simulated rolling road passed under both bike wheels at the same velocity as the roller rig experimental tests: fifteen km/h, thus allowing the results of the roller rig and the rolling road rig simulations to be compared.

As with the roller rig simulations, the most significant results of the rolling road rig simulations were derived from the vertical and horizontal measurements of displacement, and the velocity and acceleration of both the rider and the front and rear accelerometers. Significant results from the rolling road rig simulations were also obtained from the measurements of displacement, velocity and force of the front and rear suspension.

## 7.4. Simulation Results

In order to highlight comparisons and differences between the fully suspended and the hardtail bike on both the smooth surface and the surface with a bump, the results obtained from the roller rig and the rolling road rig simulations are displayed in graphical form.  The graphs illustrate the velocity, displacement and acceleration of the bikes at specific points specified on the frame and the rider, as well as the force and displacement of the front and rear suspension systems.

The bike simulations were run for a total period of 6 s, however, only the data retrieved from the relevant time period are displayed in the graphs.  Figure 7-3 is used to illustrate why this decision was made.  Figure 7-3 illustrates the vertical displacement at the front of the bike above the handlebars, the same location selected for the accelerometer in the experimental test so a comparison can be made.

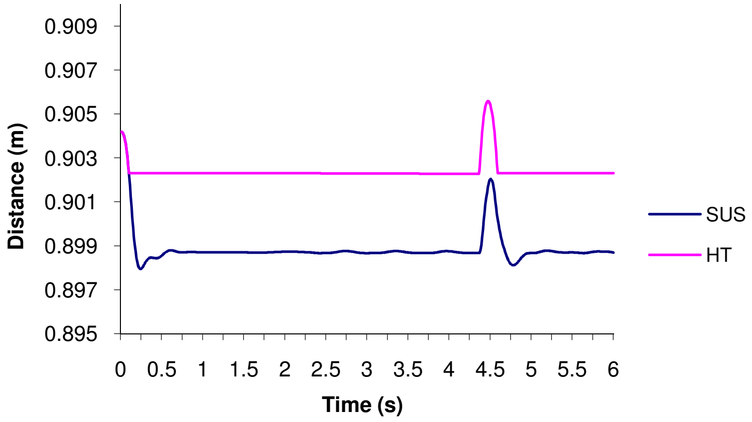


*Figure 7-3: The vertical displacement at the front of the bike comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

As illustrated in Figure 7-3 the y axis represents the position at the handlebars, a negative displacement of both bikes is evident between 0 s to 0.25 s. This is due to the compression of the spring in the suspension and the tyres when the simulated rider's weight is exerted on the bike. The main reason for this occurring is due to the suspension having no pre-load, thus the suspension system needs to stabilise prior to useful data being recorded. This initial displacement is true for both bike types on both the smooth surface and on the surface with a bump but does not represent true riding conditions. In normal riding conditions a mountain bike suspension system is pre-loaded so as to take a rider's weight into account. For this reason the data obtained from zero to 0.25 s of the simulations is not included in the graphs.

While cycling on a smooth surface at a constant speed - 15 km/h for both the roller rig and the rolling road rig simulations - the movement and forces exerted on the bike and rider are repeated, therefore only a section of the time period is required to obtain results from the hardtail and fully suspended bike on a smooth surface; in this instance the data between the third and fourth second was chosen for analysis. When considering both bike types on a rough surface, it was found that the bikes came into contact with the bump between 4 s and 5.5 s after the beginning of the simulation. Any measurements resulting from contact with the bump would therefore occur during this time; hence the decision to include only this time period in the graphs with the cyclist riding on a surface with a bump.

### 7.4.1. Roller Rig Simulations on the Smooth Surface

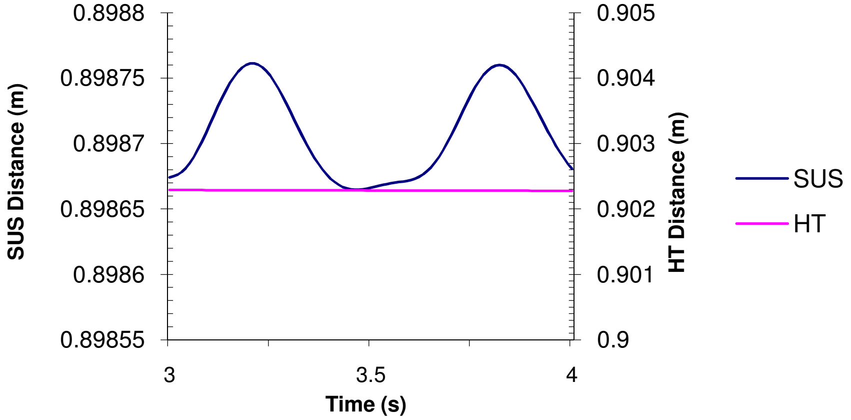


*Figure 7-4: The vertical displacement at the front of the bike comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.*

Figure 7-4 illustrates the vertical displacements at the front accelerometer (placed on top of the steerer tube) of both the fully suspended and the hardtail bike on the roller rig with a smooth surface. A secondary axis has been provided for the hardtail bike to enable both data sets to be represented on one graph. As is shown in 7-4, the initial position of the handlebars differs for both bikes: 898.71 mm for the fully suspended bike and 902.31 mm for the hardtail. A reason for the disparity in results for the average displacement is due to the compression of the rear suspension of the fully suspended bike due to the rider's weight, thus resulting in a lower average displacement for the fully suspended bike.

Figure 7-4 also illustrates that the fully suspended bike oscillates slightly (0.095 mm between the maximum and minimum turning points of the graph) at the front of the bike. Although this is a small measurement it is, however, a relevant finding as it demonstrates that a bobbing effect occurs when cycling on the fully suspended bike. Figure 7-4 clearly shows that no oscillation of the hardtail bike occurs, thus indicating that when considering the vertical displacement at the front of a bike cycling on the roller rig over a smooth surface, that a hardtail bike presents an advantage to the rider over a fully suspended bike.

Figure 7-5 illustrates the vertical displacements at the rear accelerometer (placed under the saddle of the bike) of both the fully suspended and the hardtail bike on the roller rig on the smooth surface.

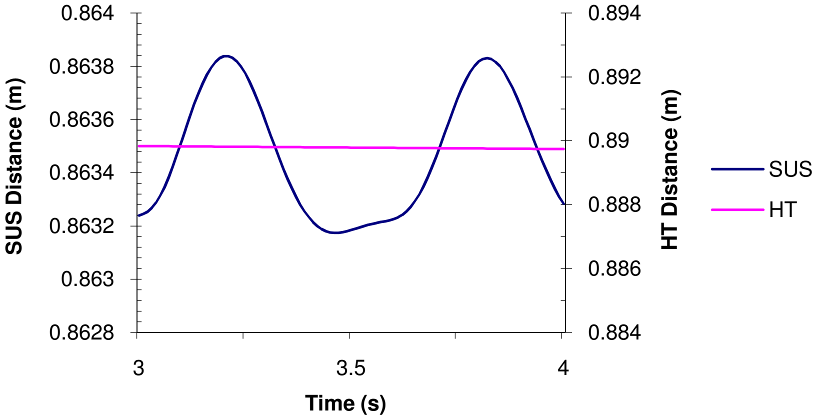


*Figure 7-5: The vertical displacement at the rear of the bike comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.*

Similar to the results obtained from the front of the bike, the graph illustrates that a slight oscillation occurs at the rear of the fully suspended bike. Although this is only a small oscillation (0.7 mm between the maximum and minimum turning points of the graph), it is substantially greater than the displacement found at the front of the fully suspended bike. This is unsurprising as the majority of the rider's weight is situated at the rear of the bike. Again, as with the data obtained from the front accelerometer, no bobbing effect occurs at the rear accelerometer on the hardtail bike. This indicates that, when considering the vertical displacement at the rear of a bike cycling on the roller rig over a smooth surface, a hardtail bike presents an advantage to the rider over a fully suspended bike.

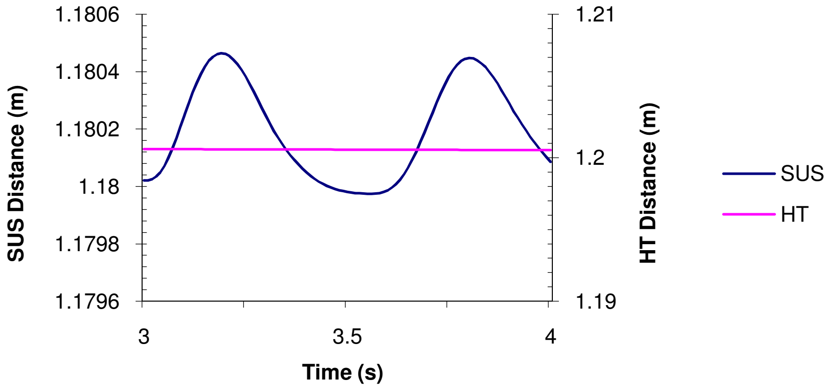


*Figure 7-6: The vertical displacement of the simulated rider's torso position comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.*

Another important aspect in the analysis of the simulation tests is the vertical displacement of the rider's body whilst cycling on the roller rig on the smooth surface. Figure 7-6 represents the vertical movement of the rider's torso due to the movement of the bike, and illustrates that the distance between the maximum and minimum turning points for the rider's displacement on the fully suspended bike on a smooth surface is 0.52 mm. Conversely, the results for the rider's displacement on the hardtail bike remain constant: there is no movement of the rider.

This concurs with the experimental test results for the vertical displacement of the rider on the roller rig, where the subjects all experienced a bobbing motion. This also concurs with the majority (76 %) of questionnaire respondents who confirmed that they experienced a bobbing effect when cycling on a fully suspended bike (Appendix A). It is also important to consider that this bobbing effect would be amplified when travelling uphill or while standing (as is the case for real life riding conditions) due to a more exaggerated uneven pedalling motion.

In order to establish if a rider's displacement is a direct result of the suspension system, the displacement and force of both the front and rear suspension systems must be analysed.

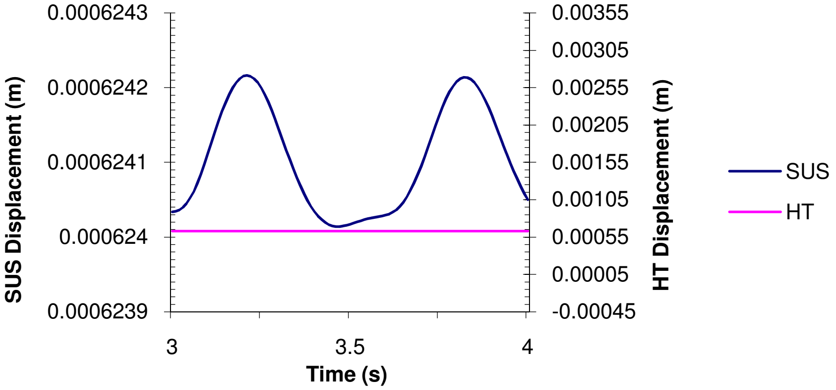


Figure 7-7: The displacement of the front suspension comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.

Figure 7-7 illustrates the displacement of the front suspension of both the hardtail and fully suspended bike on the roller rig on the smooth surface. It demonstrates that the displacement of the hardtail bike is a constant value, and does not fluctuate due to the pedalling motion of the simulated cyclist. However, the displacement of the front suspension of the fully suspended bike produces a value of 0.22 mm between the maximum and minimum turning points. This highlights that the movement at the front of the fully suspended bike is due to the movement occurring at the rear suspension. Therefore, it is apparent that incorporating a rear suspension in the bike design promotes movement in the front suspension when under these specific test conditions.

Yet, as the displacement results for the front and rear accelerometers, and front suspension for the fully suspended bike are so slight, an extremely accurate form of measurement would be required to measure these in experimental tests. Berry et al. (1993) used visual inspection to observe displacement in the suspension systems, yet the human eye would not notice the slight oscillations that are found through running the simulations.

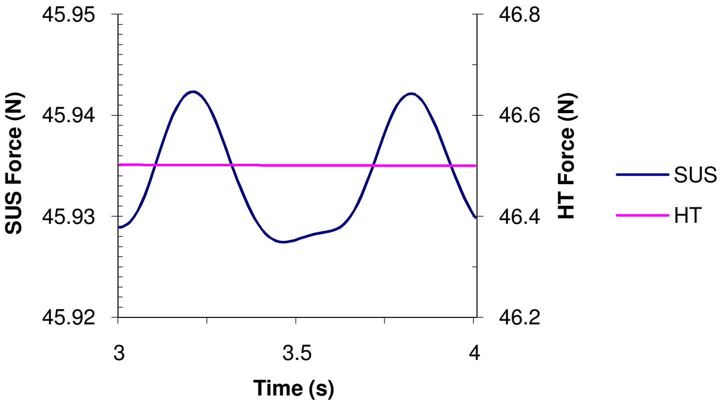


*Figure7-8: The resultant force transmitted by the front suspension system comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.*

Figure 7-8 represents the resultant force transmitted by the front suspension from wheel to frame of both the hardtail and fully suspended bike, and follows a similar pattern to the previously discussed graphs: a constant value is obtained for the force at the front suspension of the hardtail bike, and the force at the front of the fully suspended bike oscillates slightly. The average force measured for the fully suspended bike is 0.565 N less than that of the hardtail bike. The force exerted between the maximum and minimum turning points for the fully suspended bike is 0.013 N; this is in contrast to the hardtail bike, which shows no variation in force. This indicates that a rear suspension system causes the force applied to the front suspension to fluctuate, which in turn would expend a small amount of a rider's energy. However, as the amount of force measured at the front suspension of the fully suspended bike is negligible, the rear suspension system must be analysed to establish its effect on the rider.

In order to identify if, and to what extent, the displacement of the fully suspended bike occurs from the movement of the rear suspension, the compression and extension of the rear suspension (Figure 7-9) and the resultant force exerted on the spring (Figure 7-10) was analysed.

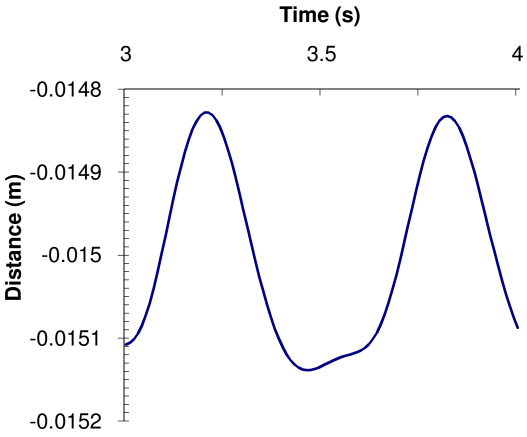


*Figure 7-9: The displacement of the rear suspension system of the fully suspended bike on a smooth surface on the roller rig*

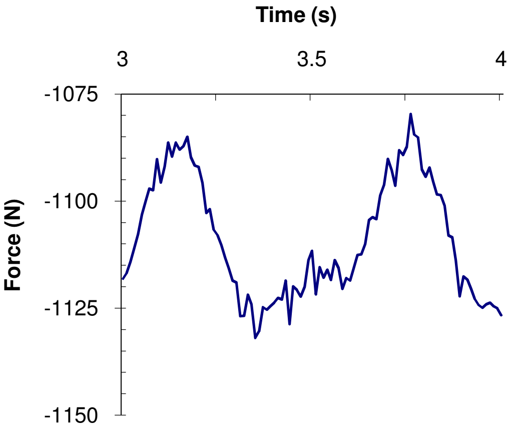


*Figure 7-10: The resultant force transmitted by the rear suspension system of the fully suspended bike on a smooth surface on the roller rig*

Figure 7-9 indicates that the displacement of the rear suspension produces a value of 0.31 mm between the maximum and minimum turning points. This highlights why the displacement is greater at the rear suspension of a fully suspended bike compared to the front suspension, as can be noticed when both of the bikes are compared in Figures 4-3 and 4-4.

Figure 7-10 illustrates the resultant force transmitted by the rear suspension from wheel to frame of a fully suspended bike travelling on the roller rig with a smooth surface between the 3 s and 4 s time period. The average compression force of the rear suspension is -1115 N; substantially greater than the force exerted on the front suspension of the hardtail and fully suspended bike. This is due to the weight of the rider compressing the spring representing a greater force than that at the front of the bike. The force measured at the rear suspension of the fully suspended bike between the maximum and minimum turning points is 52 N.

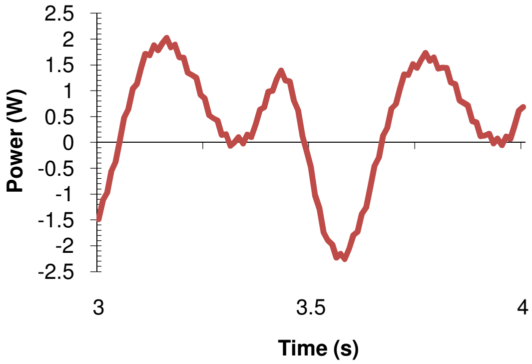


*Figure 7-11: The resultant power transmitted by the rear suspension system of the fully suspended bike on a smooth surface on the roller rig*

Figure 7-11 illustrates the resultant power transmitted by the rear suspension system of the fully suspended bike travelling on the roller rig with a smooth surface between the 3 s and 4 s time period. This indicates the level of energy absorbed by, and lost through, the rear suspension system. This is a significant finding as it demonstrates that - compared to the hardtail bike - additional energy is required to cycle the fully suspended bike on a flat surface on the roller rig simulation.

### 7.4.2. Roller Rig Simulations on the Surface with a Bump

The simulations with the hardtail and fully suspended bike were also run on the roller rig on a surface with a bump attached. As discussed previously, only the time period with the relevant data is displayed on the graphs. The time period displayed is over a 1.5 s period between 4 s and 5.5 s; this allows for the time period prior to the rear wheel coming into contact with the bump and allows sufficient time for analysis after the initial contact with the bump.

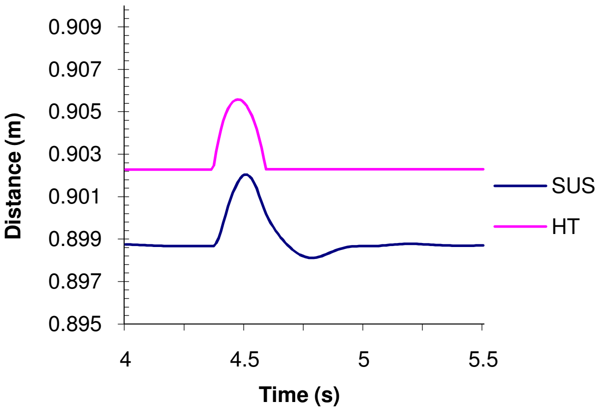


*Figure 7-12: The vertical displacement at the front of the bike comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

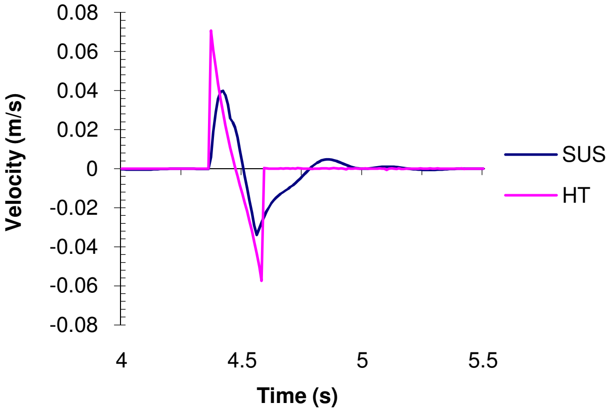


*Figure 7-13: The vertical velocity at the front of the bike comparing the fully suspended and the hardtail bike on a smooth surface on the roller rig.*

Figure 7-12 displays the vertical displacement at the front accelerometer of the hardtail and fully suspended bike on the roller rig on the surface with a bump. Similar to the results obtained from the vertical displacement at the front accelerometer on the smooth surface, the fully suspended bike again displays a lower average height of the front accelerometer on a surface with a bump, compared to the hardtail bike. Again this is due to the compression of the rear suspension of the fully suspended bike due to the rider's weight, thus resulting in a lower displacement at the front accelerometer for the fully suspended bike.

Both the front accelerometer of the hardtail and fully suspended bike rises by a similar amount when the rear wheel comes into contact with the bump. Both front accelerometers rise by 3.3 mm. However, when the fully suspended bike lands after contact with the bump, the height at the rear of the bike dips slightly by 0.6 mm before rising by 1 mm, and finally settling to the same height as that prior to hitting the bump. A key reason for this slight dip is a result of the movement in the rear suspension system this movement is studied in detail in Figure 7-14.

Figure 7-13 displays the vertical velocity at the front accelerometer of the hardtail and the fully suspended bike on the surface with a bump. As illustrated by the graph, there is a sharp rise and fall in the velocity at the front of the hardtail bike when the rear wheel impacts with the bump. The vertical velocity at the front accelerometer between the maximum and minimum turning points for the hardtail bike is 0.128 m/s, and 0.074 m/s for the fully suspended bike. As the fully suspended bike allows for a more gradual increase in velocity due to the rear suspension absorbing the impact of the bump, this in turn increases the comfort of the rider. These results concur with the views of the subjects of the experimental roller rig tests, who asserted that the fully suspended bike was more comfortable than the hardtail bike (Chapter 4).

Figure 7-14 illustrates the vertical motion of the rear accelerometer on the hardtail and fully suspended bike as the wheel impacts with the bump.

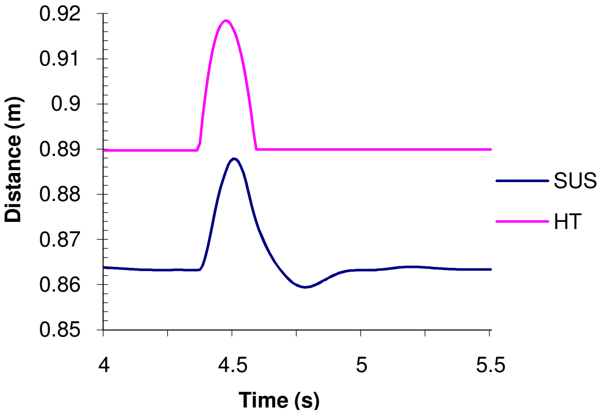


*Figure 7-14: The vertical displacement at the rear of the bike comparing the fully suspended and the hardtail bike on a rough surface on the roller rig*

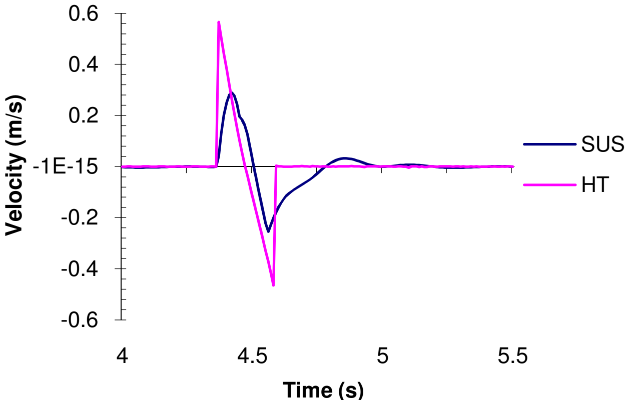


*Figure 7-15: The vertical velocity at the rear of the bike comparing the fully suspended and the hardtail bike on a rough surface on the roller rig*

Figure 7-15 displays a similar pattern to that of Figure 7-13: the fully suspended bike displays a lower average height at the rear accelerometer on a surface with a bump compared to the hardtail bike, and both the rear accelerometer of the hardtail and fully suspended bike rises when the rear wheel comes into contact with the bump. However, in this instance there is a slight difference in the displacements of the bikes upon impact with the bump: the displacement of the hardtail bike is 28 mm and the fully suspended bike has a displacement of 24.5 mm. Similar to the results relating to the vertical displacement at the front accelerometer, the rear accelerometer of the fully suspended bike also dips slightly after contact with the bump due to the compression of the rear suspension spring. However, the oscillation of the rear accelerometer is only very slight at 0.005 μm, and has only one peak before levelling as a result of the damping of the rear suspension. This indicates that there is only a slight bobbing effect after contact with the bump, yet as with the previous graphs for the roller rig on the smooth road there is still a constant, slight bobbing effect which cannot be distinguished at this scale.

Figure 7-15 highlights the vertical velocity at the rear accelerometer of the hardtail and the fully suspended bike on the roller rig on the surface with a bump. As with the results obtained from the vertical velocity at the front accelerometer of the hardtail bike, there is again a sharp rise and fall for the hardtail bike when the rear wheel impacts with the bump. However, a significant difference between the vertical velocities of the rear accelerometers for the hardtail and fully suspended bikes can, this time, be identified. The vertical velocity at the rear accelerometer is 1.1 m/s between the maximum and minimum turning points for the hardtail bike, and 0.545 m/s for the fully suspended bike. As the fully suspended bike has a lower velocity at the rear accelerometer than the hardtail bike, this lessens the impact of the bump felt by the rider and increases rider comfort.

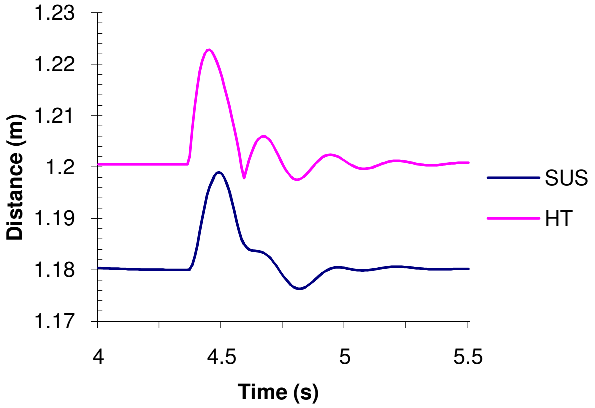


*Figure 7-16: The vertical displacement of the simulated rider's torso comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

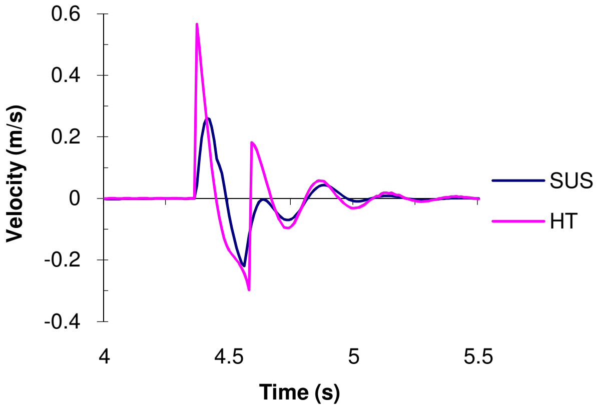


*Figure 7-17: The vertical velocity of the simulated rider's torso comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

Figures 7-16 and 7-17 illustrate the vertical displacement and velocity of the rider's body on both the hardtail and fully suspended bike. Interestingly, Figure 7-16 indicates that on the hardtail bike, compared to the fully suspended bike, the rider's torso oscillates to a greater extent after contact with the bump. This may be a result of the increased movement of the rider's torso on the hardtail bike after the initial impact with the bump occurs, and consequent impact with the ground following the bump (Figure 7-16). Figure 7-16 also shows that after initially coming into contact with the bump, the rider on the hardtail bike has a displacement of 23 mm, and 19 mm on the fully suspended bike. The fully suspended bike allows less movement of the rider when riding over rough terrain, thus increasing rider comfort as the bumps are absorbed by the rear suspension.

Figure 7-17 indicates that the rider moves less when riding on a fully suspended bike (compared to a hardtail bike) when impacting the bump, followed by the ground. The change in velocity of the rider's movement on the hardtail bike is 0.862 m/s between the maximum and minimum turning points, and 0.49 m/s on the fully suspended bike. Similarly, as with the results for the velocity at the front and rear accelerometers, the velocity of the rider's movement is lower when riding on a fully suspended bike, compared to a hardtail bike, on a surface with a bump. This finding highlights that riding over rough terrain on a fully suspended bike increases comfort as less movement of the rider occurs during cycling.

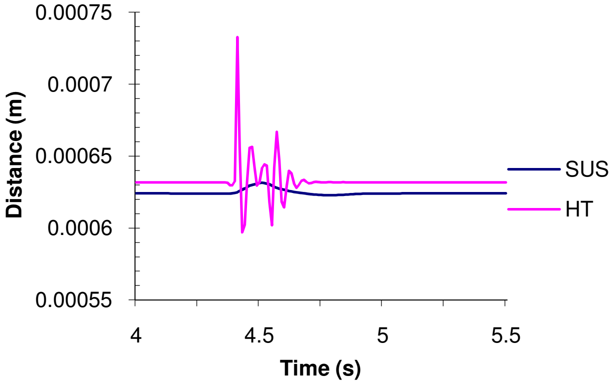


*Figure 7-18: The displacement of the front suspension system comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

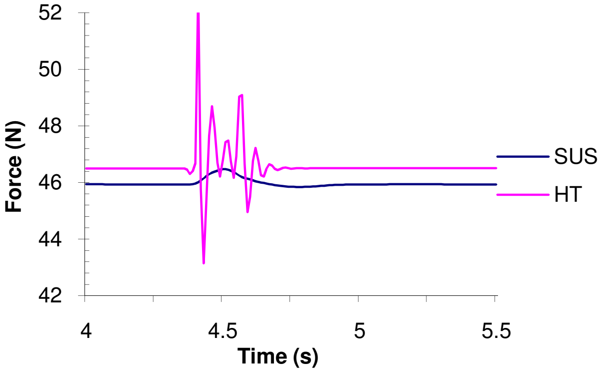


*Figure 7-19: The resultant force transmitted by the front suspension system comparing the fully suspended and the hardtail bike on a rough surface on the roller rig.*

Figures 7-18 and 7-19 illustrate the displacement and force at the front suspension of the hardtail and fully suspended bike respectively. Both graphs show a fluctuation of the displacement and force at the front suspension of the hardtail bike after contact with the bump. Figure 7-18 displays that the maximum displacement of the front suspension of the hardtail bike is 0.137 mm; this is in contrast to the fully suspended bike, which has a slight displacement of only 0.007 mm. The lower displacement value for the fully suspended bike highlights that less bobbing occurs on the fully suspended compared to the hardtail bike when cycling over rough terrain.

Figure 7-19 illustrates the force exerted on the front suspension system of the hardtail and fully suspended bike on a surface with a bump. These values are 9.2 N and 0.7 N between the maximum and minimum turning points for the hardtail and fully suspended bike respectively. A smaller amount of force acting on the front suspension of a fully suspended bike uses less of the rider's energy than the front suspension of a hardtail bike, thus suggesting that the front suspension of a fully suspended bike is more efficient for the cyclist when riding over rough terrain.

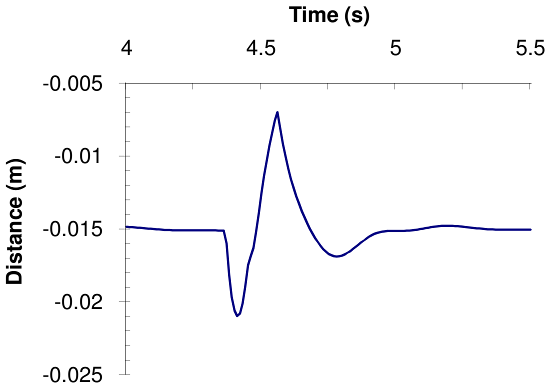


*Figure 7-20: The displacement of the rear suspension system of the fully suspended bike on a rough surface on the roller rig.*

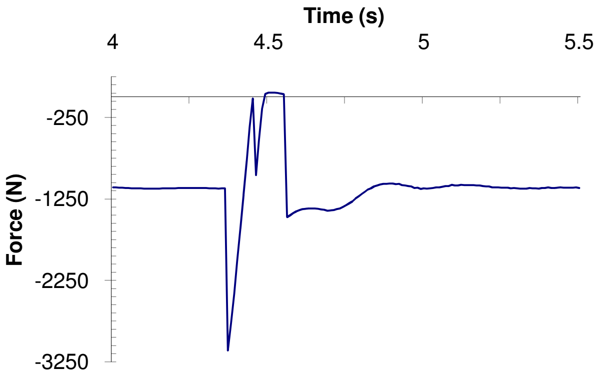


*Figure 7-21: The resultant force transmitted by the rear suspension system of the fully suspended bike on a rough surface on the roller rig.*

Figures 7-20 and 7-21 display the displacement and force exerted on the rear suspension during contact of the rear wheel with the bump. During the initial contact with the bump, the spring in the rear suspension compresses by 6 mm. The spring then extends by 14 mm and recovers after the rear tyre comes into contact with the ground (Figure 7-20).

Figure 7-21 shows that the force exerted on the spring in the rear suspension is significantly greater than that exerted on the front suspension. For the rear suspension the force exerted is 3100 N between the minimum and maximum turning points.

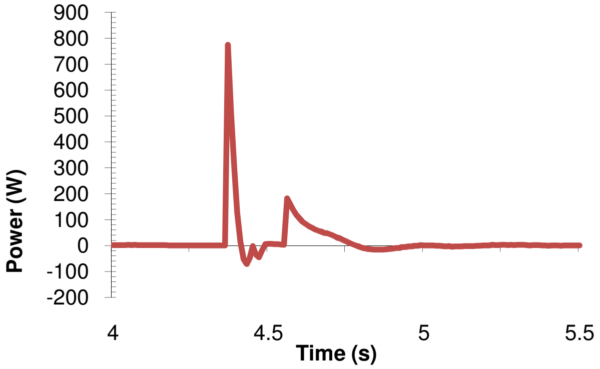


*Figure 7-22: The resultant power transmitted by the rear suspension system of the fully suspended bike on a rough surface on the roller rig.*

Figure 7-22 illustrates the power exerted on the spring of the rear suspension system. The graph indicates that some of the rider's energy will be expended by the rear suspension when cycling over the surface with a bump.

### 7.4.3. Rolling Road Rig Simulations on the Smooth Surface

Figure 7-23 illustrates the vertical displacement at the front accelerometer of both the hardtail and fully suspended bike on a smooth surface, with both bikes presenting a similar pattern for displacement. A main distinction between the data sets is that a slightly higher displacement is observed at the front accelerometer of the fully suspended bike (0.144 mm between the minimum and maximum turning points), compared to the hardtail bike (0.136 mm between the minimum and maximum turning points).

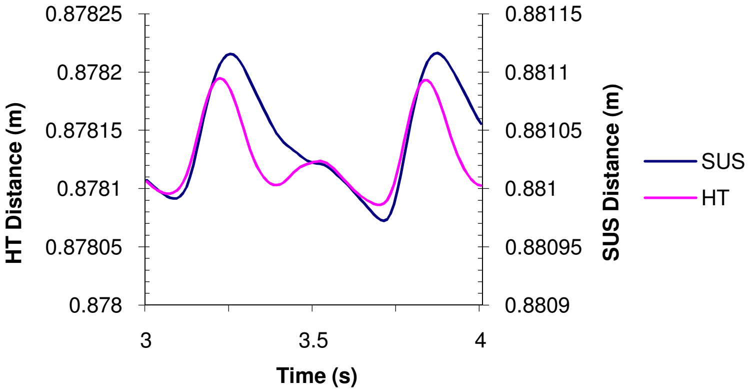


*Figure 7-23: The vertical displacement at the front of the bike comparing the fully suspended and the hardtail bike on a smooth surface on the rolling road rig.*

Although the fully suspended bike has a greater overall displacement, it does present a smoother pattern of results, indicating that the rear suspension reduces some of the oscillation at the front of the bike. This suggests that on the simulated smooth rolling road rig, the fully suspended bike reduces the effect of bobbing. Figure 7-23 also highlights the disparity between the dynamics of the roller rig and the rolling road rig. The simulated roller rig with the smooth surface did not reveal any fluctuations for the hardtail bike at the front accelerometer (Figure 7-4). In contrast, the smooth rolling road rig identifies an oscillation at the front accelerometer for the hardtail bike (Figure 7-23) indicating that a bobbing effect does occur whilst cycling on a hardtail bike on a smooth surface. This finding demonstrates that in a real life situation there is a movement for the front suspension of a hardtail bike (unlike the identical simulation on the roller rig) as the dynamics of the rolling road rig present a closer representation of true riding conditions, as the front wheel is incorporated into the simulation design, and the front axle is not fixed to the rig.

Figure 7-25 shows the vertical displacement at the rear accelerometer of the hardtail and fully suspended bike on the smooth surface. As with the identical simulation on the smooth surfaced roller rig (Figure 7-5), the vertical displacement at the rear accelerometer for the hardtail bike on the smooth surface illustrates that no bobbing occurs.

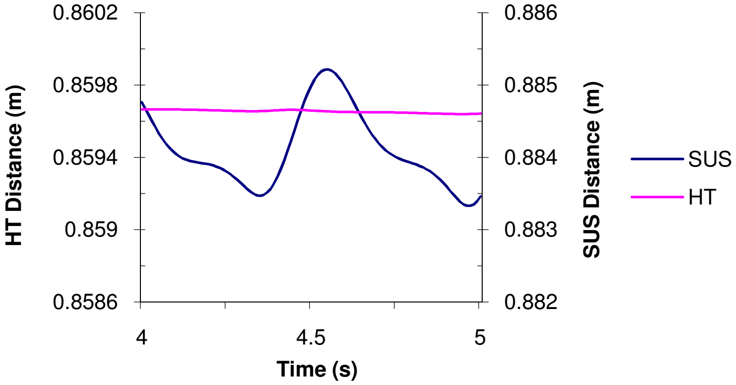


*Figure 7-24: The vertical displacement at the rear of the bike comparing the fully suspended and the hardtail bike on a smooth surface on the rolling road rig.*

In contrast to this, the fully suspended bike displays a displacement at the rear accelerometer of 0.76 mm between the maximum and minimum turning points (Figure 7-24). This is 0.06 mm greater than the displacement measured at the rear accelerometer on the smooth surfaced roller rig (Figure 7-5), and although it highlights that bobbing occurs at the rear of the fully suspended bike, it also signifies that with the incorporation of a front wheel, different results are obtained for the rolling road and roller rig simulations, despite having identical parameters.

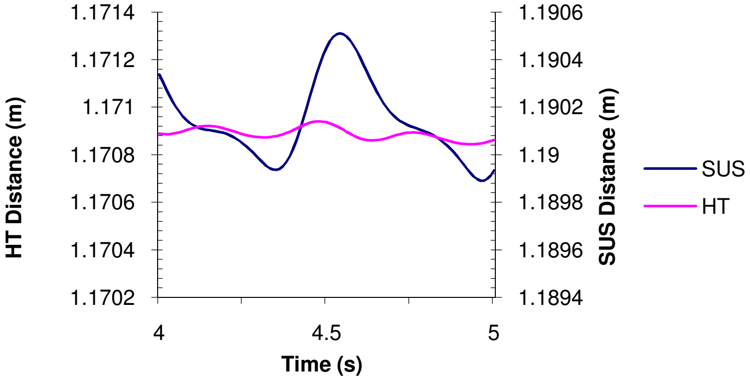


*Figure 7-25: The vertical displacement of the simulated rider's torso, comparing the fully suspended and the hardtail bike on a smooth surface on the rolling road rig.*

Figure 7-25 illustrates how riding on the hardtail and fully suspended bike effects the vertical displacement of the rider's body. As a slight displacement occurs at the front accelerometer of the hardtail bike on the smooth surfaced rolling road rig, it is unsurprising that there is also a slight vertical displacement of the rider's body on the hardtail bike (0.07 mm between the maximum and minimum turning points). This finding differs from the simulation on the roller rig: the vertical displacement of the rider's body on the hardtail bike cycling on the smooth surfaced roller rig remained constant, suggesting that no bobbing occurred. The only differences between the simulations are that on the rolling road rig, the bike is attached to the rig by the handlebars and a front wheel is incorporated into the design of the bike. As the rolling road rig design is a closer representation of true riding conditions, the findings from the results of the displacement of the rider's body on the rolling road rig can be said to be more representative of true riding conditions.

Figure 7-25 also highlights that a larger displacement of the rider's torso was found whilst riding on the fully suspended bike, compared to the hardtail, on the smooth surface. This is once again an expected result due to the larger displacement found at the rear accelerometer of the fully suspended bike, and correlates with the finding for the displacement of the rider's body on the smooth surfaced roller rig simulation. However, the displacement between the maximum and minimum turning points is 0.62 mm for the fully suspended bike on the rolling road rig. This indicates that, on the smooth surfaced rolling road rig, less bobbing occurs than on the roller rig with the smooth surface under identical simulation conditions.

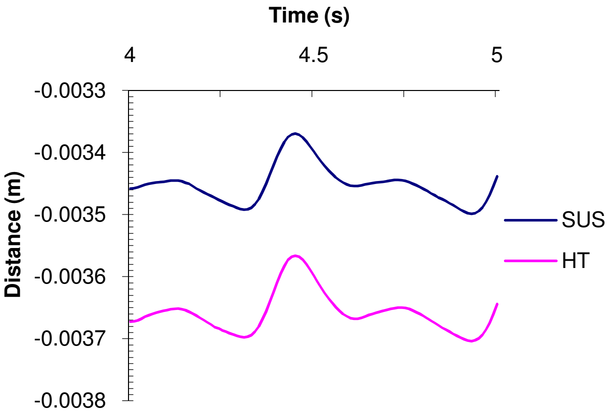


*Figure 7-26: The displacement of the front suspension system comparing the fully suspended and the hardtail bike on a smooth surface on the rolling road rig.*

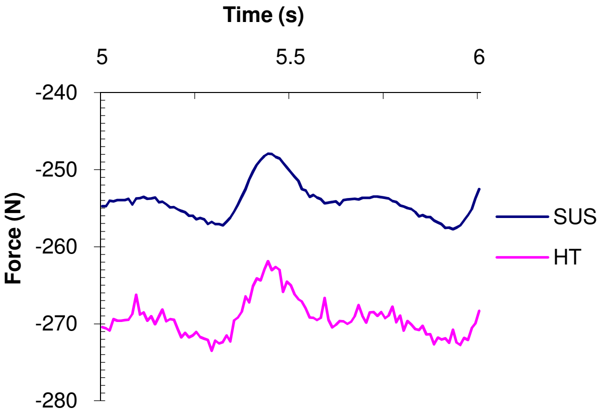


*Figure 7-27: The resultant force transmitted by the front suspension system comparing the fully suspended and the hardtail bike on a smooth surface on the rolling road rig.*

Figures 7-26 and 7-27 represent the displacement and force at the front suspension of both the hardtail and fully suspended bike on the smooth surfaced rolling road rig. The displacement patterns of the front suspension on the fully suspended and hardtail bike have virtually identical curves. The displacement of the front suspension on the fully suspended bike between the maximum and minimum turning points is 0.13 mm, and 0.135 mm between the maximum and minimum turning points for the hardtail bike. These values are higher than those obtained from the simulations relating to the displacement of the front suspension undertaken on the roller rig.

However, the hardtail bike produces a higher average displacement than the fully suspended bike (Figure 7-26). This is a direct result of the spring in the front suspension of the hardtail bike compressing slightly more than that of the fully suspended bike throughout the simulation. This is due to the rear suspension of the fully suspended bike absorbing some of the force exerted by the rider's weight. For the hardtail bike, the front suspension must absorb all of the force exerted by the rider's weight, resulting in an increased compression of the spring. Figure 7-27 shows this force exerted by the front suspension of the hardtail and fully suspended bike: 9.9 N between the maximum and minimum turning points for the fully suspended bike, and 11.5 N between the maximum and minimum turning points for the hardtail bike. As less force is absorbed by the front suspension of the fully suspended bike, less of the rider's energy is utilised on this bike type on the smooth surfaced rolling road rig simulation. Figure 7-27 illustrates that a negative force is displayed for the amount of force exerted on the front suspension of both bike types, which is to be expected as a spring compresses, and as is the case for the spring in the front suspension of the hardtail and fully suspended bikes. In comparison, the results for the force exerted by the front suspension of the hardtail and fully suspended bike on the roller rig with the smooth surface present positive force values (Figure 7-8), indicating an extension of the spring which is an unrealistic representation of true riding conditions. This is also true of the results pertaining to the displacement of the front suspension of the hardtail and fully suspended bike on the roller rig with the smooth surface (Figure 7-7); these also indicate positive displacement values which are unrealistic of true riding conditions.

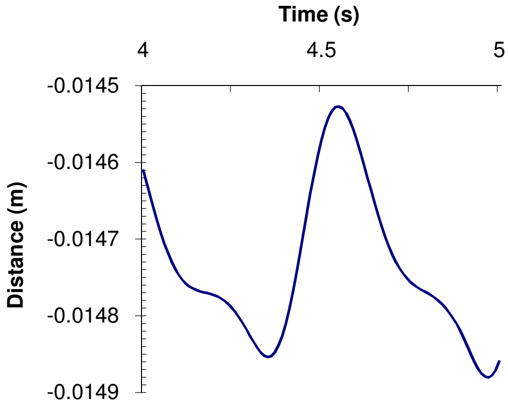


*Figure 7-28: The displacement of the rear suspension system of the fully suspended bike on a smooth surface on the rolling road rig.*

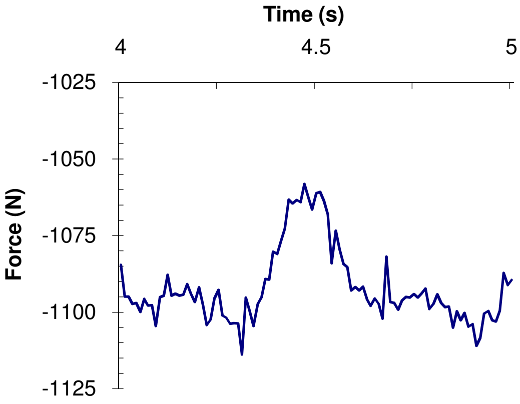


*Figure 7-29: The resultant force transmitted by the rear suspension system of the fully suspended bike on a smooth surface on the rolling road rig.*

Figures 7-28 and 7-29 illustrate the displacement of, and the amount of force exerted on, the rear suspension of the fully suspended bike. The graphs show a displacement and force between the maximum and minimum turning points of 0.355 mm and 44 N respectively.

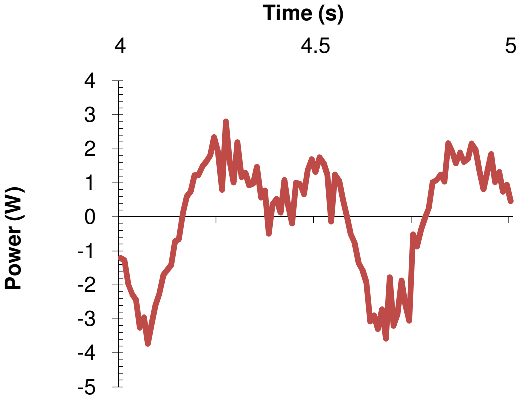


*Figure 7-30: The resultant power transmitted by the rear suspension system of the fully suspended bike on a smooth surface on the rolling road rig.*

Figure 7-30 displays similar results to the simulations relating to the amount of power dissipated by the rear suspension on the smooth surfaced roller rig (Figure 7-11). The primary difference between the simulation results obtained from the roller rig and rolling road rig - both with a smooth surface - relates to the additional power dissipated by the rear suspension whilst cycling on the rolling road rig. One explanation for this may be due to the inclusion of the front wheel of the rolling road rig simulation design.

### 7.4.4. Rolling Road Rig Simulations on the Surface with a Bump

The simulations with the hardtail and fully suspended bike were also run on the rolling road rig on a surface with a bump attached. As previously discussed, a time period must be selected to display all of the relevant data: in this instance the 1.5 s period between 3.5 s and 5 s when the front and rear wheel come into contact with the bump.

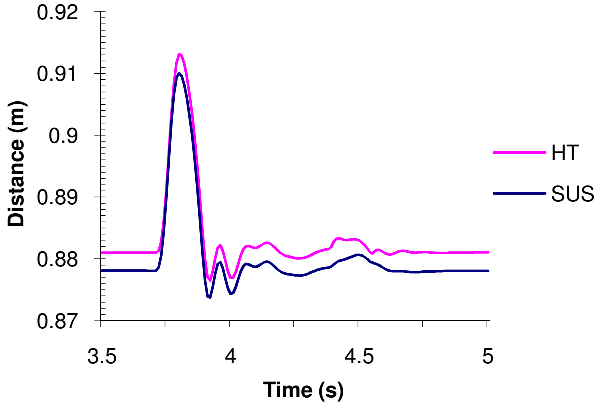


*Figure 7-31: The vertical displacement at the front of the bike comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

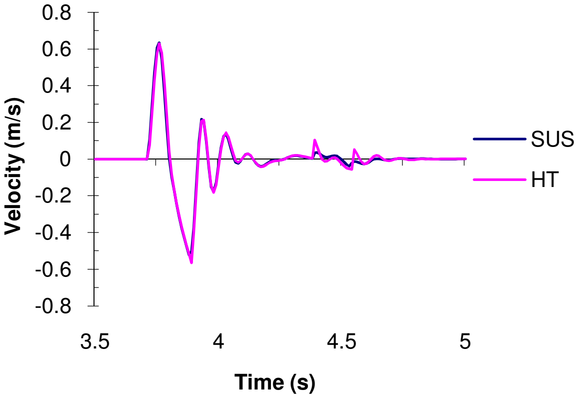


*Figure 7-32: The vertical velocity at the front of the bike comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

Figure 7-31 demonstrates the vertical displacement at the front accelerometer (placed above the steerer tube) of the hardtail and fully suspended bike on the rolling road rig with a bump attached. Both the hardtail and fully suspended system display a similar displacement, although the front accelerometer of the hardtail bike is 0.3 mm higher than on the fully suspended bike. These results differ from those obtained from the vertical displacement at the front accelerometer of the hardtail and fully suspended bike on the roller rig with a bump attached (Figure 7-12). Figure 7-12 shows no oscillation of the front accelerometer for the hardtail bike, and only a slight dip after impact with the bump for the fully suspended bike. In contrast, Figure 7-31 shows that, when the front wheel is incorporated into the design of the bike (as is the case for true riding conditions), there is an oscillation of the front accelerometers for both bikes after the initial impact with the bump.

As the displacement values for the front accelerometers of the hardtail and fully suspended bike on the rolling road rig with the bump are similar, the velocity at the front accelerometers must be considered to identify any further differences between the two types of bike. Figure 7-32 highlights the vertical velocity at the front accelerometer of the hardtail and fully suspended bike on the rolling road rig on the surface with a bump, and demonstrates that the hardtail bike has a slightly higher velocity when impact with the bump occurs; this is apparent when both the front and rear wheel come into contact with the bump. The velocity of the hardtail bike has a difference of 0.046 m/s (between the minimum and maximum turning points) which is greater than that of the fully suspended bike when initial contact with the front wheel occurs. When contact with the rear wheel occurs, the velocity of the hardtail bike is 0.09 m/s (between the minimum and maximum turning points) greater than that of the fully suspended bike. The lower velocity of the front accelerometer of the fully suspended bike indicates that the movements of the bike at the front accelerometer will be less severe, thus improving comfort for the rider.

In comparison to the simulation relating to the vertical velocity at the front accelerometer of the hardtail and fully suspended bike on the roller rig with a bump (Figure 7-13), the simulation displayed in Figure 7-32 illustrates that more oscillation occurs on the rolling road rig (compared to the roller rig) after the initial impact with the bump for both the hardtail and fully suspended bike. This increased oscillation is a result of the design of the rolling road rig, which not only incorporates a front tyre in order to provide a spring-damping effect, but where the front axle is not held rigid, as it is in the roller rig design.

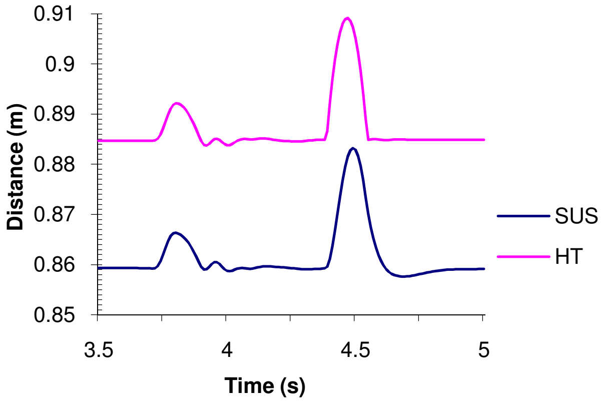


*Figure 7-33: The vertical displacement at the rear of the bike comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

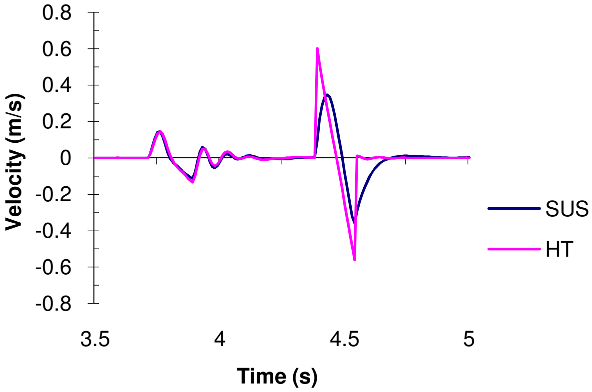
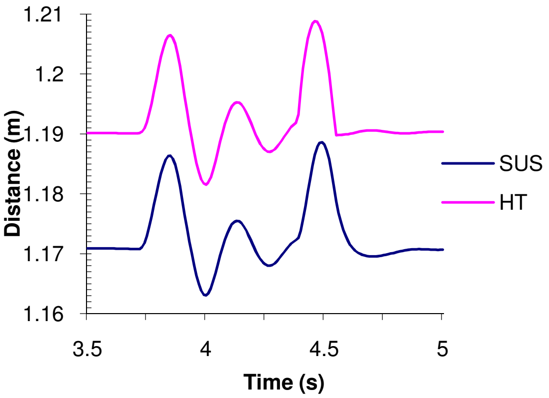


*Figure 7-34: The vertical velocity at the rear of the bike comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

Figures 7-33 and 7-34 display the results for the vertical displacement and velocity at the rear accelerometer on the hardtail and fully suspended bike on the rolling road rig with a bump. In contrast to the vertical displacement at the front accelerometer of the hardtail and fully suspended bikes (Figure 7-31) -where the impact of the rear wheel with the bump was slight for both bike types - the impact for both wheels is more prominent at the rear accelerometer for both the hardtail and fully suspended bike (Figure 7-33). When the front wheel initially contacts the bump, the rear accelerometer of the hardtail bike rises by 7.4 mm, and the rear accelerometer of the fully suspended bike by 7.05 mm. This emphasises that the contact of the front wheel still has a significant effect on the rear dynamics of a hardtail and fully suspended bike.

When the rear wheel of both the hardtail and fully suspended bike comes into contact with the bump at 4.4 s (Figure 7-33), the displacement of the rear accelerometer of both types of bike increases by a considerable degree compared to when the front wheel initially hits the bump. The rear accelerometer of the hardtail bike rises by 24.3 mm and by 24.2 mm on the fully suspended bike. However, the fully suspended bike does cause the rear of the bike to dip slightly after hitting the bump as it absorbs the impact with the ground. The displacement results for the fully suspended bike are similar to those obtained at the rear accelerometer of the fully suspended bike on the roller rig with a bump (Figure 7-14). Figure 7-14 highlights that the rear accelerometer of the fully suspended bike rises by 24.5 mm, although the displacement of the rear accelerometer of the hardtail bike is shown to be 28 mm - slightly higher than the other results.

Figure 7-33 illustrates the vertical velocity at the rear suspension of the hardtail and fully suspended bike on the rolling road rig with a bump. The velocity of the rear accelerometer of the hardtail bike rises and falls sharply with a velocity between the maximum and minimum turning points of 1.162 m/s. In contrast to this, the fully suspended bike has a velocity of 0.705 m/s between the maximum and minimum turning points. The velocity of the hardtail bike is slightly higher, when the front wheel impacts the bump (0.28 m/s), than that of the fully suspended bike when its front wheel impacts the bump (0.258 m/s). The lower velocity of the fully suspended bike lessens the impact of the bump felt by the rider and increases the comfort of the cyclist. The results from Figure 7-33 are similar to those found in Figure 7-15 on the roller rig with a bump.



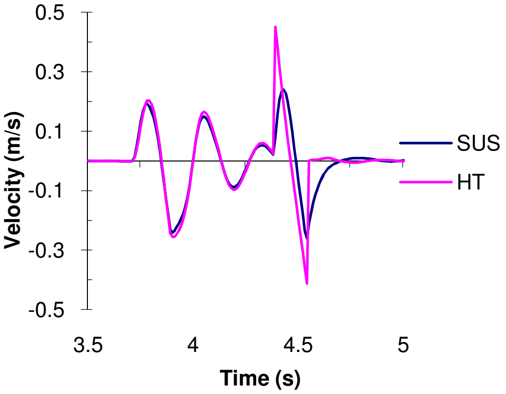


*Figure 7-35: The vertical displacement of the simulated rider, comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

*Figure 7-36: The vertical velocity of the simulated rider, comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

The vertical displacement and velocity of the rider's body on the hardtail and fully suspended bike on the rolling road rig on the surface with a bump are displayed in Figures 7-35 and 7-36. The graph for the vertical displacement of the rider's body shows a similar pattern for both bikes (Figure 7-35); the displacement of the rider's body on the hardtail bike; between the maximum and minimum turning points, is 28.4 mm, and 25.5 mm on the fully suspended bike. These displacement values are less than those obtained for the vertical displacement of the rider's body on the hardtail and fully suspended bikes on the roller rig with a bump (Figure 7-16).

As Figure 7-35 displays a similar pattern for both bikes, the velocity of the rider's body must be analysed in order to highlight any differences between the hardtail and fully suspended bike. The velocity of the rider's body is similar when the front wheel of both bikes comes into contact with the bump; however, there is a noticeable difference between both suspension systems when the rear wheel comes into contact with the bump, thus highlighting the differences between both bikes (Figure 7-36). A sharp rise and fall is shown for the hardtail bike when the rear wheel impacts the bump; the velocity of the rider's body reaches 0.45 m/s in this instance. The rider's body has a maximum velocity of 0.24 m/s on the fully suspended bike when the rear wheel impacts the bump. The curve for this result is smoother, indicating that the rider's movement is less sudden, and hence more comfort is experienced whilst cycling on the fully suspended bike. The values obtained from the vertical velocity of the rider's body on the hardtail and fully suspended bike on the rolling road rig with a bump (Figure 7-36) are less than those obtained for the vertical velocity of the rider's body on the hardtail and fully suspended bike on the roller rig with a bump (Figure 7-17). This is to be expected as the results for the vertical displacement and velocity at the rear accelerometer of the hardtail and fully suspended bike on the rolling road rig with a bump (Figures 7-33 & 7-34) are also lower than the results for the vertical displacement and velocity at the rear accelerometer of the hardtail and fully suspended bike on the roller rig with a bump (Figures 7-14 & 7-15). If the rear accelerometer has a lower displacement; consequently, the displacement, of the rider's body will also be lower.

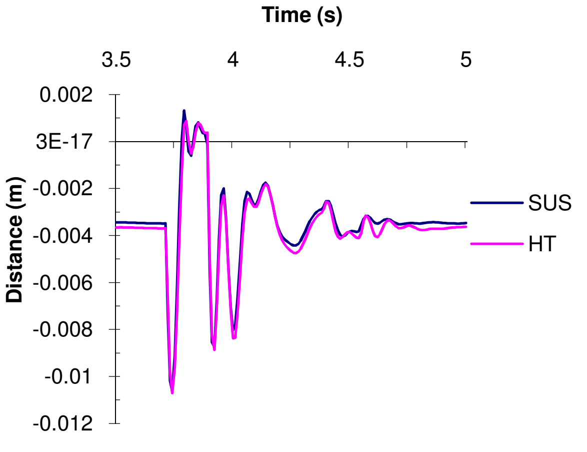


*Figure 7-37: The displacement of the front suspension system comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

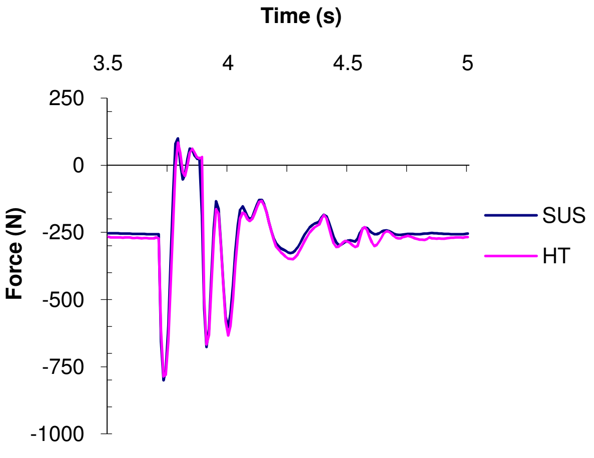


*Figure 7-38: The resultant force transmitted by the front suspension system comparing the fully suspended and the hardtail bike on a rough surface on the rolling road rig.*

Figures 7-37 and 7-38 show the displacement and force at the front suspension of the hardtail and fully suspended bike on the rolling road rig with a bump. The graphs illustrate that there is little difference between the front suspensions of both bikes, which is to be expected as the front dynamics of the hardtail and fully suspended bike should be similar. The displacement of the front suspension of the hardtail bike is 11.4 mm between the minimum and maximum turning points, and 12 mm between the minimum and maximum turning points of the fully suspended bike (Figure 7-37). The force at the front suspension of the hardtail and fully suspended bike is 875 N and 900 N between the minimum and maximum turning points respectively (Figure 7-38). One notable difference between the hardtail and fully suspended bike is that the front suspension of the hardtail bike (compared to the fully suspended bike) oscillates slightly more after the rear wheel hits the bump at 4.4 s. A reason for this slightly higher oscillation is that the fully suspended bike can absorb the impact of the bump at the rear wheel more effectively than the hardtail bike due to inclusion of the rear suspension in the bike's design.

The displacement and force at the front suspension of the hardtail bike on the roller rig with a bump, differs significantly from the displacement and force at the front suspension of the fully suspended bike on the same roller rig with a bump (Figures 7-18 & 7-19). This highlights that the results for these simulations differ as a result of the roller rig design (no front wheel being incorporated), and not due to the suspension design as Figures 7-18 and 7-19 indicate.

The displacement and force exerted on the spring of the rear suspension system are illustrated in Figures 7-39 and 7-40 respectively.

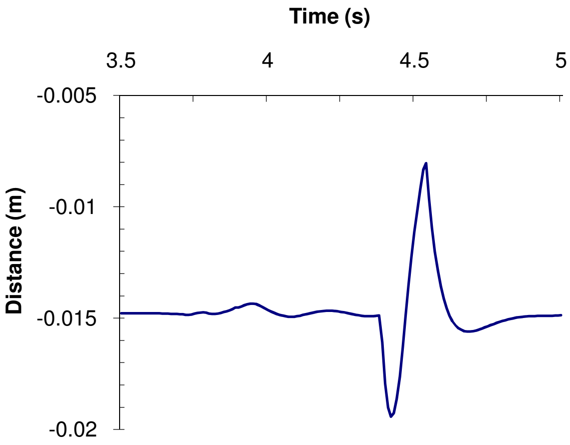


*Figure 7-39: The displacement of the rear suspension system of the fully suspended bike on a rough surface on the rolling road rig.*

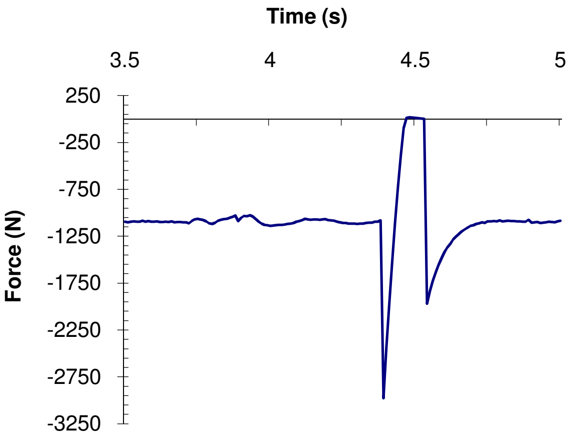


*Figure 7-40: The resultant force transmitted by the rear suspension system of the fully suspended bike on a rough surface on the rolling road rig.*

Notably, there is minimal movement and force within the spring of the rear suspension when the front wheel impacts the bump at 3.71 s: the displacement is 0.5 mm and the force 60 N. In contrast, when the rear wheel hits the bump there is considerable movement and force exerted on the spring. Initially when contact occurs, the spring compresses by 4.6 mm; extends by 11.4 mm when the wheel returns to the ground and finally returns to the initial preloaded length. The force exerted on the spring of the rear suspension is 3020 N between the minimum and maximum turning points. An important finding derives from the results of the displacement of the rear suspension (Figure 7-39): the small displacement value of 0.5 mm (occurring when the front wheel hits the bump), is much less than the displacement recorded for the rear accelerometer (Figure 7-33), which is 7.05 mm when the front wheel of the bike hits the bump. This indicates that the movement of the rear accelerometer does not occur as a result of the front suspension.

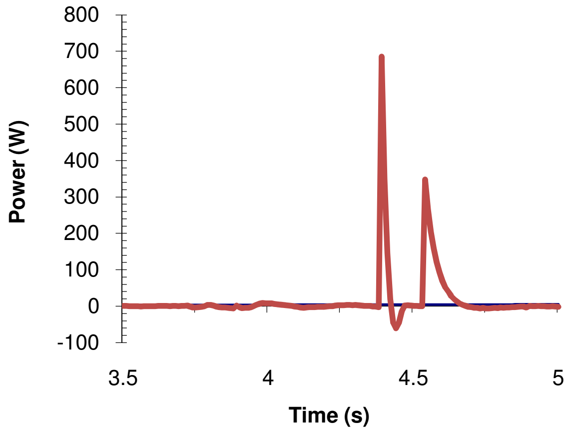


*Figure 7-41: The resultant power transmitted by the rear suspension system of the fully suspended bike on a rough surface on the rolling road rig.*

Figure 7-41 illustrates the resultant power dissipated through the rear suspension of the fully suspended bike on the rough surfaced rolling road rig. The graph highlights that much of the initial bump impact is absorbed by the spring in the rear suspension system.

# 8. Discussion

The current research was undertaken to establish if cycling on either a fully suspended bike (rear and front suspension) or a hardtail bike (front suspension only) presents an advantage to the rider in terms of performance. This was investigated through recording and analysing subjects' energy efficiency, RPE and comfort ratings, and by considering simulations and mechanical measurements taken from the bikes. A Matrix is illustrated in Figure 8-1 to indicate which suspension system is most effective under the different testing conditions.

| | Hardtail (Smooth Track) | Full Suspension (Smooth Track) | Hardtail (Rough Track) | Full Suspension (Rough Track) |
|---|---|---|---|---|
| **Simulation (Roller Rig)** | + | - | - | + |
| **Simulation (Rolling Road)** | + | - | - | + |
| **Physiology (Roller Rig)** | | | - | + |
| **Mechanical (Roller Rig)** | | | - | + |
| **Physiology (Rolling Road)** | + | - | 0 | 0 |
| **Mechanical (Rolling Road)** | + | - | - | + |
| **Physiology (Indoor Track )** | | | - | + |

Figure 8-1: Matrix

Key: + Benefit — Detrimental 0 No Difference.

As indicated by the Matrix (Figure 8-1), the fully suspended bike performs more effectively than the fully suspended bike on a rough surface. However, on a smooth surface - as indicated by the simulation results - there is a slight advantage when cycling on the hardtail bike, although this is not reflected in the laboratory tests. This may be the reason that González et al. (2008) assert that rear suspension systems are not broadly accepted by cross-country cyclists; a somewhat surprising statement given the numerous researchers who advocate the benefits of rear suspension systems (Berry et al., 1993; Burke, 1996; De Lorenzo et al., 1994; Good & McPhee, 1999; Karchin & Hull, 2002; MacRae et al., 2000; Needle & Hull, 1997; Nielens & Lejeune, 2004; Olsen, 1996; Seifert et al., 1997). However, research has also been published which details some of the drawbacks that a rear suspension system can produce (Burke, 1996; Ishii et al., 2003; Karchin & Hull, 2002; Kukoda, 1992; Olsen 1996; and Wang & Hull, 1997). Previous researchers adopted numerous forms of testing; all of which were to ascertain if the reason for the disparity in results between the researchers in this field was due to the form of testing that was implemented. The current research aims to establish a form of testing that would present a good comparison between both the fully suspended and hardtail bike.

The review of the literature pertaining to mountain bike suspension systems; the analysis of responses from the cyclists' questionnaires; the comparison of the results obtained from the experiments on the roller rig, rolling road rig, and indoor track; and the dynamic simulations, all assisted in providing a comprehensive investigation into the ways in which a front and rear suspension system will effect a cross-country cyclist. This discussion will seek to draw conclusions and identify areas for future work as presented in Chapter Nine.

The experiments on the roller rig were conducted to obtain an understanding of the effect that suspension systems have on comfort and exertion when cycling on an exaggerated rough surface. The roller rig provides advantages over other forms of laboratory testing (testing on ergometers, treadmills, time trials) undertaken by previous researchers (Berry et al., 1993; Berry et al., 2001; Ishii et al., 2003; Nielens & Lejeune, 2001). Similarly, the roller rig presents some advantages over outdoor field testing (Holden et al., 2000; Ishii et al., 2003; Seifert et al., 1997). The roller rig was specifically designed to reduce as many of the variables involved in cycling as possible; to provide controlled, repeatable experiments; and to isolate the rear wheel impact and the effect this has on the rear suspension system (the only variable between the experiments on the roller rig). The technique of isolating the bump impact of the rear wheel provides a simplistic analysis of the rear wheel dynamics of a mountain bike, allowing comparisons to be made between the hardtail and fully suspended bike. One of the main benefits of conducting experiments on the roller rig is that the only aspect of cycling that the subject has to maintain is a constant speed. All other variables which are typically present in mountain biking: balance on the bike; route selection; and whether or not a rider stands to absorb bump impact, are removed as the subject was instructed to ride passively and remain seated throughout the test.

Two bikes were used for the initial experiments on the roller rig: a hardtail and fully suspended bike. Although similar frame types were selected, the rear triangle of the fully suspended bike provided a heavier overall weight than that of the hardtail bike, which in turn presented an initial advantage to the hardtail bike over the fully suspended. Howe (1995) maintains that the reduction in the mass of a bicycle should significantly improve cycling performance. Conversely, Berry et al. (2000) proclaim that weight is not an important factor in the cyclists' energy expenditure when riding a bike.

The initial test on the roller rig was a run down test, during which the velocity of each bike (hardtail and fully suspended) was recorded to establish the time it would take for each bike to come to rest from a pre-determined velocity. The run down times were recorded for the two bikes, as illustrated in Figure 4-6, Chapter Four. Figure 4-6 highlights that 44 % more resistance acts against the hardtail bike than the fully suspended bike. At a speed of 12 km/h, this equates to an additional energy requirement of 50 W required for the cyclist on the hardtail bike to remain at the same constant speed as an equivalent cyclist on the fully suspended bike. This was perhaps an expected finding as the roller rig represents an extremely rough riding surface. The design of a rear suspension system allows for absorption of the impact of bumps, thus allowing the fully suspended bike to move efficiently over the rough riding surface. The impact of the rear wheel of the hardtail bike over the bumps results in a vertical displacement, which in turn slows the bike down. It is therefore hypothesised that for the cyclist on the hardtail bike to remain at the same constant speed, a greater torque would be required through the pedals which would subsequently require more energy from the cyclist. To examine these theories it was proposed that two tests should be conducted on the roller rig: a familiarisation test to establish if a subject improved after subsequent experiments (to eliminate bias in results), and a comparative test to establish if there are any differences between cycling on the hardtail bike compared to the fully suspended bike on the roller rig with the rough surface.

Six subjects carried out the familiarisation test to ensure that the participants did not improve after each test, thus ensuring that the results would remain unaffected. The tests were carried out at a sub-maximal level to ensure the rider reached a steady physiological state so as the physiological data remained valid. The subjects' $VO_2$, heart rate, RPE and comfort rating levels were recorded during testing to ascertain if any improvements in performance could be identified after subsequent visits to the laboratory. The test demonstrated that there was no significant improvement for any subject after subsequent tests on the rig as no significant changes in $VO_2$, heart rate, RPE or comfort rating levels were identified. Therefore, the results of a single test with each subject on each bike can be deemed to be representative for a given condition.

Following the familiarisation test, the comparative test was developed to assess the differences between riding the hardtail compared to the fully suspended bike on the rough riding surface of the roller rig. Prior to identifying any differences between cycling on either of the bikes, it was important to establish if the subjects' physiologies had stabilised so that subsequent results would provide an accurate representation of the effort provided by each rider on both of the bikes. The results displayed in Table 4-2, Chapter Four indicate that each subject's $VO_2$ and heart rate remain fairly constant from the fifth to the tenth minutes of the test. This confirms that the $VO_2$ and heart rate had stabilised and can therefore be deemed as being representative of energy efficiency. The RPE and comfort readings show that there is a consistent trend for the subjects to become increasingly conscious of their exertion and discomfort as the test progresses, despite the $VO_2$ and heart rate levels remaining constant.

Figures 4-7 to 4-10 of Chapter Four display the results obtained for each subject's $VO_{2,}$ heart rate, RPE and comfort rating when cycling on the hardtail and fully suspended bikes. The results indicate that each subject recorded higher values for $VO_2$ by 8.1 ml/kg/min, heart rate by 28.9 beats/min and RPE by 3.7; and lower results for comfort rating by 1.8 on the hardtail bike compared to the fully suspended bike. These results highlight that the fully suspended bike presents an advantage over the hardtail bike in terms of rider performance on the roller rig with a rough surface.

The results of the statistical analysis of the findings for the differences between cycling on the hardtail compared to the fully suspended bike on the roller rig are illustrated in Table 4-3, Chapter Four. The p values for these results are all below 0.05, indicating that there are real significant differences between the two bikes. The results signify that more effort is required to remain at the same constant speed on the hardtail bike compared to the fully suspended bike; this is highlighted by the recorded $VO_2$ and heart rate values. The average level of $VO_2$ is 8.1 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ higher for subjects cycling on the hardtail bike. Similarly, the average heart rate is higher - by an average 28.9 beats/min - for subjects cycling on the hardtail bike compared to the fully suspended bike.

These results coincide with the findings of Berry et al. (1993) who found that whilst cycling on a bumpy track under laboratory conditions, a rear suspension system could reduce the physiological cost to a rider. This was concluded despite Berry et al. (1993) recording a lower $VO_2$ for subjects cycling on a fully suspended bike compared to a hardtail bike, and recording higher heart rate levels for subjects cycling on either the hardtail or fully suspended bikes. The higher heart rate levels obtained for cyclists on both bikes may be due to the testing conditions. Subjects were tested on a treadmill - an unfamiliar and potentially risk posing mode of testing. It is conceivable that the high heart rates were recorded as a result of anxiety and apprehension over this form of testing. $VO_2$ levels however, would remain unaffected.

The RPE results from the comparative test also support the findings for $VO_2$ and heart rate: all of the subjects perceived that they used less effort when cycling on the fully suspended bike compared to the hardtail bike. The average RPE ratings were 3.7 higher for subjects cycling on the fully suspended bike compared to the hardtail bike. Correspondingly, comfort rating was perceived to be greater for subjects undertaking tests on the fully suspended bike: all subjects cited average comfort ratings of between 2 and 4.5. The higher comfort ratings cited by the subjects cycling on the fully suspended bike may also result in a decrease in rider fatigue as less strain is applied to the muscles due to a reduction in vibration felt whilst cycling. Needle & Hull (1997) assert that vibrational discomfort associated with riding a bike over rough terrain has been known to contribute to rider fatigue and affect rider performance. The physiological and psychological findings of the comparative tests on the roller rig all indicate that on a rough track the fully suspended bike gives a significant advantage to the rider over the hardtail bike.

The findings from the roller rig experiments concur with Titlestad et al. (2001) and Berry et al. (1993) who also found that cycling on a fully suspended bike, compared to a hardtail bike, on a rough track, presented an advantage to the rider. This finding, however, contradicts those found through MacRae et al's (2000) and Seifert et al's (1997) studies. Both researchers found no significant difference between cycling on a fully suspended or hardtail bike on a bumpy course. This disparity between results may be attributed to the form of testing adopted by each researcher; the type of rear suspension used for testing; or the roughness of the terrain on which testing occurs: all of which may determine the outcome of the results. Different forms of testing presents both advantages and disadvantages to subjects, as highlighted by Berry et al's (1993) use of a treadmill as a means of testing mountain bikes and their suspension systems. Furthermore, the type of rear suspension used can affect results. It is felt that the single swing arm rear suspension design is less efficient than others such as the four-bar linkage design (González et al., 2008). In this respect, experiments involving a mountain bike with a four bar linkage, or alternative type of rear suspension design, may offer an advantage to the subject. The roughness of the testing track should also be taken into consideration; an extremely rough track may influence results as a fully suspended bike is designed to better cope with bumpy terrain than a hardtail bike.

Mechanical measurements were also recorded during each test on the roller rig. The analysis of the measurements demonstrated the effect that cycling on the rough terrain had on the acceleration, velocity and displacement at the front and rear of the bike. Additionally, the force exerted on the pedals by the rider was recorded and was used to establish the amount of power required for each rider to maintain cycling at a constant speed. The results gained from the mechanical measurements were compared against the physiological and physiological data to establish if any correlations occurred. A total of eight mechanical measurements were recorded in total; the mean results are represented in tabulated form in Chapter Four and each individual subject's results are displayed in Appendix C.

The aspects of the mechanical measurements that are most comparable to the physiological results are those relating to the amount of force and power exerted through the pedals of the mountain bikes. The results for the amount of force and power that a subject transmits through the crank can be compared against the subject's $VO_2$ level to ascertain if these factors are proportional to one another. MacRae et al. (2000) measured the power output from an SRM training device and found that a cyclist riding on a hardtail mountain bike used less power than on a fully suspended mountain bike when cycling uphill on both a smooth and rough course. MacRae et al's (2000) mechanical and physiology results conflict with one another which may indicate that physiological data alone is not sufficient to establish which suspension system is the most efficient.

The average mean force exerted on the crank was found to be 38.36% less when cycling on the fully suspended bike compared to the hardtail bike when cycling on the roller rig. The amount of power exerted through the pedals demonstrates similar results to that of the amount of force exerted on the pedals - an expected finding as the amount of power is calculated through multiplying force by velocity. The average power required to cycle at a constant speed is 35.75 % greater for the hardtail bike compared to the fully suspended bike. Similar to the force results, there is only a slight difference between the maximum and minimum values for the amount of power exerted on the pedals: the maximum and minimum amount of power required to cycle at a constant speed is 4.43 % and 4.79 % greater for the hardtail bike respectively. This gives a difference in the overall range in power between both bikes as 4.41 % more power being required for the hardtail bike. From the results obtained from the amount of power exerted through the crank (Table 4-4), it is apparent that a greater variation in power is required by the cyclist to maintain a constant speed on a hardtail when travelling on the rough surface of the roller rig. This finding correlates with the results obtained from the physiological data which also indicates that the rider uses more energy when riding on the hardtail bike compared to the fully suspended bike. This is primarily due to the fact that the fully suspended bike absorbs more of the bump impact due to the inclusion of a rear suspension in the bike design. This may only be true for this rough surface however, and may be less apparent as the bumps become smaller and less frequent.

The most precise measure of the bikes' movements throughout the tests was through the use of accelerometers placed on the steerer tube and below the saddle of the bikes. The results from the accelerometers indicate the acceleration at the front and rear of the bike from which the velocity and displacement of the bikes at these points could be calculated.

Through analysing the results obtained from the accelerometer placed under the saddle of the bikes (Table 4-6; Chapter 4), it was found that the saddle of the hardtail bike accelerates 19.89 % more than that of the fully suspended bike . The average minimum value for the acceleration of the saddle is 0.75 % lower for the hardtail bike and the average maximum value is 1.31 % higher for the hardtail bike. The difference in the total range is overall 1.11 % greater for the hardtail bike. Consequently, this shows that the hardtail bike has a higher vertical saddle acceleration than the fully suspended bike. This corresponds with the physiological results (fully suspended bike presents an advantage to rider) and explains why all riders felt that the hardtail bike was more uncomfortable. This also gives an indication as to where some of the rider's energy is expended: via the vertical motion of the bike as it cycles over the bumps.

The results obtained during the experimental approach can be compared to the results obtained for the dynamic simulation investigating handlebar and saddle displacement (Figures 7-12 and 7-13; Chapter 7). Figure 7-12 displays the equivalent results for the dynamic simulation test for displacement of the handlebars on the roller rig surface with bumps. The dynamic simulation for handlebar displacement shows that the maximum displacement on the roller rig illustrates a similar displacement to the experimental results on the roller rig which present a displacement of 3.3 mm. The dynamic simulation investigated the seat displacement of both a hardtail and fully suspended bike on the roller rig a surface with bumps. The dynamic simulation results indicate that the hardtail bike rises by 28 mm and the fully suspended bike by 24.5 mm when impact occurs with the bump.

Conversely, the results for the maximum displacement obtained during the experiments on the roller rig (Table 4-8; Chapter 4) highlight that the saddle displacement is 10.6 mm for the fully suspended bike and 11 mm for the hardtail bike. This demonstrates that, in reality, the tyre absorbs more of the bump impact than is demonstrated in the dynamic simulation. Despite using an advanced dynamic simulation programme, it is difficult to simulate the exact properties of a complex mountain bike tyre which explains the discrepancies in simulation results compared to the practical experiments. Similarly, the simulated model indicates only a small dip after contact with the bump, when in reality there is a significant displacement in the negative direction of 7 mm prior to contact with the bump.

The findings stated in Chapter 4 highlight that for the experiments on the roller rig under constrained sub-maximal conditions on a severely bumpy track, the full suspension mountain bike provides distinct advantages to the rider over the hardtail bike. This is true for $VO_2$ (8.1 ml/kg/min higher for the hardtail bike); heart rate (28.9 beats/min higher for the hardtail bike); RPE (3.7 higher for the hardtail bike); comfort rating (1.8 less comfortable for the hardtail bike); power through the crank (35.75% higher on the hardtail bike); seat acceleration (19.89% higher for the hardtail bike) and handlebar acceleration (31.25% higher for the hardtail bike). From these results, there is a strong expectation that on a track with frequent, large bumps, the fully suspended bike would provide an advantage to the rider in terms of speed. The primary difficulty that exists with this form of laboratory rig testing is however, that the terrains of actual cross-country racetracks differ considerably from the large high frequency of bumps used for the roller rig experiment.

In contrast to the results for the roller rig, time trials conducted by Seifert et al. (1997) and MacRae et al. (2000) highlighted no difference between riding a fully suspended bike compared to a hardtail bike. An additional consideration when analysing the results is that the majority of cross-country cyclists still choose to ride a hardtail mountain bike, compared to a fully suspended mountain bike. The cyclists' responses to the questionnaire (Appendix A) support this claim: only thirty-seven percent of respondents ride a fully suspended mountain bike (Chapter 3). This evidence indicates that the roller rig test alone is not sufficient enough to draw a conclusion as to which suspension system offers an advantage to the cyclist in terms of rider performance.

Consequently, tests were undertaken on the rolling road rig in order to further investigate the effect that suspension systems have on rider performance. Although the results obtained through experimentation on the roller rig provided evidence to suggest that a fully suspended bike with a single swing arm rear suspension design presented advantages to the rider over a hardtail bike when cycling on a terrain with large, frequent bumps, the roller rig investigated only rear wheel impact. The rolling road rig however, was developed to present a more realistic representation of riding on a cross-country track by incorporating a front wheel into its design while still providing repeatable results under laboratory conditions. The rolling road rig was developed to accurately simulate the inertial effects of cycling on a road: the track of the rolling road was powered by the rider and the bumps could impact both the front and rear wheel of the bike.

The subjects undertaking testing on the roller rig stated that they experienced extreme discomfort when cycling on the hardtail bike over the rough track. On a cross-country course if a cyclist was presented with a bump of the magnitude that was represented on the roller rig, they would attempt to avoid it or rise from the saddle in order to absorb some of the impact with their legs. This was an element which was taken into consideration when designing the rolling road rig. Nielens & Lejeune (2001) stipulate that during mountain biking, riders rarely stand on the pedals because of the loss of traction of the rear wheel in that position. Many researchers have proved that seated cycling is more economical than standing when cycling uphill (Harnish et al., 2006; Ishii, 2002; Karchin & Hull, 2002; Stone & Hull, 1993; Tinaka et al., 1996; Ryschon & Stray-Gundersen, 1990). For this reason the rolling road rig was designed to run in a seated position, therefore a realistic bump size and frequency had to be selected which subjects would cycle over in a seated position.

For the purpose of testing on the roller rig, a hardtail and fully suspended bike were used for comparison. Although the bikes were similar in design, the weight and frame geometry differed, a factor which may have influenced results. For this reason a fully suspended bike was used for the purpose of testing on the rolling road rig from which a hardtail bike could be represented through disabling the rear spring and damper. In view of the new design considerations it was anticipated that the rolling road rig would obtain a more realistic set of results from which to identify any differences between using a fully suspended and hardtail bike.

The results obtained from the tests undertaken on the rolling road rig demonstrate that $VO_2$ and heart rate remained comparatively constant over the 12 minute test period, as illustrated in Table 5-3; Chapter 5. This indicates that subjects had reached a steady physiological state - therefore the results are a valid representation of the subjects' work rate. Each subject found - as was also the case for the roller rig - that cycling on the rolling road rig became slightly less comfortable as the test continued. The subjects' RPE ratings also became increasingly higher as the test progressed, however these ratings were not as high for the tests on the rolling road rig compared to the roller rig. The roller rig demonstrated a greater difference (compared to the rolling road rig) between riding a fully suspended bike compared to a hardtail bike in all physiological, psychological and mechanical measurements.

In comparing the results obtained for cycling on the hardtail bike on the roller rig to those for cycling on the hardtail bike on the rolling road rig, both on a rough surface, only a small difference between results was found. This was highlighted by the subjects' $VO_2$ levels which indicated that a subject cycling on a hardtail bike on the roller rig had, on average, a seven percent lower $VO_2$ level than when cycling on the hardtail bike on the rolling road rig. The results obtained for subjects cycling on the fully suspended bike on the rough surface signified that subjects had, on average, a thirty percent lower $VO_2$ level whilst cycling on the fully suspended bike on the roller rig compared to cycling on the fully suspended bike on the rolling road rig with a rough surface.

The results recorded for subjects' heart rates whilst cycling on the roller rig and rolling road rig, both on the rough surface, were as follows: on average, a nine percent lower heart rate was recorded for subjects cycling on the hardtail bike on the rolling road rig, compared to subjects cycling on the hardtail bike on the roller rig. Conversely, the results recorded for subjects' heart rates whilst cycling on the fully suspended bike on the rough surface indicated that on average, a subject's heart rate was eleven percent higher whilst cycling on the rolling road rig compared to the roller rig.

These findings, with the exception of the lower average heart rate recorded for cycling on the rolling road rig (compared to the roller rig) on the hardtail bike, indicate that subjects cycling on the rolling road rig use more energy than when cycling on the roller rig. This is an expected outcome as added friction is apparent when cycling on the rolling road rig due to the friction of the belt which acts as a resistive force to the cyclist. The anomaly result obtained for the higher average heart rate recorded for cycling on the roller rig compared to the rolling road rig on the hardtail bike may be attributed to the anxiety felt by the subjects due to the unrealistic testing conditions of the roller rig, and not due to an increase in work load as the result would signify.

In comparing the psychological results obtained for subjects cycling on the roller rig to those obtained for subjects cycling on the rolling road rig (both on a rough surface), it was found that, on average, subjects' RPE ratings were 4 % lower whilst cycling on the fully suspended bike on the roller rig compared to cycling on the fully suspended bike on the rolling road rig. The RPE results for cycling on the hardtail bike indicate that for a subject cycling on the rolling road rig, an average 15 % lower RPE rate was recorded compared to on the roller rig. This indicates that the subjects felt that they were exerting less energy whilst cycling on the hardtail bike on the rolling road rig with bumps. This correlates with the results for the heart rate levels of subjects cycling on the hardtail bike: on average lower heart rates were recorded for subjects cycling on the hardtail bike on the rolling road rig compared to subjects cycling on the hardtail bike on the roller rig. However, the results for $VO_2$ levels do not follow this trend: subjects cycling on the hardtail bike on the rolling road rig were found to have, on average, higher $VO_2$ levels compared to subjects cycling on the hardtail bike on the roller rig.

The reason for the high RPE levels cited by subjects cycling on the hardtail bike on the roller rig may be due to discomfort rather than an actual increase in workload; a hypothesis supported by the comfort scale ratings. The comfort scale ratings indicate that, on average, subjects cycling on the hardtail bike on the roller rig felt 45 % less comfortable than when cycling on the hardtail bike on the rolling road rig. This may be a result of the larger bumps that subjects experienced when cycling on the roller rig. Interestingly, the comfort rating results for subjects cycling on the fully suspended bike highlight that subjects felt twelve percent more comfortable when cycling on the roller rig compared to the rolling road rig; a somewhat surprising result. A possible reason for this outcome may be that subjects compared the comfort of the fully suspended bike on the roller rig to the comfort of the hardtail bike on the roller rig, and as the bumps were larger (resulting in more discomfort) on the roller rig, the rear suspension would feel more comfortable in comparison on this rig.

The physiology and psychology results from the rolling road rig experiments on a smooth surface highlight that no significant difference is apparent between cycling on the hardtail and fully suspended bikes. Significant differences highlighted were: $VO_2$ (0.6 ml/kg/min higher for the fully suspended bike); heart rate (1.4 beats/min higher for the fully suspended bike); RPE (0.5 higher for the fully suspended bike) and comfort rating (0.4 less comfortable for the fully suspended bike). The only results that demonstrate a statistically significant difference for the subjects' physiology and psychology between the two bikes is for RPE on a rough track which is recorded to be 1.5 higher for the fully suspended bike. All other results pertaining to the physiology and psychology of the subjects cycling on a rough track demonstrate that there are no statistically significant differences between the bikes: $VO_2$ (0.6 ml/kg/min higher for the hardtail bike); heart rate (1 beat/min higher for the hardtail bike) and comfort rating (0.8 less comfortable for the hardtail bike).

This is perhaps surprising as a large difference between the two bikes is apparent when analysing the results of the roller rig experiments. This may be due to a number of factors: the rolling road rig more closely represents true outdoor cycling conditions; the front wheel of the bike is incorporated into the rolling road rig design; and fewer and less severe bumps are used for the rolling road rig tests to represent a cross-country track.

One possible reason for the $VO_2$ and heart rate results obtained from the experiments on the rolling road rig not highlighting any significant differences between the fully suspended and hardtail bike may be due to the physiology measurements not being accurate enough to demonstrate the differences between cycling on each bike. Howley et al. (1995) state that the small difference between riding these two (full and hardtail) suspension systems is less than the average measurement error expected when measuring oxygen consumption in an experimental test.

The physiology results obtained from the experiments on the rolling road rig indicate that there is not a significant advantage to using a fully suspended bike over a hardtail bike on a terrain with this bump magnitude and frequency combined with the added resistance of the track. These results correspond with the results obtained from MacRae et al's (2000) and Seifert et al's (1997) research, both of whom also found that there was no significant difference between riding a fully suspended or hardtail bike on a bumpy course. The roughness of the track may have been a contributing factor as to why no significant difference is observed between both bikes for the current study and for MacRae et al's (2000) and Seifert et al's (1997) studies. Neither MacRae et al. (2000) nor Seifert et al. (1997) state how rough their test tracks are, however, bumps of a larger magnitude may have highlighted a difference between the two bikes as is the case in the roller rig experiment. Another factor which may have influenced the physiology results of the rolling road rig is that the friction from the belt acts as a resistive force to the rider. This resistive force is calculated to be the equivalent of cycling up a 7.3 degree slope, or into a head wind of 11.4 m/s. This allows the experiments on the rolling road rig to be directly comparable to those conducted by MacRae et al. (2000) whose experiments involved cyclists riding uphill on a rough terrain.

The experiments on the rolling road rig also showed that no significant difference was found between cycling on the fully suspended bike or the hardtail bike on a smooth road. This finding agrees with the results from research carried out by Berry et al. (1993); Ishii et al. (2002); MacRae et al. (2000); Nielens & Lejeune's (2001); Seifert et al. (1997); Titlestad et al. (2006); and Wang and Hull (1996); all of whom also found that there was no significant difference between suspension systems in regards to the amount of $VO_2$ and heart rate measured when cycling on a flat surface. Similar to the experiments conducted on the rough surface, a possible reason as to why no difference is apparent between both bikes when cycling on the smooth surface is that the added friction of the belt provides a resistance to the cyclist which is equivalent to cycling uphill. Therefore, once again, the most suitable comparison can be made between the current results and those obtained from MacRae et al's (2000) study.

The difference recorded for $VO_2$ levels for cycling on the rolling road rig with a smooth surface was found to be 2 % less for the hardtail bike compared to the fully suspended bike; this result however, was not statistically significant. A similar result was obtained for heart rate: subjects cycling on the hardtail bike had, on average, a 1 % lower heart rate compared to when cycling on the fully suspended bike on the smooth surfaced rolling road rig. However, this result was also found to be statistically insignificant.

The psychology results obtained from cycling on the rolling road rig with a smooth surface differ from the physiology results: a 4 % lower RPE value was recorded for subjects cycling on the fully suspended bike compared to the hardtail bike. Subjects also rated the fully suspended bike to be twelve percent more comfortable to ride on the smooth surface, in comparison to the hardtail bike. However, both RPE and comfort rating results were deemed statistically insignificant. As the physiology and psychology results highlighted no significant difference between the hardtail and fully suspended bike on the rolling road rig, an analysis of the mechanical results was undertaken to investigate if the mechanical measurements highlighted any differences between the two bikes.

The mechanical measurements were recorded during the experiments on the rolling road rig, and subsequently compared to the physiological and psychological data. Chapter Five displays the results of the mechanical data obtained from the rolling road rig experiments in tabulated form (raw data can be viewed in Appendix B). The force the rider exerts on the crank demonstrates the power, and energy required by each suspension system to remain at a constant velocity; this can be directly compared to the subjects' $VO_2$ and heart rate levels. The average force exerted on the pedals of the hardtail bike is 3.9 % less than that exerted on the pedals of the fully suspended bike on a smooth road - a statistically significant result. Similarly, both the average maximum and minimum force exerted on the crank of the hardtail bike is lower, by 2.9 % and 3.5 % respectively, compared to that exerted on the crank of the fully suspended bike; two results which are statistically significant. These findings (Table 5-9) demonstrate that, on average, additional force is required by the rider on the fully suspended system to maintain the bike at a constant speed on a flat road.

In comparison, the experiments on the rolling road rig with a rough surface show that the force exerted on the crank of the fully suspended bike is less than that amount exerted on the crank of the hardtail bike. However, this result is not statistically significant. In comparison, the results for the amount of force exerted on the crank for the experiments on the roller rig with a rough surface indicate that the average force required for the hardtail bike is on average, 38.36 % greater than that required for the fully suspended bike (Table 4-5; Chapter 4), this result is statistically significant. A possible reason for this could be that the bumps on the roller rig are more severe than those on the rolling road, and thus highlight a greater difference between the bikes.

The amount of power applied to the crank was calculated through multiplying the crank torque by the rotational velocity. On the smooth track of the rolling road rig, the hardtail system indicated a 3.5 % lower mean power than the fully suspended bike; a result deemed statistically significant due to the low p value. This highlights that the hardtail bike offers an improvement, in terms of the amount of power required to remain at a constant speed, on a smooth road compared to the fully suspended bike. On the contrary, it was the fully suspended bike which indicated a 0.7 % lower mean power than the hardtail bike- this time on the rough track. This result however, is not statistically significant. Comparable results obtained from the amount of power exerted through the crank on the roller rig (Table 4-4; Chapter 4) illustrate that more power is required to cycle on the hardtail bike compared to the fully suspended bike when travelling on the rough surface.

The results obtained for the amount of power applied to, and the force exerted on the crank provide valuable data verifying that a subject uses less force, and in turn power, when cycling on the hardtail bike compared to the fully suspended bike on a smooth surface. This finding highlights the benefits of measuring the amount of power and force exerted by the subjects on the pedals of the bikes as it is a more accurate means of distinguishing the differences between cycling on the two bikes. This difference could not be ascertained through studying the subjects' physiology and psychology alone.

Additional points of interaction between the bike and rider studied in detail in the rolling road rig experiments, in addition to the pedals, are the saddle and handlebars. The average range in the amount of force exerted on the saddle highlights a considerable variation between the hardtail and fully suspended bike on the smooth surface (Table 5-10; Chapter 5). Despite the finding that no statistical difference is apparent between the two bikes for the amount of average force exerted on the saddle whilst cycling on the smooth surface, a significant difference is highlighted between the maximum and minimum amount of force exerted on the seat of the bikes, thus indicating that the variation in force is far greater on the fully suspended bike when cycling on the smooth surface on the rolling road rig. This could be a result of the bobbing effect experienced when pedalling. A lower minimum force is measured (Table 5-10; Chapter 5) whilst cycling on the hardtail bike on the rolling road rig with bumps attached. The force range exerted on the saddle was also found to be 33.6 % less whilst cycling on the fully suspended bike on the bumpy surface.

The results pertaining to the vertical and horizontal force exerted on the handlebars of the hardtail and fully suspended bike whilst cycling on the rolling road rig were also analysed. The recorded measurements were: the vertical force exerted on the right and left handlebar of both bikes; and the horizontal force exerted on the right and left handlebar of both bikes. All subjects were instructed to keep their hands placed on the handlebars for the duration of the tests - with the exception of when indicating RPE and comfort scale ratings- where the grip was released for a short time period only.

The results highlight that, although a greater average vertical force is exerted on the handlebars of the hardtail bike, the amount of force exerted on the handlebars of the fully suspended bike fluctuates more due to the rear suspension, thus indicating that a bobbing effect may be apparent when cycling on the hardtail bike.

The results obtained from the measurement of the amount of vertical force exerted on the handlebars of the hardtail, compared to the fully suspended bike whilst cycling on the rough track, produced no statistically significant results. As these results are statistically insignificant this indicates that there is little difference between the hardtail and fully suspended bike when considering the amount of vertical force exerted on the handlebars whilst cycling on the rough track. This is due to both bikes having a front suspension system, therefore it is expected that the same amount of force is exerted on the handlebars for both bikes.

The horizontal force exerted on the handlebars represents the force exerted between the frame of the rolling road rig and the bike. The results obtained for the amount of horizontal force exerted on the handlebars of the hardtail and fully suspended bike are displayed in Table 5-13 and 5-24; Chapter 5. The results highlight that the average horizontal force exerted on the handlebars is greater for the fully suspended bike compared to the hardtail bike for cycling on a smooth surface. In contrast the results obtained for the amount of horizontal force exerted on the handlebars of the hardtail and fully suspended bike on the rough surface indicates that there is no significant difference between the bikes. The results do indicate that a greater range is apparent on the hardtail bike, indicating that that the fully suspended bike provides an advantage to the rider over the hardtail bike.

Accelerometers were used during experimentation on the rolling road rig to ascertain the movement of the hardtail and fully suspended bikes and to establish how this in turn affects rider performance. The results obtained from measuring the acceleration of the handlebars are illustrated in Table 5-15; Chapter 5. The RMS value is given to provide a representation of the average acceleration. All of the results pertaining to the acceleration of the handlebars when cycling on the smooth road of the rolling road rig are statistically significant and indicate that less acceleration occurs at the handlebars of the fully suspended bike, compared to the hardtail bike. Analysis of individual's results show that all subjects obtained similar handlebar acceleration values to the averages that are displayed in Table 5-15; Chapter 5.

From obtaining the values for saddle and handlebar acceleration, the velocity of the handlebars and saddle of the hardtail and fully suspended bike could be ascertained. The results obtained from calculating the velocity at the handlebars of both bikes whilst cycling on the smooth road (Table 5-18) all suggest that less velocity occurs at the handlebars of the fully suspended bike compared to the hardtail bike. However, the RMS result relating to the difference in average handlebar velocities of both bikes when cycling on the smooth road - suggesting that the fully suspended bike presents an advantage to the rider - is statistically insignificant. This highlights a difference between the results recorded for handlebar velocity and the results recorded for handlebar acceleration: the results relating to handlebar acceleration were all statistically insignificant, with the exception of the results for RMS, which highlight a significant difference between the two suspension systems.

The comparable dynamic simulation results (Figure 7-29; Chapter 7) indicate that the fully suspended bike has a similar handlebar velocity to the hardtail bike. Once again, the reason that the dynamic simulation results do not highlight a significant difference between the bikes is that the dynamic model is not complex enough to detect slight differences.

The results relating to the velocity of the saddle of the hardtail and fully suspended bikes (Table 5-18) show similar results to those obtained from measuring the velocity at the handlebars of both bikes. The results obtained from calculating the velocity of the saddle of both the hardtail and fully suspended bike when cycling on the smooth road on the rolling road rig show that the seat of the hardtail bike has a greater velocity than that of the fully suspended bike.

In comparing these results to those obtained from the dynamic simulation of the rolling road rig, it is evident that the results for saddle velocity are significantly higher for the experimental results on the rolling road rig. The results for saddle velocity obtained during the dynamic simulation (Figure 7-31; Chapter 7) also highlight that the hardtail bike exerts a higher velocity compared to the fully suspended bike, yet the velocity values are lower during the simulation.

The saddle and handlebar displacements are calculated from the results obtained from the accelerometers placed at the front and rear of the bikes. Through analysis of the handlebar displacement results for cycling on the smooth road (Table 5-20), it is apparent that these results do not highlight a significant a difference between the hardtail and fully suspended bikes as the results for the acceleration and velocity of the handlebars. The results indicate that less displacement occurs at the handlebars of the fully suspended bike compared to the hardtail bike - although these findings are all statistically insignificant.

The findings illustrated in Figures 5-67 and 5-68 can be compared to those obtained from the dynamic computer simulation. Figure 7-21 (Chapter 7) displays the vertical displacement at the front accelerometer of both the hardtail and fully suspended bike whilst cycling on the rolling road rig with a smooth surface. The results indicate that the fully suspended bike presents a higher displacement at the handlebars than the hardtail bike; the opposite is true for the experimental results on the rolling road rig. Additionally, the results for the displacement of the handlebars during the experiments on the rolling road rig are considerably higher than the results obtained through simulating the same experiment. This is perhaps surprising as the results for the displacement of the handlebars obtained from the experiments on the roller rig were found to be similar to the handlebar displacement results obtained through the simulation of the same experiment. One reason for the discrepancy between the experimental rolling road rig and simulation results may be that the simulated model has a smaller variation in power exerted through the crank, which in turn may present less bobbing (and less displacement of the handlebars) on a smooth surface compared to the experiments. Another possible reason is that the complex tyre model used in the DADS simulation differs from the tyres of the bike used for the experiments on the rolling road rig. Yet another factor which may present a discrepancy between the results is that the simulation model is two-dimensional and does not consider the lateral movement of the cyclist - a consideration which may significantly affect the handlebar displacement results. Yet another reason for the differing results may be attributed to the added resistance present during the experimental rolling road rig tests.

In contrast to the results obtained from the displacement of the handlebars whilst cycling on the smooth road, the results for the displacement of the handlebars whilst cycling on the rough road highlight that the average displacement is greater for subjects cycling on the fully suspended bike. When comparing the results for the handlebar displacement obtained through the experiments on the rolling road rig on the rough surface (Table 5-20; Chapter 5) to those obtained from the dynamic simulation tests (Figure 7-28; Chapter 7), it was found that the simulation tests produced greater displacement values than the experiments. The average maximum displacement of the handlebars of both the hardtail and fully suspended bikes for the simulation tests was 32 mm, compared to the handlebar displacement results during the experiments which were recorded to be 30 mm and 28.7 mm for the hardtail and fully suspended bike respectively. Once again a possible reason for this is that the tyre of the bike used during the experiments absorbs more of the impact when the tyre hits the bump compared to the simulation tyre model.

The results obtained for saddle displacement accurately highlight the effect of bobbing when cycling. The results for cycling on the rolling road rig on the smooth road indicate that less displacement of the saddle occurs when cycling on the fully suspended bike compared to the hardtail bike (Table 5-19; Chapter 5). Although the results are all statistically insignificant, suggesting that the results for velocity and acceleration are a more valid means of highlighting differences between the two bikes, the results are still meaningful to the discussion.

These results can again be compared to the dynamic simulation of the rolling road rig: the dynamic simulation results display a saddle displacement of 0.76 mm for the fully suspended bike and indicate that no displacement of the saddle occurs on the hardtail bike (Figure 7-22; Chapter 7). The dynamic simulation results for saddle displacement contradict those found during the experiments on the rolling road rig. This suggests that there is more rider movement than that which is simulated in the dynamic computer model, suggesting that the rider and tyre model of the dynamic simulation may not be complex enough to accurately simulate a rider on the rolling road rig.

The experimental results for saddle displacement obtained from the rolling road rig on the rough track conflict with those obtained from the dynamic simulation (Figure 7-30; Chapter 7). The dynamic simulation results indicate that the hardtail bike has a greater maximum saddle displacement (24.3 mm) compared to the fully suspended bike (24.2 mm). Conversely, the results for the rolling road rig on the rough surface indicate that the fully suspended bike has a greater maximum saddle displacement (43.3 mm) compared to the hardtail bike (39.9 mm). In contrast to these two sets of results, the roller rig produced maximum saddle displacements of 11 mm and 10 mm for the hardtail and fully suspended bike respectively. It is not a surprising result that the displacement values are considerably lower for subjects on the roller rig as the bikes were attached to the rig. The roller rig's movement is restricted as there is no front wheel incorporated into the design and the front axle is fixed to the roller rig, thus less displacement of the saddle can occur.

The subjects' physiology and psychology results obtained from the rolling road rig experiments (Chapter 5) highlight that, on both the rough and smooth track, only small differences are found between the bikes compared to the results obtained from the experiments conducted on the roller rig. A statistically significant difference was found between both bikes for results pertaining to RPE recorded while cycling on a rough track - this was measured to be 1.5 higher for the fully suspended bike. All additional physiology and psychology results obtained from cyclists on both the smooth and rough track were statistically insignificant.

The mechanical results highlight statistically significant differences between the bikes on the rolling road with the smooth surface: pedal power (3.5 % more power is required on the fully suspended bike); vertical force exerted on the handlebar (21 % and 11.7 higher vertical force for the hardtail bike on the left and right handlebar respectively); horizontal force exerted on the handlebar (35.7 % and 15.9 % higher horizontal force for the fully suspended bike on the left and right handlebar respectively); handlebar acceleration (38.4 % higher for the hardtail bike); and seat acceleration (38.3 % higher for the hardtail bike). These results signify that the rear suspension affects the forces acting on the bike when cycling on a smooth surface. The most significant result indicates that less power is required to cycle the hardtail bike compared to the fully suspended bike. This result is not shown when comparing the physiological results; however, this could explain the higher rating for RPE when cycling on the fully suspended bike.

Similar to the results obtained from testing on the rolling road rig with a smooth surface, the physiology and psychology results obtained from subjects cycling on the rough surface (Chapter 5) indicate that there is no significant difference between the hardtail and fully suspended bike. Conversely, the mechanical results obtained through experimentation on the rolling road with the rough surface highlight significant differences between the two bikes: horizontal force exerted on the handlebar (26.6 % and 6.8 % higher horizontal force for the fully suspended bike on the left and right handlebar respectively); handlebar acceleration (35.9 % higher for the hardtail bike); seat acceleration (35.9 % higher for the hardtail bike). Although only four of the mechanical results are statistically significant, the results indicate that the fully suspended bike offers an advantage to the rider as there is a substantially lower acceleration recorded at the front and rear of the bike.

The results pertaining to the sub-maximal indoor track test were conclusive: all physiological and psychological measurements highlight that the fully suspended bike presents an advantage to the rider, in terms of rider performance, compared to the hardtail bike. This is supported by the statistical analysis of the results (Table 4-3; Chapter 4) which highlights that all results yielded a p value of less than 0.05, thus rendering all of the results statistically significant. . The differences that were recorded are: $VO_2$ (1.2 ml/kg/min higher for the hardtail bike); heart rate (3.9 beats/min higher for the hardtail bike); RPE (1.2 higher for the hardtail bike) and comfort rating (1.1 less comfortable for the hardtail bike).

The results for heart rate (Figure 4-8; Chapter 4) and RPE (Figure 4-9; Chapter 4) were lower for all ten subjects cycling on the fully suspended bike, compared to the hardtail bike. All ten subjects participating in the indoor track tests also gave higher (5 being the most comfortable) comfort ratings (Figure 4-10; Chapter 4) when cycling on the fully suspended bike, indicating that the subjects perceived this bike to be more comfortable than hardtail bike.

Interestingly, nine out of the ten subjects recorded a lower $VO_2$ level (Figure 4-7; Chapter 4) when cycling on the fully suspended bike compared to the hardtail bike. A possible reason for one subject obtaining a higher $VO_2$ level on the fully suspended bike than the other results is that the subject who recorded this result experienced considerably more bobbing than the other subjects. This may have been a result of the subject's weight: the suspension was configured for a rider weighing 70 kg - the subject weighed 85 kg, a factor which may have promoted a bobbing effect. Yet another possible reason for the result anomaly could be attributed to the riding style of the individual subject.

As the experiments on the indoor track measured only the subjects' $VO_2$, heart rate, RPE and comfort ratings, only these results could be compared to those obtained from the roller rig and rolling road rig. The results obtained from the indoor track tests all concur with those obtained from the experiments on the roller rig, where each subject recorded a lower $VO_{2,}$ heart rate, RPE, and higher comfort rating whilst cycling on the fully suspended bike compared to the hardtail bike. This is an unsurprising result as both experiments were conducted on a flat surface with bumps with cyclists cycling at approximately the same constant speed (10.5 km/h for the track test and between 10 km/h and 15 km/h for the roller rig respectively). Despite the two differing forms of experimentation, both the experiments on the roller rig and indoor track indicate that the fully suspended bike presents an advantage to the cyclist over the hardtail bike when cycling on a rough surface. This suggests that there is a real significant difference between cycling on these two bikes.

The experiments on the roller rig however, highlight a greater difference between cycling on the hardtail compared to the fully suspended bike than the results from the track test. This greater difference is due to the greater frequency and magnitude of the bumps used for the tests on the roller rig. The bumps used for the roller rig experiments measured 7 cm by 3 cm and the bump was a rectangular block, compared to the bumps of dimension 3 cm by 3 cm with rounded edges used for the indoor track tests. One bump was placed on the roller rig every metre in comparison to the one bump which was placed on the indoor track every 3 m. This greater frequency and magnitude of the bumps on the roller rig results in the bikes on this rig being subjected to greater vibrations, which in turn highlights greater differences between the two bikes.

In contrast to the results obtained from the roller rig experiments, those obtained from the rolling road rig experiments on the rough surface do not concur with the results from the indoor track tests. The results for $VO_2$, heart rate, RPE and comfort rating for subjects on the rolling road rig on the bumpy track (Table 5-4; Chapter 5) do also indicate that, on average, the fully suspended bike presents an advantage to the rider compared to the hardtail bike. However, these physiology and psychology results obtained from the rolling road rig are all statistically insignificant. The reason for the discrepancy between the results obtained from the rolling road rig experiments and the indoor track tests is that an additional force acts against the cyclist on the rolling road rig due to the friction of the belt; a reason for this may be due to the effort required to overcome the effects of friction dominates the results meaning that the difference between the bikes is insignificant in comparison. As the indoor track test has no resistance, the results therefore conflict with those obtained from the rolling road rig.

Another explanation for the difference in the results could be that the added resistance equates to the resistance by gravity when cycling uphill. MacRae et al. (2001) conducted experiments on a rough track with subjects cycling uphill and found that riding uphill on a bumpy surface highlights no difference between the hardtail and fully suspended bike as the added resistance whilst cycling uphill affects the function of the suspension. This may also account for the reason why MacRae et al's (2001) research results and the results of the indoor track test produced contrasting findings despite both experiments being conducted in field test environments.

Similarly, the results from the indoor track test conflict (with the exception of all of the results for comfort rating being higher for cycling on the fully suspended bike) with those obtained from Seifert et al's (1997) field test. Similar to Seifert et al. (1997), MacRae et al. (2001) also found that no significant difference is evident between the hardtail and the fully suspended bike for measurements of heart rate, $VO_2$, and RPE. A possible reason for the discrepancy between these results and the indoor track test results is that the type of rear suspension system used for testing may not have been as effective as the suspension system used for the indoor track test. Another possible reason relates to the speed and duration of the experiments: Seifert et al's (1997) subjects were instructed to cycle at a speed of 16.1 km/h over a period of 63 min, compared to the 12 mi at a speed of 10.5 km/h for subjects conducting the indoor track tests. A possible explanation for the variation in results may be attributed to the fact that a higher speed may cause the cyclist's energy to be dissipated through the rear suspension due to a bobbing effect.

Ishii et al. (2002) also conducted field tests on a rough surface to ascertain the benefits of cycling on a bike with a rear suspension. The single measurement taken during the study which is comparable to those taken during the indoor track tests is that of $VO_2$. In contrast to the results obtained during the indoor track tests, Ishii et al. (2002) found that subjects cycling on the fully suspended bike recorded higher levels of $VO_2$ compared to those cycling on the hardtail bike. A possible reason for this is that Ishii et al's (2002) experiment (as with MacRae et al., 2000) was conducted with subjects cycling at a higher speed (cycling as fast as possible) and the course consisted of both ascending and descending sections.

# 9. Conclusion and Future Work

## 9.1. Physiological and Psychological Effects

The physiological and psychological results from the sub-maximal experiments on both the roller rig and the indoor track both show that at a constant speed, when cycling over frequent, regular bumps, the fully suspended bike presents a significant advantage over the hardtail bike in terms of $VO_2$, heart rate, RPE and comfort rating. These findings indicate that a fully suspended bike improves rider performance on rough tracks through reducing the amount of energy expended by the cyclist.

The physiology and psychological results obtained from the sub-maximal tests on the rolling road rig with bumps, and no bumps, both highlight that when cycling at a constant speed, no significant difference is apparent between the hardtail and fully suspended bike in terms of energy efficiency - measured in terms of a subject's $VO_2$, heart rate, RPE and comfort rating levels. The findings from the rolling road rig indicate that neither the hardtail nor the fully suspended bike improves rider performance on a rough or smooth track.

## 9.2. Mechanical Effects

### 9.2.1. Experimental Results

The mechanical results from the roller rig sub-maximal experiments show that whilst cycling at a constant speed over frequent, regular bumps, the fully suspended bike presents a significant advantage to the rider in comparison to the hardtail bike. The results pertaining to the power through the crank; force exerted on the crank; saddle and handlebar acceleration; saddle and handlebar velocity; and saddle and handlebar displacement are significantly lower for the fully suspended bike compared to the hardtail bike. This finding indicates that the fully suspended bike presents the rider with an advantage over the hardtail bike when cycling over a rough surface.

The mechanical results obtained from the tests conducted on the rolling road rig with bumps attached show that when cycling at constant speed over frequent, regular bumps, no significant difference is found between cycling on the hardtail or the fully suspended bike. The results relating to the power through the crank; velocity and force of the crank; force exerted on the handlebars and saddle; saddle and handlebar velocity; and saddle and handlebar displacement, all illustrate that no significant difference is evident when cycling on either the hardtail or fully suspended bike. During the rolling road rig tests with bumps, a slight advantage was observed for the hardtail bike in terms of the amount of horizontal force exerted on the handlebars of the bikes; however, this difference is slight. A slight advantage was also recorded for the fully suspended bike for results pertaining to handlebar and saddle acceleration, but once again, the difference recorded for these acceleration measurements were small. The mechanical findings obtained from the tests on the rolling road rig with bumps indicate that no difference is noticeable between the hardtail and fully suspended bike when cycling on a rough track with bumps of this magnitude and frequency.

The mechanical results calculated from the experiments on the rolling road rig with no bumps are varied. The results indicate that whilst cycling at a constant speed on a flat surface no difference is apparent between the hardtail and fully suspended bike for results pertaining to the crank, handlebar and saddle velocity; force exerted on the saddle; and handlebar and saddle displacement. During the experiments on the rolling road rig with no bumps there was a slight advantage for the fully suspended bike in regards to the amount of vertical force applied to the handlebars, and for saddle and handlebar acceleration. For the same experiment, there was a slight advantage for the hardtail bike in terms of the amount of force exerted on the crank; the amount of horizontal force exerted on the handlebars; and the power through the crank.

### 9.2.2. Simulation Results

The dynamic simulation of the roller rig produced similar results to the experimental roller rig results, indicating that, in this instance, a dynamic computer simulation aids in the understanding of test results. The results obtained from the dynamic simulation of the roller rig on a smooth surface indicate that at a constant speed, the hardtail bike provides a slight advantage over the fully suspended bike in terms of rider performance. The results show that there is no displacement of the handlebars, saddle, rider or front suspension, and no variation in the amount of force transmitted by the front suspension whilst cycling on the hardtail bike on the roller rig with a smooth surface. In comparison, a slight displacement is recorded at the handlebars, saddle, front suspension and rider, in addition to a slight variation in the amount of force transmitted by the front suspension, when cycling on the fully suspended bike. These findings indicate that the hardtail bike improves rider performance on a flat surface in comparison to the fully suspended bike.

The results from the dynamic simulation model of the roller rig with bumps indicate that whilst cycling at a constant speed, the fully suspended bike provides an advantage to the rider over the hardtail bike. Despite the handlebar displacement being similar for both bikes, the saddle, front suspension and rider displacement; handlebar, saddle, and rider velocity; and the amount of force transmitted through the front suspension, are all lower for the fully suspended bike in comparison to the hardtail bike. These findings indicate that a fully suspended bike can improve rider performance on rough tracks.

The dynamic simulation of the rolling road rig produced varied results from those obtained during the rolling road rig experimental results. The results from the dynamic simulation of the rolling road rig with no bumps show that at a constant speed, the hardtail bike provides a slight advantage over the fully suspended bike. The hardtail offers an advantage evidenced by lower handlebar, saddle and rider displacement values. The displacement of, and the force transmitted through, the front suspension is lower for the fully suspended bike; this is however, only slightly lower than that of the hardtail bike. These results indicate that a hardtail bike has an advantage over a fully suspended bike during the simulation of the rolling road rig with a smooth surface.

Conversely, the results from the simulation of the rolling road rig with bumps indicate that, at a constant speed, the fully suspended bike offers a significant advantage over the hardtail bike. The findings for the displacement of, and the resultant force transmitted through, the front suspension, are lower for the hardtail bike. However, the results pertaining to handlebar, saddle and rider displacement; and rider, saddle and handlebar velocity, are all lower for the fully suspended bike, indicating that this bike type, compared to the hardtail bike, provides an advantage to the rider on a rough track.

## 9.3. Correlation of Results

### 9.3.1. Physiology and Psychology Results

The physiology and psychology results obtained from the experiments on the roller rig and the indoor track correlate well, with both sets of results producing lower $VO_2$, heart rate, RPE and higher comfort ratings levels for subjects cycling on the fully suspended bike on rough terrain. On the contrary, the physiology and psychology results obtained from the experiments on the rolling road rig indicate that there is no significant difference between the hardtail and fully suspended bike for $VO_2$, heart rate, RPE and comfort rating, despite subjects experiencing the same frequency and magnitude of bumps as those encountered on the straight sections of the track test. This indicates that when there is greater resistance (equivalent to that of riding uphill), as experienced by cyclists on the rolling road rig due to the added friction caused by the belt of the rig, a fully suspended bike does not present any significant advantage to the rider - as it does when cycling on the indoor track.

### 9.3.2. Mechanical and Simulation Results

The mechanical results obtained from the roller rig correlate with those obtained during the simulation of the roller rig with bumps. All of the experimental and simulation results obtained from the measurements recorded at the crank, saddle, handlebars, front suspension and rider, are significantly lower for the fully suspended bike.

There is, however, a lack of correlation between the experimental mechanical results and the simulation results obtained from the smooth surfaced rolling road rig. The handlebar displacement is greater for the fully suspended bike during the dynamic simulation tests, yet this displacement is only slightly greater than that recorded on the hardtail bike. The experimental mechanical results show that there is no significant difference between the bikes in terms of handlebar displacement. The results for saddle displacement obtained during the dynamic simulation highlight that there is a displacement of the saddle of the fully suspended bike, with no displacement occurring at the saddle of the hardtail bike. Conversely, the rolling road rig experimental results show that there is a similar saddle displacement for both the hardtail and fully suspended bike.

There is also a lack of correlation between the results obtained from the experiments on the rolling road rig with bumps and the results from the simulation of the rolling road rig with bumps. The simulation results pertaining to handlebar displacement signify that the fully suspended bike has a lower displacement, but once again, this difference is only slight. The experimental results indicate that the handlebar displacement is greater for the fully suspended bike. The results for saddle displacement show a greater displacement for the hardtail bike during the dynamic simulation, whilst no difference is apparent between the two bikes when considering the displacement of the saddle during the experimental results. Once more, the discrepancies between the experimental and simulation results may be attributed to the added resistance experienced by subjects conducting tests on the rolling road rig. This added resistance equates to the resistance of cycling uphill; the dynamic simulations, however, simulate a cyclist on the rolling road rig with bumps on a flat surface only, thus attributing to the conflicting results. The conflicting results are due to the added resistance being the overriding factor over the effect of cycling over bumps, therefore the differences between the two bikes is less defined. This highlights that cycling on a fully suspended bike provides an advantage to a cyclist on rough ground as demonstrated from the results of the roller rig and indoor track. Whereas no significant difference was found between the bikes when there is an added resistance as was the case on the rolling road rig.

### 9.3.3. Physiology, Psychology and Mechanical Results

The differences measured between the fully suspended and hardtail bike for the physiology and psychology results of $VO_2$, heart rate, RPE and comfort rating obtained during the experiments on the roller rig correlate well with the mechanical results of power through, and force exerted on, the crank; and saddle and handlebar acceleration, velocity and displacement. The physiology and psychology results show that subjects exert less energy whilst cycling on the fully suspended bike, thus improving rider performance. Correspondingly, less power is required by the subject to cycle at a constant speed, and fewer vibrations are felt whilst cycling on the fully suspended bike.

The physiology and psychology results of $VO_2$, heart rate, RPE and comfort rating obtained during the rolling road rig tests on a rough surface, correlate well with the mechanical results pertaining to the amount of power through the crank; force exerted on the crank and saddle; vertical and horizontal force exerted on the handlebars; crank, handlebar and saddle velocity; and handlebar and saddle acceleration and displacement. The physiology, psychology and mechanical results do not highlight any significant differences between the hardtail and fully suspended bikes.

There is a further correlation between the physiology and psychology results of $VO_2$, heart rate, RPE and comfort rating, and the mechanical results of saddle, handlebar and crank velocity; force exerted on the saddle; and saddle and handlebar velocity obtained during the experiments on the rolling road rig with a smooth surface. These results all indicate that there is no significant difference between the hardtail and fully suspended bike. There is, however, a lack of correlation between the physiology and psychology results and the mechanical results of power through the crank; the force exerted on the crank; and the horizontal force exerted on the handlebars - all of which are lower for the hardtail bike compared to the fully suspended bike.

Additionally, the mechanical results of vertical force exerted on the handlebars; and handlebar and saddle acceleration, do not correlate with the physiology and psychology results. It is, however, important to note that the differences between the hardtail and fully suspended bikes recorded during the experiments on the rolling road with a smooth surface are slight. The most notable difference is between the physiology and psychology results and mechanical result relating to the amount of power exerted through the crank. The results of $VO_2$, heart rate, RPE and comfort rating all indicate that no significant difference is apparent between cycling on the hardtail and fully suspended bike, indicating that no more energy is exerted on one bike compared to the other. However, the mechanical result pertaining to the mean power transmitted through the crank is lower for the hardtail bike, indicating that less energy is required to cycle on the hardtail bike compared to the fully suspended bike.

The current study has shown that the roller rig can be used to isolate rear wheel dynamics and produces consistent results, which correlate well with the dynamic simulations. The rolling road rig not only allowed the rear wheel dynamics to be considered, but also investigated front wheel dynamics, thus providing a more realistic representation of true riding conditions. However, as aforementioned, due to the added friction caused by the rig belt, the rolling road rig was representative of a cyclist riding uphill, and for this reason there is less correlation between the rolling road rig experimental and simulation results. Although no difference was highlighted between either bike for the rider's physiology and psychology measurements when cycling on the rolling road rig with no bumps, less power was exerted through the pedals of the hardtail bike, compared to the fully suspended bike. This finding suggests that when cycling with added resistance (as experienced on the rolling road rig) on a smooth surface, the hardtail bike performs better than the fully suspended bike.

The experiments conducted on the rolling road rig with bumps provided results which showed no difference between the bikes with regards to the physiology, psychology, and mechanical results, highlighting that neither bike provides an advantage to the cyclist when cycling on a track with the equivalent magnitude and frequency of bumps, and added resistance, as experienced on the rolling road rig.

The indoor track tests highlighted a difference between the hardtail and fully suspended bikes for subjects cycling on this track with the same bump magnitude and frequency as the rolling road, thus highlighting that it was the added friction which prevented a difference being apparent between the bikes on the rolling rig. The indoor track test provided yet a more realistic means of testing and closely represented true riding conditions; however, mechanical aspects were not measured during the tests as it proved impractical to attach additional instrumentation to the subject and bike.

The dynamic simulation models have shown that there are definite uses for simulations in future research in terms of optimising suspension systems and the design of new testing instrumentation. All of the results from the experimental roller rig, rolling road rig, indoor track and dynamic simulations provide interesting results which can be used for further research into suspension systems.

## 9.4. Future Work

Further research is necessary in order to further improve understanding of how rear suspension systems impact on rider performance. This requires further experimentation on the rolling road rig at a maximal testing level under race conditions, where subjects are instructed to cycle as fast as possible as would be in true race conditions. Furthermore, the subjects should have no restrictions on rider style as is also true of real race conditions. A more accurate form of recording rider movement is necessary for the reconstruction of movement kinematics for differing riding styles. The control exerted by the rider over the bike is likely to prove a critical factor and further research should explore whether particular riding styles need to be adopted to realise the best performance from different types of bike; whether these can be categorised and whether riders can optimise their riding technique through training.

In addition to the physiology and psychology measurements of $VO_2$, heart rate, RPE and comfort ratings, lactate levels should be recorded during the maximal tests; this can be identified by either blood sampling or from gas exchange data. Further maximal testing on the rolling road rig would allow the effect of the rear suspension to be investigated under conditions which have equivalent speeds and riding styles to those in race conditions.

A new indoor track test should be developed which incorporates sections of varying terrain with bumps of different magnitudes and frequencies. In addition to this, both uphill and downhill sections should be implemented in order to investigate the effects of rear suspension whilst cycling under these conditions. Instrumentation should be attached to the bike during testing which record the mechanical measurements in order to investigate the effects of the varying terrain on the bikes. It would be beneficial to also investigate the effects that different types of rear suspension has on rider performance and not limit research to one particular rear suspension design.

A clear link has emerged between conducting experiments and validating results with the aid of dynamic computer simulations.  With this in mind, further, more complex, dynamic simulations should be run which simulate a more complex model of a rider to research in greater detail how rider interaction affects suspension systems.

# 10. References

Anon. (1992) Suspension vs. Ridged, Mountain Bike Action, Volume 7, Number 4: 28-40.

Astrand PO and Rodahl K. (1986) Textbook of Work Physiology, 3rd Edition, Singapore, McGraw-Hill.

Berry M, Woodard C, Dunn C, Edwards D and Pittman C. (1993) The effects of a mountain biking suspension system on metabolic energy expenditure, Cycling Science, spring issue: 8-14.

Berry M, Koves TR and Benedetto JJ. (2000) The influence of speed, grade and mass during simulated off road bicycling, Applied Ergonomics, Volume 31, Issue 5: 531-536.

Borg GAV. (1982) Psychophysical bases of perceived exertion and pain scale. Medicine & Science in Sports & Exercise, Volume 14: 377-81.

Bu Y, Xiang ZX and Huang T. (2009) Optimal design and dynamic simulation of mountain bike with rear suspension, Chinese Journal of Mechanical Engineering, Volume 22, Number 1: 21-26.

Burke. (1996) High Tech Cycling, Human Kinetics, Champaign, 45-64.

Champoux Y, Vittecoq P, Maltais P, Auger E, and Gauthier B. (2004) Measuring the dynamic structural load of an off-road bicycle frame, Experimental Techniques, Volume 28, Issue 3: 33 - 36

Chandler RF, Clauser CE, McConville JT, Reynolds HM, and Young JW. (1979) Investigation of inertial properties of the human body, Aerospace Medical Research Laboratory, Report No. DOT HS-801430.

Clarkson PM, Litchfield P, Graves J, Kirwan J and Byrnes WC. (1985) Serum creatine kinase activity following forearm flexion isometric exercise, European Journal of Applied Physiology, Volume 53: 368-71.

De Lorenzo DS, Wang EL and Hull ML. (1994) Quantifying off road suspension hub stiffness, Cycling Science, Volume 3: 12-26.

De Lorenzo DS and Hull ML. (1999) Quantification of structural loading during off-road bicycling, Journal of Biomechanical Engineering, Volume 121: 339-405.

Demchak TJ and Linderman JK. (1999) Ultra Endurance Cycling: A Field Study of Human Performance During A 12 Hour Mountain Bike Race, Medicine & Science in Sports & Exercise, Volume 31, Issue 5: S107.

Fordham S, Garbutt G and Lopes P. (2004) Epodemology of injuries in adventure racing athletes, British Journal of Sports Medicine, Issue 38: 300-303.

Fregly BJ, Zajac FE, and Dairaghi CA. (2000) Bicycle Drive System Dynamics: Theory and Experimental Validation, Journal of Biomechanical Engineering, Volume 122 Issue 4: 446.

González M, Cuadrado J, González F and Dopico D. (2008) Optimization of an off-road bicycle with four-bar linkage rear suspension, Proceedings of MUSME 2008, the International Symposium on Multibody Systems and Mechatronics, San Juan (Argentina), 8-12 April 2008.

Good C and McPhee J. (1999) Dynamics of Mountain Bicycles with Rear Suspensions: Modeling and Simulation, Sports Engineering, Volume 2: 129-143.

Good C, and McPhee J. (2000) Dynamics of mountain bicycles with rear suspensions: design optimization, Sports Engineering, Volume 3: 49-55.

Gorman D. and Kennedy W. (1998) Applied Solid Dynamics, Butterworth & Co. (Publishers) Ltd. London

Gould D, Dieffenbach K and Moffett A. (2002) Psychological Characteristics and their Development in Olympic Champions. Journal of Applied Sport Psychology, 1533-1571, Volume 14, Issue 3: 172 – 204

Greene PR and McMahon TA. (1979) Reflex stiffness of mans antigravity muscles during knee bends while carrying extra weights, Journal of biomechanics, Volume 12: 881-891.

Harmon D. (2006) The Competitive Mountain bike industry in the UK, University of Warwick.

Harnish C, King D and Swensen T. (2007) Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs, European Journal of Applied Physiology, Volume 99, Number 4: 387-391.

Henderson Me, Morris CT, Fitz-Gibson CT. (1987) How to measure Attitudes. California: Sage.

Hopkins W. (2002) Quantative Research Sport Science, Sports Science, Volume 4, Issue 1.

Howe CR. (1995) Course terrain and bicycle set-up, Cycling Science, Volume 6: 14–26.

Howley ET, Bassett DRJ and Welch HG. (1995) Criteria for maximal oxygen uptake: review and commentary. Medicine and Science in Sports Exercise, Volume 27: 1292–1301.

Hrovat D and Hubbard M. (1981) Optimum vehicle suspensions minimizing rms rattlespace, sprung-mass acceleration and jerk, ASME Journal of Dynamics Systems Measurement and Control, Volume 103: 228–236.

Hrovat D. (1988) Influences of unsprung weight on vehicle ride quality, Journal of sound and vibration, Volume 124, Issue 3: 497-516.

Impellizzeri FM, Sassi A, Rodriguez-alonso M, Mognoni P and Marcora S. (2002) Exercise intensity during off-road cycling competitions, Medicine & Science in Sports & Exercise, Volume 34, Issue 11: 1808-1813.

Impellizzeri FM, Rampinini E, Marcora SM, et al. (2005) Corrolations between physiological variables and performance in high level cross country off road cyclists, British Journal of Sports Medicine, Volume 39: 747-751.

Ishii T, Umerura Y and Kitagawa K. (2003) Influences of mountain bike suspension systems on energy supply and performance, Japanese Journal of Biomechanics in Sports and Exercise, Volume 7: 2-9.

Kane TR and Levinson DA. (1985) Dynamics: Theory and Application, McGraw-Hill, New York.

Karchin A and Hull ML. (2002) Experimental Optimization of Pivot Point Height for Swing-Arm Type Rear Suspensions in Off-Road Bicycles, ASME. Journal of Biomechanical Engineering, Volume 124: 101-106.

Karnopp DC and Margolis. (1984) Adaptive suspension concepts for road vehicles, Vehicle system dynamics, Volume 13, Issue 3: 145-160.

Karnopp DC and Trikha AK. (1960) Comparative study of optimization techniques for shock and vibration isolation, ASME Journal of Engineering for Industry, Volume 91: 1128–1132.

Kooijman JDG and Schwab AL. (2009) Experimental validation of the lateral dynamics of a bicycle on a treadmill, In Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, San Diego, CA.

Kooijman JDG, Schwab AL and Moore JK. (2009) Some observations on human control of a bicycle, In Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, San Diego, CA.

Kukoda J. (1992) Impact eaters, Bicycling, Volume 33, Issue 4: 148-166.

Kyle C. (1990) Chain Friction, Windy Hills and Other Quick Calculations, Cycling Science, Volume 2: 23-26.

Kyle CR. (1991) Ergogenics for bicycling, Lamb, D.R., Williams, M.H. (Eds.), Perspectives in Exercise Science and Sports Medicine, Volume 4: Ergonomics-Enhancement of Performance in Exercise and Sport. Wm. C. Brown, Indianapolis, IN: 373–419.

Leventon W. (1993) Mountain Bike Suspension Allows Easy Adjustment, Design News, July 19, 1993: 75.

Levy M, and Smith GA. (2005) Effectiveness of vibration damping with bicycle suspension systems Sports Engineering, Volume 8, Number 2: 99-106.

Lopes B and McCormack L. (2005) Mastering mountain bike skills, Human Kinetics

MacRae HSH, Hise KJ and Allen PJ. (2000) Effects of front and dual suspension mountain bike systems on uphill cycling performance, Medicine & Science in Sports & Exercise, Volume 32, Issue 7: 1276-1280.

Martin JC, Milliken DL, Cobb JE, McFadden KL, and Coggan AR. (1998) Validation of a mathematical model for road cycling power, Journal of applied biomechanics, Volume 14: 276-291.

McArdle W, Katch F and Katch V. (2001) Exercise physiology: energy, nutrition, and human performance, 4th edition, Williams and Wilkins, London.

Munroe-Chandler KJ. (2005). A discussion on qualitative research in physical activity, Athletic Insight – The Online Journal of Sport Psychology, Volume 7, Issue 1.

Needle S and Hull ML. (1997) An Off-Road Bicycle With Adjustable Suspension Kinematics, ASME. Journal of Mechanical Design, Volume 119: 370-375.

Nielens H and Lejeune TM. (2001) Energy cost of riding bicycles with shock absorption systems on a flat surface. International Journal of Sports Medicine, Volume 22, Issue 6: 400-404.

Nielens H and Lejeune TM. (2004) Bicycle shock absorption systems and energy expended by the cyclist. Sports Medicine, Volume 34, Issue 2: 71-80.

Olsen J. (1992) Bicycle Suspension Systems Meet Mr. Simple Dynamics, Cycling Science, Volume 4: 6-12

Olsen J. (1996) Bicycle Suspension Systems, High- Tech Cycling Human Kinetics, Champaign, IL, USA: 45-64.

Oppenheim AN. (1992) Questionnaire design, interviewing and attitude measurement, London New York, Printer.

Pennestri  and Strozzieri A. (1988) Optimal design and dynamic simulation of a motorcycle with linkage suspension, International Journal of Vehicle Design, Volume 9, Issue 3: 339-350.

Powers SK, and Howley ET. (1990) Exercise Physiology, Wm. C. Brown.

Prins L, Terblanche E, Myburgh K H. (2007) Field and laboratory correlates of performance in competitive cross-country mountain bikers, Journal of Sports Sciences, Volume 25 Issue 8: 927 - 935

Ricci J, and Leger LA. (1983) VO2max of cyclists from treadmill, bicycle ergometer and velodrome tests, European Journal of Applied Physiology and Occupational Physiology, Volume 50: 283-289.

Ryschon TW, and Stray-Gundersen J. (1991) The effect of body position on the energy cost of cycling, Medicine and Science in Sports and Exercise, Volume 23 Number 8: 949-953.

Samuelson B, Jorfeldt L and Ahlborg B. (1989) Influence of Vibration on Work Performance during Ergometer Cycling, Upsala Journal of Medical Sciences, Volume 94 Issue 1: 73 – 79.

Seifert JG, Luetkemeier MJ, Spencer MK, Miller D, Burke ER. (1997) The effects of mountain bike suspension system on energy expenditure, physical exertion, and time trial performance during mountain bicycling. International Journal of Sports Medicine, Volume 18 Issue 3: 197-200.

Sharma HD, Kale SM and UmaShankar N. (2005) Simulation model for studying inherent stability characteristics of autonomous bicycle, Proceedings of the IEEE International conference on mechatronics and automation, Niagra Falls, Canada: 193-198.

Shepard RJ. (1969) Exercise Pysiology and performance of sport, Sport Science Review 1: 1-12.

Stone C. (1990) Rider/Bicycle Interaction Loads During Seated and Standing Treadmill Cycling, M.S. Thesis, Department of Mechanical Engineering, University of California at Davis.

Stone C, and Hull ML. (1993) Rider/bicycle interaction loads during standing treadmill cycling, Journal of Applied Biomechanics, Volume 9 Issue 3: 202–218.

Stone C, and Hull ML. (1995) The Effect of Rider Weight on Rider-Induced Loads During Common Cycling Situations. Journal of Biomechanics, Volume 28 Issue 4: 365-375.

Sunter RJ and Sayers AT. (2001), Aerodynamic drag of mountain bike tyres. Sports Engineering, Volume 4: 63–73.

Tanaka H, Bassett DR, Best SK, and Baker KR. (1996) Seated versus standing cycling in competitive road cyclists: uphill climbing and maximal oxygen uptake. Canadian Journal of Applied Physiology, Volume 21 Issue 2: 149-154.

Thomas JR and Nelson JK. (1996) Research Methods in Physical Activity, third edition, Champaign, Human Kinetics.

Titlestad J, Whittaker A, Fairlie-Clarke AC, Davie M, and Grant S. (2003a) Numerical and Experimental Simulation of Mountain Bike Suspension Systems Subject to Regular Impact Excitation. In Proceedings of Fifth International Conference on Modern Practice in Stress and Vibration Analysis: 111-118. Glasgow: Trans Tech Publishing Ltd, Uetikon-Zuerich.

Titlestad J, Fairlie-Clarke AC, Davie M, Whittaker A and Grant S. (2003b). Experimental Evaluation of Mountain Bicycle Suspension Systems, Acta Polytechnica, Volume 43 Issue 5: 15-19.

Titlestad J, Fairlie-Clarke T, Whittaker A, Davie M, Watt I and Grant S. (2006) Effect of suspension systems on the physiological and psychological responses to sub-maximal biking on simulated smooth and bumpy tracks. Journal of Sports Sciences, Volume 24 Issue 2: 125-135.

Vliet VM and Sankar S. (1983) Computer aided analysis and experimental verification of a motorcycle suspension, ASME Journal of Vibration Acoustics stress and reliability in design, Volume 105 Number 1: 120-131.

Whitt FR, Wilson DG. (1982) Bicycling Science 2nd ed, MIT Press, Cambridge, MA chapters 5, 7.

Wang EL and Hull ML. (1994) Power dissipated by off-road bicycle suspension systems, Cycling Science winter: 10-26.

Wang EL and Hull ML. (1996) A Model for Determining Rider Induced Energy Losses in Bicycle Suspension Systems, Vehicle System Dynamics, Volume 25 Issue 3: 223-246.

Wang EL and Hull ML. (1997) Minimization of Pedaling Induced Energy Losses in Off-Road Bicycle Rear Suspension Systems, Vehicle System Dynamics, Volume 28 Issue 4 & 5: 291-306.

Wasserman K, Hansen JE, Sue DY, Whipp BJ, and Casaburi R. (1994) Principles of exercise testing and interpretation. Lea and Febiger, 2nd edition.

Wilczynski H and Hull ML. (1994) A dynamic system model for estimating surface induced frame loads during off-road cycling, Journal of Mechanical Design, Volume 116: 816-822.

Wong M and Hull ML. (1981) Transfer function measurement of the arms in flexion, Advances in bioengineering, American Society of Mechanical Engineers, New York, pages 167-170.

Wong MG and Hull ML. (1983) Analysis of Road Induced Loads in Bicycle Frames, Journal of Mechanisms, Transmissions and Automation in Design, Volume 105: 138-145.

# 11. Appendix

# Appendix A

## Questionnaire

UNIVERSITY
of
GLASGOW

# Cyclist Questionnaire

The purpose of this questionnaire is to obtain information from mountain bikers. It has been designed to establish which type of suspension system you use; your opinion on the various suspension systems available and the riding styles that you adopt.

**(Please tick only one box)**

1) Sex

Male

Female

2) Age

18-25

26-30

30+

3) How long have you been cycling?

Less than 1 year

1-5 years

5-10 years

More than 10 years

4) How often do you cycle per week?

1-2 times

3-5 times

5-7 times

More than 7 times

5) Do you take part in cycling races?

Yes No (If No please go to Question 7)

6) At which level do you race at?

Amateur Cyclist
Recreational Cyclist
Competitive Cyclist
Professional Cyclist

7) Which type of bike do you ride?

Hard Tail Bike (front suspension only)
Full Suspension Bike (both front and back suspension)

8) Which make of bike do you ride most often?

Specialized
Cannondale
Orange
Santacruze
Gary Fisher
Marin
Trek
Giant
Scott
GT
Other ________________________

9) Which make of front suspension do you use?

Rock Shox
Fox
Manitou
Marzocchi
Other ________________________

10) Which type of rear suspension do you use?

Single Pivot
Four Bar Linkage
Virtual Pivot Point
Unified Rear Triangle
Horst Link
Other ________________________

11) How much travel do you allow your front suspension?

0 – 3 inches
3 – 4 inches
4 – 5 inches
More than 5 inches

12) How much travel do you allow your rear suspension?

0 – 3 inches
3 – 4 inches
4 – 5 inches
More than 5 inches

13) Which rear suspension system do you feel is the most effective?

Single Pivot
Four Bar Linkage
Virtual Pivot Point
Unified Rear Triangle
Horst Link
Other ______________________

14) When riding a full suspension bike do you feel a bobbing effect when riding uphill?

Yes No

15) When riding uphill do you…

Stand and jam
Stay seated and spin

16) Do you use a different technique when riding a full suspension bike compared to a hard tail bike?

Yes No

17) Please briefly describe your riding technique and body positioning whilst riding your bike in the following situations (i.e. do you remain seated or stand; which way do you shift your weight etc.)

a) When riding uphill

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………..

b) When riding downhill

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………..

Please add any further comments if necessary.

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………..

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………

…………………………………………………………………………………………………………..

Thank you for completing this questionnaire. The results will be confidential and there will be no way of identifying the respondents.

Mark Davie

# Appendix B

---

## Physiology Results

- Physiology Results for the Roller rig
- Physiology results for the rolling road rig
- Physiology results for the track test

**TEST RESULTS**

**Roller rig**

| SUBJECT CODE | AGE | MASS kg | SPEED km/h | TEST CODE | MINUTE 5 | | MINUTE 6 | |
|---|---|---|---|---|---|---|---|---|
| | | | | | VO2 | HR | VO2 | HR |
| **Training effect bump tests** | | | | | | | | |
| subject 01 | 31 | 75 | 11 | HTB | 38.958 | 166 | 36.322 | 166 |
| subject 01 | | | | HTB | 34.949 | 143 | 33.693 | 145 |
| subject 01 | | | | HTB | 33.112 | 150 | 40.207 | 148 |
| subject 02 | 23 | 94 | 10 | HTB | 26.355 | 145 | 29.669 | 138 |
| subject 02 | | | | HTB | 29.903 | 161 | 27.19 | 157 |
| subject 02 | | | | HTB | 28.996 | 172 | 27.65 | 164 |
| subject 03 | 22 | 74.5 | 12 | HTB | 34.611 | 154 | 31.641 | 156 |
| subject 03 | | | | HTB | 38.092 | 162 | 33.51 | 168 |
| subject 03 | | | | HTB | 37.151 | 165 | 34.57 | 167 |
| subject 04 | 23 | 83.5 | 14 | SUB | 22.86 | 98 | 30.451 | 96 |
| subject 04 | | | | SUB | 25.1 | 112 | 25.511 | 112 |
| subject 04 | | | | SUB | 23.796 | 114 | 23.063 | 115 |
| subject 05 | 26 | 75 | 10 | SUB | 15.395 | 119 | 18.686 | 119 |
| subject 05 | | | | SUB | 18.325 | 110 | 18.009 | 107 |
| subject 05 | | | | SUB | 19.589 | 130 | 20.975 | 123 |
| subject 06 | 23 | 78 | 10 | SUB | 17.66 | 136 | 18.33 | 138 |
| subject 06 | | | | SUB | 18.501 | 143 | 19.294 | 142 |
| subject 06 | | | | SUB | 17.136 | 135 | 19.575 | 136 |
| **Suspension effect bump tests** | | | | | | | | |
| subject 01 | 30 | 72 | 10 | HTB | 25.396 | 175 | 31.784 | 160 |
| subject 02 | | | | HTB | 38.258 | 144 | 39.5 | 148 |
| subject 03 | | | | HTB | 24.993 | 141 | 25.179 | 140 |
| subject 04 | 22 | 77 | 10 | HTB | 27.973 | 120 | 25.34 | 118 |
| subject 05 | | | | HTB | 39.162 | 166 | 43.346 | 168 |
| subject 06 | 22 | 80 | 10 | HTB | 26.477 | 149 | 28.804 | 141 |
| subject 01 | | | | SUB | 30.614 | 154 | 30.683 | 152 |
| subject 02 | 21 | 68 | 12.5 | SUB | 28.411 | 123 | 29.299 | 124 |
| subject 03 | 23 | 74 | 10 | SUB | 21.421 | 117 | 21.82 | 116 |
| subject 04 | | | | SUB | 15.49 | 99 | 20.12 | 99 |
| subject 05 | 23 | 64 | 11 | SUB | 17.336 | 110 | 22.107 | 109 |
| subject 06 | | | | SUB | 16.801 | 104 | 26.016 | 105 |
| MEAN | 24.89 | 76.67 | | | | | | |
| SD | 3.37 | 8.28 | | | | | | |

## TEST RESULTS

**Roller rig (continued)**

| SUBJECT CODE | MINUTE 9 VO2 | MINUTE 9 HR | MINUTE 10 VO2 | MINUTE 10 HR | AVERAGE (9 & 10) VO2 | AVERAGE (9 & 10) HR |
|---|---|---|---|---|---|---|
| **Training effect bump tests** | | | | | | |
| subject 01 | 39.023 | 168 | 35.79 | 169 | 37.41 | 168.50 |
| subject 01 | 35.774 | 150 | 34.18 | 151 | 34.98 | 150.50 |
| subject 01 | 31.347 | 150 | 34.071 | 152 | 32.71 | 151.00 |
| subject 02 | 24.249 | 137 | 30.619 | 138 | 27.43 | 137.50 |
| subject 02 | 27.777 | 162 | 26.938 | 158 | 27.36 | 160.00 |
| subject 02 | 26.371 | 160 | 26.207 | 158 | 26.29 | 159.00 |
| subject 03 | 34.619 | 162 | 32.897 | 160 | 33.76 | 161.00 |
| subject 03 | 35.922 | 169 | 35.881 | 169 | 35.90 | 169.00 |
| subject 03 | 37.374 | 166 | 37.065 | 167 | 37.22 | 166.50 |
| subject 04 | 24.34 | 102 | 23.854 | 102 | 24.10 | 102.00 |
| subject 04 | 25.36 | 115 | 25.017 | 113 | 25.19 | 114.00 |
| subject 04 | 24.397 | 116 | 25.892 | 114 | 25.14 | 115.00 |
| subject 05 | 19.253 | 124 | 19.729 | 119 | 19.49 | 121.50 |
| subject 05 | 18.791 | 110 | 15.845 | 108 | 17.32 | 109.00 |
| subject 05 | 19.733 | 129 | 19.539 | 129 | 19.64 | 129.00 |
| subject 06 | 18.311 | 142 | 18.176 | 128 | 18.24 | 135.00 |
| subject 06 | 18.55 | 142 | 18.471 | 141 | 18.51 | 141.50 |
| subject 06 | 18.781 | 135 | 15.835 | 137 | 17.31 | 136.00 |
| | | | | | | |
| **Suspension effect bump tests** | | | | | | |
| subject 01 | 31.47 | 163 | 33.411 | 162 | 32.44 | 162.50 |
| subject 02 | 36.156 | 147 | 34.978 | 147 | 35.57 | 147.00 |
| subject 03 | 25.499 | 140 | 25.097 | 143 | 25.30 | 141.50 |
| subject 04 | 28.837 | 119 | 27.393 | 120 | 28.12 | 119.50 |
| subject 05 | 38.751 | 162 | 38.202 | 163 | 38.48 | 162.50 |
| subject 06 | 28.257 | 150 | 28.148 | 149 | 28.20 | 149.50 |
| subject 01 | 27.667 | 148 | 26.988 | 147 | 27.33 | 147.50 |
| subject 02 | 28.274 | 125 | 28.963 | 126 | 28.62 | 125.50 |
| subject 03 | 22.649 | 118 | 22.55 | 115 | 22.60 | 116.50 |
| subject 04 | 20.86 | 99 | 20.68 | 100 | 20.77 | 99.50 |
| subject 05 | 20.633 | 114 | 23.297 | 112 | 21.97 | 113.00 |
| subject 06 | 17.679 | 108 | 18.391 | 106 | 18.04 | 107.00 |
| | | | | | | |
| MEAN | | | HTB | MEAN | 31.35 | 147.08 |
| SD | | | | SD | 5.04 | 15.96 |
| | | | | Cv | 0.16 | 0.11 |
| | | | SUB | MEAN | 23.22 | 118.17 |
| | | | | SD | 4.02 | 16.83 |
| | | | | Cv | 0.17 | 0.14 |

## TEST RESULTS

### Roller rig (continued)

| SUBJECT | MINUTE 3 | | MINUTE 6 | | MINUTE 9 | | AVERAGE | |
|---|---|---|---|---|---|---|---|---|
| CODE | RPE | COMFORT | RPE | COMFORT | RPE | COMFORT | RPE | COMFORT |
| **Training effect bump tests** | | | | | | | | |
| subject 01 | 8 | 4 | 9 | 4 | 10 | 3 | 9.0 | 3.7 |
| subject 01 | 7 | 5 | 8 | 4 | 8 | 4 | 7.7 | 4.3 |
| subject 01 | 7 | 4 | 8 | 3 | 9 | 3 | 8.0 | 3.3 |
| subject 02 | 11 | 3 | 12 | 3 | 12 | 3 | 11.7 | 3.0 |
| subject 02 | 11 | 3 | 12 | 3 | 13 | 3 | 12.0 | 3.0 |
| subject 02 | 12 | 3 | 13 | 3 | 13 | 3 | 12.7 | 3.0 |
| subject 03 | 11 | 1 | 12 | 1 | 12 | 1 | 11.7 | 1.0 |
| subject 03 | 11 | 2 | 11 | 1 | 11 | 1 | 11.0 | 1.3 |
| subject 03 | 11 | 1 | 12 | 1 | 12 | 1 | 11.7 | 1.0 |
| subject 04 | 10 | 3 | 11 | 3 | 11 | 3 | 10.7 | 3.0 |
| subject 04 | 9 | 3 | 10 | 3 | 11 | 3 | 10.0 | 3.0 |
| subject 04 | 9 | 3 | 10 | 3 | 10 | 3 | 9.7 | 3.0 |
| subject 05 | 9 | 3 | 9 | 4 | 9 | 4 | 9.0 | 3.7 |
| subject 05 | 11 | 3 | 11 | 3 | 11 | 3 | 11.0 | 3.0 |
| subject 05 | 12 | 3 | 12 | 3 | 12 | 3 | 12.0 | 3.0 |
| subject 06 | 7 | 5 | 11 | 5 | 11 | 4 | 9.7 | 4.7 |
| subject 06 | 11 | 5 | 12 | 4 | 13 | 4 | 12.0 | 4.3 |
| subject 06 | 12 | 4 | 14 | 3 | 15 | 3 | 13.7 | 3.3 |
| **Suspension effect bump tests** | | | | | | | | |
| subject 01 | 18 | 4 | 16 | 2 | 17 | 2 | 17.0 | 2.7 |
| subject 02 | 13 | 1 | 15 | 1 | 16 | 1 | 14.7 | 1.0 |
| subject 03 | 14 | 2 | 14 | 2 | 15 | 1 | 14.3 | 1.7 |
| subject 04 | 11 | 3 | 12 | 2 | 13 | 1 | 12.0 | 2.0 |
| subject 05 | 14 | 1 | 16 | 1 | 16 | 1 | 15.3 | 1.0 |
| subject 06 | 10 | 2 | 12 | 1 | 12 | 1 | 11.3 | 1.3 |
| subject 01 | 10 | 5 | 10 | 4 | 10 | 4 | 10.0 | 4.3 |
| subject 02 | 11 | 2 | 11 | 2 | 12 | 2 | 11.3 | 2.0 |
| subject 03 | 11 | 4 | 11 | 3 | 12 | 3 | 11.3 | 3.3 |
| subject 04 | 8 | 4 | 9 | 4 | 10 | 4 | 9.0 | 4.0 |
| subject 05 | 11 | 3 | 11 | 3 | 11 | 2 | 11.0 | 2.7 |
| subject 06 | 8 | 5 | 10 | 4 | 11 | 4 | 9.7 | 4.3 |
| MEAN | | | | | HTB | MEAN | 14.11 | 1.61 |
| SD | | | | | | SD | 2.12 | 0.65 |
| | | | | | | Cv | 0.15 | 0.40 |
| | | | | | SUB | MEAN | 10.39 | 3.44 |
| | | | | | | SD | 0.98 | 0.96 |
| | | | | | | Cv | 0.09 | 0.28 |

**Rolling Road test**

| SUBJECT CODE | AGE | MASS kg | SPEED km/h | TEST CODE | MINUTE 4 | | MINUTE 5 | |
|---|---|---|---|---|---|---|---|---|
| | | | | | VO2 | HR | VO2 | HR |
| subject 01 | 31 | 85 | 8 | REST | 3.944 | 55 | | |
| subject 01 | | | | SUB | 30.391 | 130 | 28.418 | 127 |
| subject 01 | | | | HTB | 30.496 | 131 | 30.135 | 127 |
| subject 01 | | | | SUS | 28.61 | 130 | 27.872 | 130 |
| subject 01 | | | | HTS | 25.879 | 130 | 26.252 | 128 |
| subject 02 | 30 | 69.7 | 8 | REST | 4.923 | 69 | | |
| subject 02 | | | | HTB | 34.634 | 147 | 34.902 | 146 |
| subject 02 | | | | SUB | 36.593 | 148 | 35.099 | 147 |
| subject 02 | | | | HTS | 32.454 | 135 | 30.841 | 134 |
| subject 02 | | | | SUS | 33.16 | 140 | 33.532 | 147 |
| subject 03 | 25 | 68.9 | 8 | REST | 5.118 | 51 | | |
| subject 03 | | | | SUB | 36.599 | 129 | 31.547 | 132 |
| subject 03 | | | | HTB | 37.387 | 135 | 35.555 | 135 |
| subject 03 | | | | HTS | 32.12 | 130 | 32.397 | 130 |
| subject 03 | | | | SUS | 30.526 | 130 | 32.628 | 130 |
| subject 04 | 24 | 103.2 | 8 | REST | 6.576 | 72 | | |
| subject 04 | | | | HTB | 28.393 | 120 | 29.019 | 123 |
| subject 04 | | | | SUB | 29.182 | 120 | 28.265 | 120 |
| subject 04 | | | | SUS | 28.571 | 128 | 30.019 | 131 |
| subject 04 | | | | HTS | 28.207 | 121 | 28.543 | 130 |
| subject 05 | 32 | 67 | 8 | REST | 4.865 | 60 | | |
| subject 05 | | | | SUS | 29.374 | 116 | 31.236 | 118 |
| subject 05 | | | | HTS | 34.61 | 118 | 29.808 | 117 |
| subject 05 | | | | SUB | 35.024 | 122 | 35.832 | 124 |
| subject 05 | | | | HTB | 39.758 | 126 | 38.786 | 128 |
| subject 06 | 25 | 72 | 8 | REST | 5.923 | 87 | | |
| subject 06 | | | | HTS | 28.981 | 139 | 33.735 | 140 |
| subject 06 | | | | SUS | 32.403 | 133 | 33.869 | 138 |
| subject 06 | | | | HTB | 32.697 | 144 | 33.297 | 148 |
| subject 06 | | | | SUB | 33.268 | 140 | 33.086 | 143 |
| subject 07 | 26 | 85.2 | 8 | REST | 3.944 | 55 | | |
| subject 07 | | | | SUS | 28.842 | 109 | 24.717 | 117 |
| subject 07 | | | | HTS | 27.228 | 114 | 27.024 | 115 |
| subject 07 | | | | HTB | 30.059 | 121 | 29.796 | 119 |
| subject 07 | | | | SUB | 30.627 | 115 | 29.343 | 120 |
| subject 08 | 30 | 69.7 | 8 | REST | 4.923 | 69 | | |
| subject 08 | | | | HTS | 31.762 | 134 | 32.126 | 130 |
| subject 08 | | | | SUS | 32.196 | 135 | 33.334 | 139 |
| subject 08 | | | | SUB | 32.407 | 138 | 39.35 | 138 |
| subject 08 | | | | HTB | 36.221 | 135 | 37.159 | 135 |
| **MEAN** | 24.78 | 77.59 | | | | | | |
| **SD** | 9.76 | 12.60 | | | | | | |

**Rolling Road test (continued)**

| SUBJECT CODE | MINUTE 9 | | MINUTE 10 | | AVERAGE (9 & 10) | |
|---|---|---|---|---|---|---|
| | **VO2** | **HR** | **VO2** | **HR** | **VO2** | **HR** |
| subject 01 | | | | | | |
| subject 01 | 30.04 | 125 | 28.927 | 129 | 29.4 | 127.8 |
| subject 01 | 30.697 | 128 | 30.66 | 131 | 30.5 | 129.3 |
| subject 01 | 27.649 | 126 | 27.132 | 130 | 27.8 | 129.0 |
| subject 01 | 25.713 | 124 | 26.374 | 130 | 26.1 | 128.0 |
| subject 02 | | | 5 | | | |
| subject 02 | 35.309 | 149 | 35.191 | 151 | 35.0 | 148.3 |
| subject 02 | 34.799 | 154 | 35.231 | 153 | 35.4 | 150.5 |
| subject 02 | 30.78 | 134 | 30.582 | 138 | 31.2 | 135.3 |
| subject 02 | 34.85 | 149 | 35.814 | 149 | 34.3 | 146.3 |
| subject 03 | | | | | | |
| subject 03 | 33.826 | 140 | 36.121 | 138 | 34.5 | 134.8 |
| subject 03 | 35.59 | 140 | 35.022 | 140 | 35.9 | 137.5 |
| subject 03 | 33.039 | 132 | 30.219 | 134 | 31.9 | 131.5 |
| subject 03 | 31.42 | 133 | 30.572 | 131 | 31.3 | 131.0 |
| subject 04 | | | | | | |
| subject 04 | 28.585 | 124 | 28.438 | 123 | 28.6 | 122.5 |
| subject 04 | 29.181 | 122 | 28.626 | 120 | 28.8 | 120.5 |
| subject 04 | 29.835 | 134 | 28.061 | 134 | 29.1 | 131.8 |
| subject 04 | 28.22 | 128 | 27.162 | 131 | 28.0 | 127.5 |
| subject 05 | | | | | | |
| subject 05 | 34.616 | 118 | 32.398 | 121 | 31.9 | 118.3 |
| subject 05 | 34.025 | 119 | 29.911 | 125 | 32.1 | 119.8 |
| subject 05 | 38.046 | 126 | 37.065 | 125 | 36.5 | 124.3 |
| subject 05 | 39.305 | 127 | 40.754 | 130 | 39.7 | 127.8 |
| subject 06 | | | | | | |
| subject 06 | 32.649 | 140 | 36.251 | 141 | 32.9 | 140.0 |
| subject 06 | 35.471 | 140 | 29.806 | 138 | 32.9 | 137.3 |
| subject 06 | 34.271 | 149 | 32.818 | 149 | 33.3 | 147.5 |
| subject 06 | 33.883 | 148 | 33.877 | 148 | 33.5 | 144.8 |
| subject 07 | | | | | | |
| subject 07 | 26.974 | 113 | 27.47 | 112 | 27.0 | 112.8 |
| subject 07 | 28.375 | 116 | 29.326 | 118 | 28.0 | 115.8 |
| subject 07 | 29.105 | 121 | 29.85 | 118 | 29.7 | 119.8 |
| subject 07 | 30.157 | 120 | 29.986 | 120 | 30.0 | 118.8 |
| subject 08 | | | | | | |
| subject 08 | 32.636 | 136 | 31.194 | 137 | 31.9 | 134.3 |
| subject 08 | 32.261 | 136 | 32.251 | 137 | 32.5 | 136.8 |
| subject 08 | 36.145 | 141 | 34.432 | 140 | 35.6 | 139.3 |
| subject 08 | 35.267 | 137 | 34.094 | 136 | 35.7 | 135.8 |
| **MEAN** | | | **HTB** | **MEAN** | 33.54 | 133.53 |
| **SD** | | | | **SD** | 3.74 | 10.66 |
| | | | | **Cv** | 0.11 | 0.08 |
| | | | **SUB** | **MEAN** | 32.98 | 132.56 |
| | | | | **SD** | 3.08 | 11.64 |
| | | | | **Cv** | 0.09 | 0.09 |
| | | | **HTS** | **MEAN** | 30.26 | 129.00 |
| | | | | **SD** | 2.52 | 8.09 |
| | | | | **Cv** | 0.08 | 0.06 |
| | | | **SUS** | **MEAN** | 30.86 | 130.38 |
| | | | | **SD** | 2.60 | 10.70 |
| | | | | **Cv** | 0.08 | 0.08 |

**Rolling Road test (continued)**

| SUBJECT | MINUTE 3 | | MINUTE 6 | | MINUTE 9 | | AVERAGE | |
|---|---|---|---|---|---|---|---|---|
| CODE | RPE | COMFORT | RPE | COMFORT | RPE | COMFORT | RPE | COMFORT |
| subject 01 | | | | | | | | |
| subject 01 | 10 | 4 | 10 | 4 | 10 | 4 | 10.0 | 4.0 |
| subject 01 | 9 | 4 | 10 | 4 | 10 | 4 | 9.7 | 4.0 |
| subject 01 | 11 | 2 | 11 | 1 | 10 | 2 | 10.7 | 1.7 |
| subject 01 | 9 | 4 | 9 | 4 | 9 | 4 | 9.0 | 4.0 |
| subject 02 | | | | | | | | |
| subject 02 | 15 | 2 | 14 | 2 | 16 | 2 | 15.0 | 2.0 |
| subject 02 | 13 | 2 | 13 | 2 | 12 | 2 | 12.7 | 2.0 |
| subject 02 | 9 | 4 | 10 | 4 | 9 | 4 | 9.3 | 4.0 |
| subject 02 | 10 | 4 | 11 | 4 | 11 | 4 | 10.7 | 4.0 |
| subject 03 | | | | | | | | |
| subject 03 | 11 | 1 | 10 | 1 | 10 | 1 | 10.3 | 1.0 |
| subject 03 | 10 | 3 | 10 | 3 | 9 | 3 | 9.7 | 3.0 |
| subject 03 | 10 | 4 | 11 | 4 | 11 | 4 | 10.7 | 4.0 |
| subject 03 | 10 | 4 | 11 | 4 | 11 | 4 | 10.7 | 4.0 |
| subject 04 | | | | | | | | |
| subject 04 | 15 | 1 | 15 | 1 | 17 | 1 | 15.7 | 1.0 |
| subject 04 | 10 | 4 | 10 | 4 | 12 | 4 | 10.7 | 4.0 |
| subject 04 | 8 | 4 | 9 | 4 | 9 | 4 | 8.7 | 4.0 |
| subject 04 | 11 | 4 | 11 | 4 | 13 | 3 | 11.7 | 3.7 |
| subject 05 | | | | | | | | |
| subject 05 | 11 | 5 | 11 | 5 | 11 | 5 | 11.0 | 5.0 |
| subject 05 | 12 | 3 | 12 | 3 | 12 | 3 | 12.0 | 3.0 |
| subject 05 | 11 | 5 | 11 | 5 | 11 | 5 | 11.0 | 5.0 |
| subject 05 | 12 | 2 | 13 | 1 | 13 | 1 | 12.7 | 1.3 |
| subject 06 | | | | | | | | |
| subject 06 | 8 | 4 | 9 | 4 | 9 | 4 | 8.7 | 4.0 |
| subject 06 | 7 | 5 | 8 | 5 | 8 | 5 | 7.7 | 5.0 |
| subject 06 | 13 | 2 | 13 | 2 | 13 | 2 | 13.0 | 2.0 |
| subject 06 | 12 | 1 | 12 | 1 | 12 | 1 | 12.0 | 1.0 |
| subject 07 | | | | | | | | |
| subject 07 | 10 | 4 | 12 | 4 | 11 | 4 | 11.0 | 4.0 |
| subject 07 | 10 | 4 | 11 | 4 | 10 | 4 | 10.3 | 4.0 |
| subject 07 | 9 | 4 | 10 | 4 | 10 | 4 | 9.7 | 4.0 |
| subject 07 | 9 | 4 | 9 | 4 | 9 | 4 | 9.0 | 4.0 |
| subject 08 | | | | | | | | |
| subject 08 | 11 | 2 | 11 | 2 | 12 | 1 | 11.3 | 1.7 |
| subject 08 | 9 | 4 | 9 | 4 | 9 | 4 | 9.0 | 4.0 |
| subject 08 | 8 | 5 | 12 | 3 | 12 | 3 | 10.7 | 3.7 |
| subject 08 | 12 | 2 | 12 | 1 | 15 | 1 | 13.0 | 1.3 |
| **MEAN** | | | | | **HTB** | **MEAN** | 12.29 | 2.33 |
| **SD** | | | | | | **SD** | 2.41 | 1.20 |
| | | | | | | **Cv** | 0.20 | 0.51 |
| | | | | | **SUB** | **MEAN** | 10.79 | 3.08 |
| | | | | | | **SD** | 1.14 | 1.53 |
| | | | | | | **Cv** | 0.11 | 0.50 |
| | | | | | **HTS** | **MEAN** | 10.38 | 3.54 |
| | | | | | | **SD** | 1.27 | 0.83 |
| | | | | | | **Cv** | 0.12 | 0.24 |
| | | | | | **SUS** | **MEAN** | 9.92 | 3.96 |
| | | | | | | **SD** | 1.28 | 1.03 |
| | | | | | | **Cv** | 0.13 | 0.26 |

**TRACK TEST**

| **SUBJECT CODE** | **AGE** | **MASS kg** | **SPEED km/h** | **TEST CODE** | **AVERAGE over 2-11th** | | **MINUTE 3** | |
|---|---|---|---|---|---|---|---|---|
| | | | | | **VO2** | **HR** | **RPE** | **COMFORT** |
| am01 | 23 | 70 | 10.5 | HTB | 21.89 | 106.4 | 7 | 4 |
| dl01 | 27 | 80 | 10.5 | HTB | 17.87 | 127.2 | 11 | 4 |
| am01 | 23 | 78 | 10.5 | HTB | 20.17 | 105.1 | 8 | 4 |
| er01 | 23 | 70 | 10.5 | HTB | 17.64 | 109.3 | 8 | 4 |
| rc01 | 24 | 60 | 10.5 | HTB | 20.58 | 105.3 | 8 | 4 |
| pr02 | 18 | 55 | 10.5 | HTB | 24.69 | 108.4 | 8 | 4 |
| ld02 | 22 | 87 | 10.5 | HTB | 15.70 | 94.1 | 7 | 3 |
| de02 | 20 | 60 | 10.5 | HTB | 22.76 | 104.6 | 9 | 3 |
| cm02 | 23 | 70 | 10.5 | HTB | 17.65 | 102.7 | 8 | 4 |
| km02 | 23 | 78 | 10.5 | HTB | 14.56 | 104.2 | 8 | 3 |
| am02 | 23 | 70 | 10.5 | SUB | 19.517 | 102.1 | 7 | 5 |
| dl02 | 27 | 80 | 10.5 | SUB | 17.07 | 121.3 | 8 | 4 |
| am02 | 23 | 78 | 10.5 | SUB | 19.96 | 103.1 | 6 | 5 |
| er02 | 23 | 70 | 10.5 | SUB | 16.23 | 96.9 | 7 | 5 |
| rc02 | 24 | 60 | 10.5 | SUB | 18.93 | 100.3 | 7 | 4 |
| pr01 | 18 | 55 | 10.5 | SUB | 22.45 | 107.7 | 7 | 5 |
| ld01 | 22 | 87 | 10.5 | SUB | 13.06 | 93.9 | 6 | 4 |
| de01 | 20 | 60 | 10.5 | SUB | 22.63 | 96.9 | 8 | 4 |
| cm01 | 23 | 70 | 10.5 | SUB | 16.24 | 102.6 | 7 | 5 |
| km01 | 23 | 78 | 10.5 | SUB | 15.6 | 103.9 | 8 | 3 |
| **MEAN** | 22.60 | 70.80 | **HTB** | **MEAN** | 19.35 | 106.73 | | |
| **SD** | 2.37 | 10.20 | | **SD** | 3.22 | 8.2994043 | | |
| | | | **SUB** | **MEAN** | 18.17 | 102.87 | | |
| | | | | **SD** | 3.08 | 7.6239462 | | |

## TRACK TEST (continued)

| SUBJECT CODE | MINUTE 6 | | MINUTE 9 | | AVERAGE | |
|---|---|---|---|---|---|---|
| | RPE | COMFORT | RPE | COMFORT | RPE | COMFORT |
| am01 | 8 | 3 | 8 | 3 | 7.7 | 3.3 |
| dl01 | 12 | 3 | 13 | 2 | 12.0 | 3.0 |
| am01 | 8 | 4 | 8 | 4 | 8.0 | 4.0 |
| er01 | 8 | 4 | 8 | 3 | 8.0 | 3.7 |
| rc01 | 9 | 3 | 9 | 2 | 8.7 | 3.0 |
| pr02 | 8 | 3 | 8 | 3 | 8.0 | 3.3 |
| ld02 | 7 | 4 | 7 | 3 | 7.0 | 3.3 |
| de02 | 10 | 3 | 10 | 2 | 9.7 | 2.7 |
| cm02 | 8 | 4 | 9 | 3 | 8.3 | 3.7 |
| km02 | 8 | 2 | 8 | 2 | 8.0 | 2.3 |
| am02 | 7 | 5 | 7 | 5 | 7.0 | 5.0 |
| dl02 | 8 | 4 | 9 | 4 | 8.3 | 4.0 |
| am02 | 7 | 5 | 6 | 5 | 6.3 | 5.0 |
| er02 | 7 | 5 | 7 | 5 | 7.0 | 5.0 |
| rc02 | 8 | 4 | 8 | 4 | 7.7 | 4.0 |
| pr01 | 7 | 4 | 7 | 4 | 7.0 | 4.3 |
| ld01 | 6 | 4 | 6 | 4 | 6.0 | 4.0 |
| de01 | 8 | 4 | 9 | 4 | 8.3 | 4.0 |
| cm01 | 7 | 5 | 8 | 4 | 7.3 | 4.7 |
| km01 | 8 | 3 | 8 | 3 | 8.0 | 3.0 |
| **MEAN** | | | **HTB** | **MEAN** | 8.53 | 3.23 |
| **SD** | | | | **SD** | 1.40 | 0.50 |
| | | | **SUB** | **MEAN** | 7.30 | 4.30 |
| | | | | **SD** | 0.79 | 0.64 |

## DIFFERENCE ANALYSIS (HT - SU)

| SUBJECT | BUMPS | | | | | SMOOTH (NO BUMPS) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | VO2 | HR | EXERTION | COMFORT | | VO2 | HR | EXERTION | COMFORT |
| **Rolling Road** | | | | | | | | | |
| subject 01 | 1.1 | 1.5 | -0.3 | 0.0 | | -1.8 | -1.0 | -1.7 | 2.3 |
| subject 02 | -0.4 | -2.3 | 2.3 | 0.0 | | -3.2 | -11.0 | -1.3 | 0.0 |
| subject 03 | 1.4 | 2.8 | -0.7 | 2.0 | | 0.7 | 0.5 | 0.0 | 0.0 |
| subject 04 | -0.2 | 2.0 | 5.0 | -3.0 | | -1.1 | -4.3 | 3.0 | -0.3 |
| subject 05 | 3.2 | 3.5 | 1.7 | -3.7 | | 0.2 | 1.5 | 1.0 | -2.0 |
| subject 06 | -0.3 | 2.8 | 1.0 | 1.0 | | 0.0 | 2.8 | 1.0 | -1.0 |
| subject 07 | -0.3 | 1.0 | 0.7 | 0.0 | | 1.0 | 3.0 | -0.7 | 0.0 |
| subject 08 | 0.1 | -3.5 | 2.3 | -2.3 | | -0.6 | -2.5 | 2.3 | -2.3 |
| **NULL HYPOTHESIS** | | | | | | | | | |
| **n** | 8 | 8 | 8 | 8 | | 8 | 8 | 8 | 8 |
| **average** | 0.6 | 1.0 | 1.5 | -0.8 | | -0.6 | -1.4 | 0.5 | -0.4 |
| **sum** | 4.5 | 7.8 | 12.0 | -6.0 | | -4.8 | -11.0 | 3.7 | -3.3 |
| **sum of squares** | 13.4 | 51.9 | 40.7 | 32.9 | | 16.1 | 165.4 | 21.4 | 16.0 |
| **sd** | 1.25 | 2.52 | 1.80 | 2.01 | | 1.38 | 4.63 | 1.68 | 1.44 |
| **sd(mean)** | 0.44 | 0.89 | 0.64 | 0.71 | | 0.49 | 1.64 | 0.59 | 0.51 |
| **t** | 1.27 | 1.09 | 2.36 | 1.05 | | 1.22 | 0.84 | 0.77 | 0.82 |
| **p** | 24.510% | 31.280% | 5.051% | 32.717% | | 26.167% | 42.896% | 46.565% | 44.153% |
| **Cv** | 2.23 | 2.60 | 1.20 | -2.69 | | -2.32 | -3.37 | 3.67 | -0.29 |
| **95% CONFIDENCE LIMITS** | | | t'crit = | 2.36 | | | | | |
| **Upper** | 1.6 | 3.1 | 3.0 | 0.9 | | 0.6 | 2.5 | 1.9 | 0.8 |
| **Lower** | -0.5 | -1.1 | 0.0 | -2.4 | | -1.7 | -5.2 | -0.9 | -1.6 |
| **Effect Size** | 0.45 | 0.38 | 0.83 | -0.37 | | -0.43 | -0.30 | 0.27 | -0.29 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| | | | | | | | | | |
| **HT mean** | 33.5 | 133.5 | 12.3 | 2.3 | | 30.3 | 129.0 | 10.4 | 3.5 |
| **% improvement** | 1.7% | 0.7% | 12.2% | -32.1% | | -2.0% | -1.1% | 4.4% | -11.8% |

## DIFFERENCE ANALYSIS (HT - SU)

| **SUBJECT** | **BUMPS** | | | |
|---|---|---|---|---|
| | **VO2** | **HR** | **EXERTION** | **COMFORT** |
| **Track test** | | | | |
| subject 01 | 2.4 | 4.3 | 0.7 | -1.7 |
| subject 02 | 0.8 | 5.9 | 3.7 | -1.0 |
| subject 03 | 0.2 | 2.0 | 1.7 | -1.0 |
| subject 04 | 1.4 | 12.4 | 1.0 | -1.3 |
| subject 05 | 1.7 | 5.0 | 1.0 | -1.0 |
| subject 06 | 2.2 | 0.7 | 1.0 | -1.0 |
| subject 07 | 2.6 | 0.2 | 1.0 | -0.7 |
| subject 08 | 0.1 | 7.7 | 1.3 | -1.3 |
| subject 09 | 1.4 | 0.1 | 1.0 | -1.0 |
| subject 10 | -1.0 | 0.3 | 0.0 | -0.7 |
| **NULL HYPOTHESIS** | | | | |
| **n** | 10 | 10 | 10 | 10 |
| **average** | 1.2 | 3.9 | 1.2 | -1.1 |
| **sum** | 11.8 | 38.6 | 12.3 | -10.7 |
| **sum of squares** | 26.1 | 296.0 | 23.4 | 12.2 |
| **sd** | 1.16 | 4.04 | 0.96 | 0.31 |
| **sd(mean)** | 0.37 | 1.28 | 0.30 | 0.10 |
| **t** | 3.22 | 3.02 | 4.08 | 11.01 |
| **p** | 1.046% | 1.447% | 0.277% | 0.000% |
| **Cv** | 0.98 | 1.05 | 0.78 | -0.29 |
| **95% CONFIDENCE LIMITS** | | | t'crit = | 2.36 |
| **Upper** | 2.0 | 6.9 | 1.9 | -0.8 |
| **Lower** | 0.3 | 0.8 | 0.5 | -1.3 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | |
| **HT mean** | 19.4 | 106.7 | 8.4 | 3.2 |
| **% improvement** | 6.1% | 3.6% | 14.7% | -33.0% |

## DIFFERENCE ANALYSIS (HT - SU)

| **SUBJECT** | **BUMPS** | | | |
|---|---|---|---|---|
| | **VO2** | **HR** | **EXERTION** | **COMFORT** |
| **Roller Rig** | | | | |
| subject 01 | 5.11 | 15.00 | 7.00 | -1.67 |
| subject 02 | 6.95 | 21.50 | 3.33 | -1.00 |
| subject 03 | 2.70 | 25.00 | 3.00 | -1.67 |
| subject 04 | 7.35 | 20.00 | 3.00 | -2.00 |
| subject 05 | 16.51 | 49.50 | 4.33 | -1.67 |
| subject 06 | 10.17 | 42.50 | 1.67 | -3.00 |
| | | | | |
| **NULL HYPOTHESIS** | | | | |
| **n** | 6 | 6 | 6 | 6 |
| **average** | 8.1 | 28.9 | 3.7 | -1.8 |
| **sum** | 48.8 | 173.5 | 22.3 | -11.0 |
| **sum of squares** | 511.7 | 5968.8 | 99.7 | 22.3 |
| **sd** | 4.80 | 13.80 | 1.82 | 0.66 |
| **sd(mean)** | 1.96 | 5.63 | 0.74 | 0.27 |
| **t** | 4.15 | 5.13 | 5.01 | 6.82 |
| **p** | 0.889% | 0.366% | 0.406% | 0.103% |
| **Cv** | 0.59 | 0.48 | 0.49 | -0.36 |
| **95% CONFIDENCE LIMITS** | | | t'crit = | 2.57 |
| **Upper** | 13.2 | 43.4 | 5.6 | -1.1 |
| **Lower** | 3.1 | 14.4 | 1.8 | -2.5 |
| | | | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | |
| | | | | |
| **HT mean** | 31.3 | 147.1 | 14.1 | 1.6 |
| **% improvement** | 25.9% | 19.7% | 26.4% | -113.8% |

**EFFECT SIZE**

| Rolling Road | BUMPS (HT) | | | | BUMPS (SU) | | | |
|---|---|---|---|---|---|---|---|---|
| **SUBJECT** | **VO2** | **HR** | **EXERTION** | **COMFORT** | **VO2** | **HR** | **EXERTION** | **COMFORT** |
| al | 30.5 | 129.3 | 9.7 | 4.0 | 29.4 | 127.8 | 10.0 | 4.0 |
| jt | 35.0 | 148.3 | 15.0 | 2.0 | 35.4 | 150.5 | 12.7 | 2.0 |
| fj | 35.9 | 137.5 | 9.7 | 3.0 | 34.5 | 134.8 | 10.3 | 1.0 |
| sb | 28.6 | 122.5 | 15.7 | 1.0 | 28.8 | 120.5 | 10.7 | 4.0 |
| ns | 39.7 | 127.8 | 12.7 | 1.3 | 36.5 | 124.3 | 11.0 | 5.0 |
| nr | 33.3 | 147.5 | 13.0 | 2.0 | 33.5 | 144.8 | 12.0 | 1.0 |
| db | 29.7 | 119.8 | 9.7 | 4.0 | 30.0 | 118.8 | 9.0 | 4.0 |
| jw | 35.7 | 135.8 | 13.0 | 1.3 | 35.6 | 139.3 | 10.7 | 3.7 |
| | | | | | | | | |
| **N** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **Mean** | 33.5 | 133.5 | 12.3 | 2.3 | 33.0 | 132.6 | 10.8 | 3.1 |
| **SD** | 3.741519 | 10.66238 | 2.40658818 | 1.195228609 | 3.0792826 | 11.639488 | 1.140001392 | 1.530120858 |
| **MeanHT -MeanSU** | 0.6 | 1.0 | 1.5 | -0.8 | | | | |
| **SDp** | 3.426437 | 11.16163 | 1.88298564 | 1.372924118 | | | | |
| **Effect Size** | 0.2 | 0.1 | 0.8 | -0.5 | | | | |

**EFFECT SIZE**

| Rolling Road | SMOOTH (NO BUMPS) (HT) | | | | SMOOTH (NO BUMPS) (SU) | | | |
|---|---|---|---|---|---|---|---|---|
| SUBJECT | VO2 | HR | EXERTION | COMFORT | VO2 | HR | EXERTION | COMFORT |
| al | 26.1 | 128.0 | 9.0 | 4.0 | 27.8 | 129.0 | 10.7 | 1.7 |
| jt | 31.2 | 135.3 | 9.3 | 4.0 | 34.3 | 146.3 | 10.7 | 4.0 |
| fj | 31.9 | 131.5 | 10.7 | 4.0 | 31.3 | 131.0 | 10.7 | 4.0 |
| sb | 28.0 | 127.5 | 11.7 | 3.7 | 28.0 | 127.5 | 11.7 | 3.7 |
| ns | 32.1 | 119.8 | 12.0 | 3.0 | 31.9 | 118.3 | 11.0 | 5.0 |
| nr | 32.9 | 140.0 | 8.7 | 4.0 | 32.9 | 137.3 | 7.7 | 5.0 |
| db | 28.0 | 115.8 | 10.3 | 4.0 | 27.0 | 112.8 | 11.0 | 4.0 |
| jw | 31.9 | 134.3 | 11.3 | 1.7 | 32.5 | 136.8 | 9.0 | 4.0 |
| | | | | | | | | |
| **N** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **Mean** | 30.3 | 129.0 | 10.4 | 3.5 | 30.7 | 129.8 | 10.3 | 3.9 |
| **SD** | 2.523619 | 8.0910003 | 1.265381554 | 0.83452296 | 2.731168 | 10.72958 | 1.302470181 | 1.035098339 |
| **MeanHT -MeanSU** | -0.5 | -0.8 | 0.1 | -0.4 | | | | |
| **SDp** | 2.629442 | 9.50232 | 1.284059782 | 0.94017476 | | | | |
| **Effect Size** | -0.2 | -0.1 | 0.1 | -0.4 | | | | |

**EFFECT SIZE**

| Track test | BUMPS (HT) | | | | BUMPS (SU) | | | |
|---|---|---|---|---|---|---|---|---|
| **SUBJECT** | **VO2** | **HR** | **EXERTION** | **COMFORT** | **VO2** | **HR** | **EXERTION** | **COMFORT** |
| am01 | 21.89 | 106.4 | 7.7 | 3.3 | 19.517 | 102.1 | 7.0 | 5.0 |
| dl01 | 17.87 | 127.2 | 12.0 | 3.0 | 17.07 | 121.3 | 8.3 | 4.0 |
| am01 | 20.17 | 105.1 | 8.0 | 4.0 | 19.96 | 103.1 | 6.3 | 5.0 |
| er01 | 17.64 | 109.3 | 8.0 | 3.7 | 16.23 | 96.9 | 7.0 | 5.0 |
| rc01 | 20.58 | 105.3 | 8.7 | 3.0 | 18.93 | 100.3 | 7.7 | 4.0 |
| pr02 | 24.69 | 108.4 | 8.0 | 3.3 | 22.45 | 107.7 | 7.0 | 4.3 |
| ld02 | 15.70 | 94.1 | 7.0 | 3.3 | 13.06 | 93.9 | 6.0 | 4.0 |
| de02 | 22.76 | 104.6 | 9.7 | 2.7 | 22.63 | 96.9 | 8.3 | 4.0 |
| cm02 | 17.65 | 102.7 | 8.3 | 3.7 | 16.24 | 102.6 | 7.3 | 4.7 |
| km02 | 14.56 | 104.2 | 8.0 | 2.3 | 15.6 | 103.9 | 8.0 | 3.0 |
| | | | | | | | | |
| **N** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **Mean** | 19.4 | 106.7 | 8.5 | 3.2 | 18.2 | 102.9 | 7.3 | 4.3 |
| **SD** | 3.215443 | 8.299404 | 1.398411798 | 0.498144706 | 3.0771847 | 7.6239462 | 0.792713733 | 0.637316907 |
| **MeanHT -MeanSU** | 1.2 | 3.9 | 1.2 | -1.1 | | | | |
| **SDp** | 3.147073 | 7.968835 | 1.136650918 | 0.571979452 | | | | |
| **Effect Size** | 0.4 | 0.5 | 1.1 | -1.9 | | | | |

**EFFECT SIZE**

| Roller Rig | BUMPS (HT) | | | | BUMPS (SU) | | | |
|---|---|---|---|---|---|---|---|---|
| SUBJECT | VO2 | HR | EXERTION | COMFORT | VO2 | HR | EXERTION | COMFORT |
| ba01 | 32.44 | 162.50 | 17.00 | 2.67 | 27.33 | 147.50 | 10.00 | 4.33 |
| er02 | 35.57 | 147.00 | 14.67 | 1.00 | 28.62 | 125.50 | 11.33 | 2.00 |
| mh02 | 25.30 | 141.50 | 14.33 | 1.67 | 22.60 | 116.50 | 11.33 | 3.33 |
| nm01 | 28.12 | 119.50 | 12.00 | 2.00 | 20.77 | 99.50 | 9.00 | 4.00 |
| rc02 | 38.48 | 162.50 | 15.33 | 1.00 | 21.97 | 113.00 | 11.00 | 2.67 |
| rm01 | 28.20 | 149.50 | 11.33 | 1.33 | 18.04 | 107.00 | 9.67 | 4.33 |
| | | | | | | | | |
| **N** | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| **Mean** | 31.3 | 147.1 | 14.1 | 1.6 | 23.2 | 118.2 | 10.4 | 3.4 |
| **SD** | 5.035037 | 15.957496 | 2.115200717 | 0.64693007 | 4.021495 | 16.8335 | 0.975628952 | 0.958393718 |
| **MeanHT -MeanSU** | 8.1 | 28.9 | 3.7 | -1.8 | | | | |
| **SDp** | 4.556535 | 16.401346 | 1.647107453 | 0.81762982 | | | | |
| **Effect Size** | 1.8 | 1.8 | 2.3 | -2.2 | | | | |

# Appendix C

---

## Mechanical Results

- **Mechanical Results for the Roller rig**

- **Mechanical results for the rolling road rig**

## The Roller Rig on the Rough track
## Individual subjects average results for the hardtail bike

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 |
|---|---|---|---|---|---|
| **Accel Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Accel Handlebar** | 1.201 | 1.394 | 1.332 | 1.305 | 1.301 |
| **Min Accel Handlebar** | -1.064 | -1.163 | -1.096 | -1.161 | -1.179 |
| **Difference** | 2.265 | 2.558 | 2.428 | 2.466 | 2.480 |
| | | | | | |
| **Velocity Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Velocity Handlebar** | 0.138 | 0.148 | 0.136 | 0.154 | 0.157 |
| **Min Velocity Handlebar** | -0.118 | -0.133 | -0.123 | -0.126 | -0.130 |
| **Difference** | 0.256 | 0.281 | 0.259 | 0.280 | 0.287 |
| | | | | | |
| **Displ Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Displ Handlebar** | 0.004 | 0.004 | 0.003 | 0.004 | 0.004 |
| **MinDispl Handlebar** | -0.004 | -0.004 | -0.004 | -0.004 | -0.004 |
| **Difference** | 0.007 | 0.008 | 0.007 | 0.008 | 0.008 |
| | | | | | |
| **Accel Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Impact Accel** | 1.947 | 2.244 | 2.092 | 2.196 | 2.126 |
| **Max landing Acel Seat** | 5.385 | 5.897 | 5.752 | 5.789 | 5.848 |
| **Min impact Accel Seat** | -2.944 | -3.291 | -3.278 | -3.231 | -3.193 |
| **Difference** | 8.329 | 9.188 | 9.030 | 9.020 | 9.041 |
| | | | | | |
| **Velocity Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Velocity Seat** | 0.405 | 0.438 | 0.420 | 0.433 | 0.438 |
| **Min Velocity Seat** | -0.481 | -0.547 | -0.507 | -0.529 | -0.521 |
| **Difference** | 0.887 | 0.985 | 0.927 | 0.962 | 0.959 |
| | | | | | |
| **Displ Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Displ Seat** | 0.011 | 0.011 | 0.010 | 0.011 | 0.011 |
| **Min Displ Seat** | -0.006 | -0.007 | -0.007 | -0.007 | -0.007 |
| **Difference** | 0.017 | 0.018 | 0.017 | 0.018 | 0.018 |
| | | | | | |
| **Crank Velocity** | 0.514 | 0.353 | 0.649 | 0.509 | 0.576 |
| **Crank Force** | 129.898 | 66.360 | 120.362 | 146.361 | 119.794 |
| **Max Crank Force** | 184.112 | 211.626 | 201.293 | 227.191 | 222.932 |
| **Min Crank force** | 7.399145 | 6.981442 | 5.747619 | 5.902222 | 6.729149 |
| **Difference** | 176.713 | 204.644 | 195.545 | 221.289 | 216.202 |
| | | | | | |
| **Crank Power** | 132.932 | 34.162 | 155.561 | 148.452 | 137.460 |
| **Max Crank Power** | 198.855 | 222.370 | 221.927 | 244.347 | 238.578 |
| **Min Crank Power** | 7.572 | 10.521 | 7.428 | 5.987 | 7.722 |
| **Difference** | 191.283 | 211.848 | 214.498 | 238.360 | 230.857 |
| | | | | | |
| **Ground velocity** | 3.180 | 2.394 | 4.095 | 3.556 | 3.468 |
| **Force on roller** | 42.145 | 13.527 | 27.947 | 34.217 | 18.757 |
| **Horiz force from pedal** | 41.806 | 14.267 | 37.990 | 41.744 | 39.639 |
| **Horiz force from other** | 0.339 | -0.741 | -10.043 | -7.526 | -20.883 |
| | | | | | |
| **Max Front bracket force** | 247.751 | 255.223 | 250.853 | 255.581 | 256.638 |
| **Min Front bracket force** | -346.283 | -371.265 | -352.018 | -375.420 | -375.178 |
| **Front bracket power** | 134.010 | 32.389 | 114.436 | 121.687 | 65.045 |
| **Max Front bracket power** | 882.176 | 928.793 | 921.741 | 934.201 | 934.419 |
| **Min Front bracket power** | -1226.648 | -1336.478 | -1280.201 | -1359.353 | -1353.570 |

## The Roller Rig on the Rough track (continued)
## Individual subjects average results for the hardtail bike

| | Subject 6 | mean | sd |
|---|---|---|---|
| **Accel Handlebar** | 0.000 | **0.000** | **0.000** |
| **Max Accel Handlebar** | 1.205 | **1.290** | **0.075** |
| **Min Accel Handlebar** | -1.113 | **-1.129** | **0.045** |
| **Difference** | 2.317 | **2.419** | **0.109** |
| | | | |
| **Velocity Handlebar** | 0.000 | **0.000** | **0.000** |
| **Max Velocity Handlebar** | 0.142 | **0.146** | **0.009** |
| **Min Velocity Handlebar** | -0.120 | **-0.125** | **0.006** |
| **Difference** | 0.262 | **0.271** | **0.013** |
| | | | |
| **Displ Handlebar** | 0.000 | **0.000** | **4.90038E-07** |
| **Max Displ Handlebar** | 0.004 | **0.004** | **0.000257049** |
| **MinDispl Handlebar** | -0.004 | **-0.004** | **0.000242009** |
| **Difference** | 0.007 | **0.008** | **0.000459469** |
| | | | |
| **Accel Seat** | 0.000 | **0.000** | **0.000** |
| **Max Impact Accel** | 2.061 | **2.111** | **0.105** |
| **Max landing Acel Seat** | 5.446 | **5.686** | **0.216** |
| **Min impact Accel Seat** | -3.047 | **-3.164** | **0.139** |
| **Difference** | 8.493 | **8.850** | **0.350** |
| | | | |
| **Velocity Seat** | 0.000 | **0.000** | **0.000** |
| **Max Velocity Seat** | 0.411 | **0.424** | **0.014** |
| **Min Velocity Seat** | -0.491 | **-0.513** | **0.025** |
| **Difference** | 0.902 | **0.937** | **0.038** |
| | | | |
| **Displ Seat** | 0.000 | **0.000** | **4.8131E-07** |
| **Max Displ Seat** | 0.010 | **0.011** | **0.000382263** |
| **Min Displ Seat** | -0.006 | **-0.007** | **0.000214465** |
| **Difference** | 0.017 | **0.017** | **0.000538914** |
| | | | |
| **Crank Velocity** | 0.620 | **0.537** | **0.106** |
| **Crank Force** | 82.080 | **110.809** | **30.336** |
| **Max Crank Force** | 202.166 | **208.220** | **15.835** |
| **Min Crank force** | 6.736195 | **6.583** | **0.637** |
| **Difference** | 195.430 | **201.637** | **16.15067554** |
| | | | |
| **Crank Power** | 101.389 | **118.326** | **45.263** |
| **Max Crank Power** | 221.640 | **224.619** | **15.931** |
| **Min Crank Power** | 8.321 | **7.925** | **1.488** |
| **Difference** | 213.319 | **216.694** | **16.46466528** |
| | | | |
| **Ground velocity** | 3.839 | **3.422** | **0.594** |
| **Force on roller** | 9.077 | **24.278** | **12.717** |
| **Horiz force from pedal** | 26.409 | **33.643** | **11.089** |
| **Horiz force from other** | -17.332 | **-9.364** | **8.585** |
| | | | |
| **Max Front bracket force** | 252.869 | **253.152** | **3.373** |
| **Min Front bracket force** | -357.003 | **-362.861** | **12.703** |
| **Front bracket power** | 34.848 | **83.736** | **45.357** |
| **Max Front bracket power** | 921.687 | **920.503** | **19.606** |
| **Min Front bracket power** | -1293.630 | **-1308.313** | **51.228** |

## The Roller Rig Statistical Results (hardtail - full suspension)

**% Improvement by fitting suspension = 100*(average diff. / HT mean)**

| | n | average | % Improvement | sum | sum of squares |
|---|---|---|---|---|---|
| **Accel Handlebar** | 6 | 1.284E-05 | 135.97% | 0.000 | 0.000 |
| **Max Accel Handlebar** | 6 | 0.028561 | 2.21% | 0.171 | 0.015 |
| **Min Accel Handlebar** | 6 | -0.0250053 | 2.21% | -0.150 | 0.015 |
| **Difference** | 6 | 0.0535663 | 2.21% | 0.321 | 0.060 |
| | | | | | |
| **Velocity Handlebar** | 6 | 8.863E-06 | 122.80% | 0.000 | 0.000 |
| **Max Velocity Handlebar** | 6 | 0.0065622 | 4.50% | 0.039 | 0.001 |
| **Min Velocity Handlebar** | 6 | -0.0036009 | 2.88% | -0.022 | 0.000 |
| **Difference** | 6 | 0.010163 | 3.75% | 0.061 | 0.002 |
| | | | | | |
| **Displ Handlebar** | 6 | -1.169E-07 | 119.04% | 0.000 | 0.000 |
| **Max Displ Handlebar** | 6 | 0.0001725 | 4.55% | 0.001 | 0.000 |
| **MinDispl Handlebar** | 6 | -0.0001009 | 2.63% | -0.001 | 0.000 |
| **Difference** | 6 | 0.0002734 | 3.59% | 0.002 | 0.000 |
| | | | | | |
| **Accel Seat** | 6 | 1.435E-05 | 118.85% | 0.000 | 0.000 |
| **Max Impact Accel** | 6 | 0.0715967 | 3.39% | 0.430 | 0.098 |
| **Max landing Acel Seat** | 6 | 0.0744895 | 1.31% | 0.447 | 0.103 |
| **Min impact Accel Seat** | 6 | -0.023652 | 0.75% | -0.142 | 0.009 |
| **Difference** | 6 | 0.0981415 | 1.11% | 0.589 | 0.151 |
| | | | | | |
| **Velocity Seat** | 6 | 5.336E-06 | 72.45% | 0.000 | 0.000 |
| **Max Velocity Seat** | 6 | 0.010065 | 2.37% | 0.060 | 0.002 |
| **Min Velocity Seat** | 6 | -0.0154542 | 3.01% | -0.093 | 0.005 |
| **Difference** | 6 | 0.0255192 | 2.72% | 0.153 | 0.012 |
| | | | | | |
| **Displ Seat** | 6 | 1.097E-07 | -2571.10% | 0.000 | 0.000 |
| **Max Displ Seat** | 6 | 0.0004004 | 3.72% | 0.002 | 0.000 |
| **Min Displ Seat** | 6 | -0.0001165 | 1.75% | -0.001 | 0.000 |
| **Difference** | 6 | 0.0005169 | 2.97% | 0.003 | 0.000 |
| | | | | | |
| **Crank Velocity** | 6 | -0.0290473 | -5.41% | -0.174 | 0.101 |
| **Crank Force** | 6 | 42.80264 | 38.63% | 256.816 | 14063.978 |
| **Max Crank Force** | 6 | 9.0659 | 4.35% | 54.395 | 926.036 |
| **Min Crank force** | 6 | -0.130461 | -1.98% | -0.783 | 0.611 |
| **Difference** | 6 | 9.196361 | 4.56% | 55.178 | 940.055 |
| | | | | | |
| **Crank Power** | 6 | 42.29974 | 35.75% | 253.798 | 20439.067 |
| **Max Crank Power** | 6 | 9.9438833 | 4.43% | 59.663 | 993.539 |
| **Min Crank Power** | 6 | 0.3797435 | 4.79% | 2.278 | 7.484 |
| **Difference** | 6 | 9.5641399 | 4.41% | 57.385 | 908.895 |
| | | | | | |
| **Ground velocity** | 6 | -0.2122007 | -6.20% | -1.273 | 2.154 |
| **Force on roller** | 6 | 6.8529502 | 28.23% | 41.118 | 2178.859 |
| **Horiz force from pedal** | 6 | 12.824493 | 38.12% | 76.947 | 1524.344 |
| **Horiz force from other** | 6 | -5.9715498 | 63.77% | -35.829 | 1902.974 |
| | | | | | |
| **Max Front bracket force** | 6 | 1.5703167 | 0.62% | 9.422 | 99.967 |
| **Min Front bracket force** | 6 | -9.42415 | 2.60% | -56.545 | 1593.199 |
| **Front bracket power** | 6 | 22.527258 | 26.90% | 135.164 | 29175.494 |
| **Max Front bracket power** | 6 | 5.0324667 | 0.55% | 30.195 | 1239.710 |
| **Min Front bracket power** | 6 | -31.791167 | 2.43% | -190.747 | 18261.168 |

## The Roller Rig Statistical Results (hardtail - full suspension) (continued)

**% Improvement by fitting suspension = 100*(average diff. / HT mean)**

| | sd | sd(mean) | t | p | Cv | Upper | Lower |
|---|---|---|---|---|---|---|---|
| **Accel Handlebar** | 0.000 | 0.000 | 1.283 | 25.563% | 1.909 | 0.000 | 0.000 |
| **Max Accel Handlebar** | 0.046 | 0.019 | 1.532 | 18.605% | 1.599 | 0.029 | 0.028 |
| **Min Accel Handlebar** | 0.048 | 0.020 | 1.277 | 25.767% | -1.918 | -0.025 | -0.025 |
| **Difference** | 0.093 | 0.038 | 1.415 | 21.612% | 1.731 | 0.054 | 0.053 |
| | | | | | | | |
| **Velocity Handlebar** | 0.000 | 0.000 | 2.212 | 7.787% | 1.107 | 0.000 | 0.000 |
| **Max Velocity Handlebar** | 0.009 | 0.004 | 1.755 | 13.963% | 1.396 | 0.007 | 0.007 |
| **Min Velocity Handlebar** | 0.007 | 0.003 | 1.341 | 23.748% | -1.826 | -0.004 | -0.004 |
| **Difference** | 0.016 | 0.006 | 1.593 | 17.194% | 1.537 | 0.010 | 0.010 |
| | | | | | | | |
| **Displ Handlebar** | 5.5E-07 | 0.000 | 0.523 | 62.316% | -4.681 | 0.000 | 0.000 |
| **Max Displ Handlebar** | 0.00022 | 0.000 | 1.913 | 11.400% | 1.281 | 0.000 | 0.000 |
| **MinDispl Handlebar** | 0.00015 | 0.000 | 1.666 | 15.664% | -1.470 | 0.000 | 0.000 |
| **Difference** | 0.00036 | 0.000 | 1.862 | 12.170% | 1.316 | 0.000 | 0.000 |
| | | | | | | | |
| **Accel Seat** | 0.000 | 0.000 | 0.704 | 51.300% | 3.481 | 0.000 | 0.000 |
| **Max Impact Accel** | 0.116 | 0.047 | 1.518 | 18.954% | 1.614 | 0.072 | 0.071 |
| **Max landing Acel Seat** | 0.118 | 0.048 | 1.542 | 18.367% | 1.588 | 0.075 | 0.074 |
| **Min impact Accel Seat** | 0.035 | 0.014 | 1.673 | 15.526% | -1.464 | -0.024 | -0.024 |
| **Difference** | 0.136 | 0.056 | 1.762 | 13.843% | 1.390 | 0.099 | 0.098 |
| | | | | | | | |
| **Velocity Seat** | 0.000 | 0.000 | 0.668 | 53.362% | 3.666 | 0.000 | 0.000 |
| **Max Velocity Seat** | 0.014 | 0.006 | 1.786 | 13.408% | 1.371 | 0.010 | 0.010 |
| **Min Velocity Seat** | 0.028 | 0.011 | 1.376 | 22.718% | -1.780 | -0.015 | -0.016 |
| **Difference** | 0.041 | 0.017 | 1.523 | 18.821% | 1.608 | 0.026 | 0.025 |
| | | | | | | | |
| **Displ Seat** | 8.7E-07 | 0.000 | 0.308 | 77.066% | 7.959 | 0.000 | 0.000 |
| **Max Displ Seat** | 0.0006 | 0.000 | 1.641 | 16.163% | 1.492 | 0.000 | 0.000 |
| **Min Displ Seat** | 0.00014 | 0.000 | 2.024 | 9.882% | -1.210 | 0.000 | 0.000 |
| **Difference** | 0.00073 | 0.000 | 1.729 | 14.442% | 1.417 | 0.001 | 0.001 |
| | | | | | | | |
| **Crank Velocity** | 0.138 | 0.056 | 0.515 | 62.878% | -4.760 | -0.028 | -0.030 |
| **Crank Force** | 24.785 | 10.119 | 4.230 | 0.825% | 0.579 | 42.911 | 42.695 |
| **Max Crank Force** | 9.305 | 3.799 | 2.387 | 6.265% | 1.026 | 9.106 | 9.025 |
| **Min Crank force** | 0.319 | 0.130 | 1.002 | 36.243% | -2.445 | -0.129 | -0.132 |
| **Difference** | 9.30179 | 3.797 | 2.422 | 5.999% | 1.011 | 9.237 | 9.156 |
| | | | | | | | |
| **Crank Power** | 44.053 | 17.985 | 2.352 | 6.540% | 1.041 | 42.492 | 42.108 |
| **Max Crank Power** | 8.947 | 3.653 | 2.722 | 4.166% | 0.900 | 9.983 | 9.905 |
| **Min Crank Power** | 1.151 | 0.470 | 0.808 | 45.555% | 3.030 | 0.385 | 0.375 |
| **Difference** | 8.48597 | 3.464 | 2.761 | 3.980% | 0.887 | 9.601 | 9.527 |
| | | | | | | | |
| **Ground velocity** | 0.614 | 0.251 | 0.847 | 43.574% | -2.893 | -0.210 | -0.215 |
| **Force on roller** | 19.479 | 7.952 | 0.862 | 42.820% | 2.842 | 6.938 | 6.768 |
| **Horiz force from pedal** | 10.369 | 4.233 | 3.030 | 2.909% | 0.808 | 12.870 | 12.779 |
| **Horiz force from other** | 18.379 | 7.503 | 0.796 | 46.221% | -3.078 | -5.891 | -6.052 |
| | | | | | | | |
| **Max Front bracket force** | 4.127 | 1.685 | 0.932 | 39.413% | 2.628 | 1.588 | 1.552 |
| **Min Front bracket force** | 14.562 | 5.945 | 1.585 | 17.377% | -1.545 | -9.361 | -9.488 |
| **Front bracket power** | 72.292 | 29.513 | 0.763 | 47.973% | 3.209 | 22.843 | 22.212 |
| **Max Front bracket power** | 14.750 | 6.022 | 0.836 | 44.139% | 2.931 | 5.097 | 4.968 |
| **Min Front bracket power** | 49.390 | 20.164 | 1.577 | 17.570% | -1.554 | -31.576 | -32.007 |

## The Roller Rig on the Rough track
## Individual subjects average results for the full suspension bike

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 |
|---|---|---|---|---|---|
| **Accel Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Accel Handlebar** | 1.153 | 1.334 | 1.395 | 1.257 | 1.270 |
| **Min Accel Handlebar** | -1.042 | -1.090 | -1.162 | -1.116 | -1.141 |
| **Difference** | 2.195 | 2.424 | 2.557 | 2.373 | 2.412 |
| | | | | | |
| **Velocity Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Velocity Handlebar** | 0.129 | 0.135 | 0.147 | 0.144 | 0.145 |
| **Min Velocity Handlebar** | -0.112 | -0.123 | -0.133 | -0.121 | -0.125 |
| **Difference** | 0.241 | 0.258 | 0.280 | 0.265 | 0.271 |
| | | | | | |
| **Displ Handlebar** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Displ Handlebar** | 0.003 | 0.003 | 0.004 | 0.004 | 0.004 |
| **MinDispl Handlebar** | -0.003 | -0.004 | -0.004 | -0.004 | -0.004 |
| **Difference** | 0.007 | 0.007 | 0.007 | 0.008 | 0.008 |
| | | | | | |
| **Accel Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Impact Accel** | 1.900 | 2.076 | 2.240 | 2.044 | 2.009 |
| **Max landing Acel Seat** | 5.254 | 5.759 | 5.889 | 5.771 | 5.742 |
| **Min impact Accel Seat** | -2.952 | -3.283 | -3.290 | -3.201 | -3.115 |
| **Difference** | 8.206 | 9.042 | 9.179 | 8.971 | 8.857 |
| | | | | | |
| **Velocity Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Velocity Seat** | 0.390 | 0.419 | 0.437 | 0.420 | 0.421 |
| **Min Velocity Seat** | -0.461 | -0.505 | -0.545 | -0.502 | -0.501 |
| **Difference** | 0.851 | 0.925 | 0.983 | 0.922 | 0.922 |
| | | | | | |
| **Displ Seat** | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| **Max Displ Seat** | 0.010 | 0.010 | 0.011 | 0.010 | 0.011 |
| **Min Displ Seat** | -0.006 | -0.007 | -0.007 | -0.007 | -0.007 |
| **Difference** | 0.016 | 0.017 | 0.018 | 0.017 | 0.017 |
| | | | | | |
| **Crank Velocity** | 0.598 | 0.627 | 0.669 | 0.450 | 0.550 |
| **Crank Force** | 56.428 | 64.628 | 72.623 | 90.899 | 69.774 |
| **Max Crank Force** | 173.737 | 195.976 | 209.988 | 218.938 | 211.233 |
| **Min Crank force** | 7.390989 | 6.954234 | 5.737585 | 6.682507 | 6.753455 |
| **Difference** | 166.346 | 189.021 | 204.250 | 212.256 | 204.480 |
| | | | | | |
| **Crank Power** | 67.231 | 80.687 | 96.674 | 81.420 | 76.444 |
| **Max Crank Power** | 190.206 | 211.680 | 228.261 | 230.090 | 226.626 |
| **Min Crank Power** | 8.806 | 8.682 | 7.638 | 5.986 | 7.399 |
| **Difference** | 181.400 | 202.998 | 220.624 | 224.105 | 219.227 |
| | | | | | |
| **Ground velocity** | 3.246 | 3.803 | 4.113 | 3.707 | 3.476 |
| **Force on roller** | 16.459 | 14.922 | -2.574 | 20.707 | 28.296 |
| **Horiz force from pedal** | 20.711 | 21.217 | 23.505 | 21.966 | 21.993 |
| **Horiz force from other** | -4.251 | -6.296 | -26.079 | -1.259 | 6.303 |
| | | | | | |
| **Max Front bracket force** | 245.672 | 249.377 | 255.205 | 258.174 | 252.127 |
| **Min Front bracket force** | -337.296 | -350.139 | -370.709 | -364.108 | -355.339 |
| **Front bracket power** | 53.430 | 56.744 | -10.586 | 76.754 | 98.351 |
| **Max Front bracket power** | 884.427 | 914.121 | 931.835 | 945.786 | 913.109 |
| **Min Front bracket power** | -1209.749 | -1269.769 | -1339.673 | -1322.205 | -1278.155 |

## The Roller Rig on the Rough track (continued)
## Individual subjects average results for the full suspension bike

| | Subject 6 | mean | sd |
|---|---|---|---|
| **Accel Handlebar** | 0.000 | **0.000** | **0.000** |
| **Max Accel Handlebar** | 1.158 | **1.261** | **0.096** |
| **Min Accel Handlebar** | -1.073 | **-1.104** | **0.045** |
| **Difference** | 2.231 | **2.365** | **0.134** |
| | | | |
| **Velocity Handlebar** | 0.000 | **0.000** | **0.000** |
| **Max Velocity Handlebar** | 0.134 | **0.139** | **0.007** |
| **Min Velocity Handlebar** | -0.115 | **-0.121** | **0.007** |
| **Difference** | 0.249 | **0.261** | **0.014** |
| | | | |
| **Displ Handlebar** | 0.000 | **1.86981E-08** | **2.71467E-07** |
| **Max Displ Handlebar** | 0.004 | **0.003621905** | **0.000201404** |
| **MinDispl Handlebar** | -0.004 | **-0.00372833** | **0.000244723** |
| **Difference** | 0.007 | **0.007350235** | **0.000423539** |
| | | | |
| **Accel Seat** | 0.000 | **0.000** | **0.000** |
| **Max Impact Accel** | 1.967 | **2.039** | **0.116** |
| **Max landing Acel Seat** | 5.254 | **5.611** | **0.282** |
| **Min impact Accel Seat** | -3.001 | **-3.140** | **0.143** |
| **Difference** | 8.255 | **8.752** | **0.417** |
| | | | |
| **Velocity Seat** | 0.000 | **0.000** | **0.000** |
| **Max Velocity Seat** | 0.397 | **0.414** | **0.017** |
| **Min Velocity Seat** | -0.470 | **-0.497** | **0.030** |
| **Difference** | 0.867 | **0.911** | **0.047** |
| | | | |
| **Displ Seat** | 0.000 | **-1.13946E-07** | **7.75505E-07** |
| **Max Displ Seat** | 0.010 | **0.010374472** | **0.000465064** |
| **Min Displ Seat** | -0.006 | **-0.006525118** | **0.000269182** |
| **Difference** | 0.016 | **0.01689959** | **0.000711952** |
| | | | |
| **Crank Velocity** | 0.502 | **0.566** | **0.081** |
| **Crank Force** | 53.686 | **68.007** | **13.409** |
| **Max Crank Force** | 185.051 | **199.154** | **17.376** |
| **Min Crank force** | 6.759768 | **6.713** | **0.543** |
| **Difference** | 178.292 | **192.4408937** | **17.71918344** |
| | | | |
| **Crank Power** | 53.702 | **76.026** | **14.512** |
| **Max Crank Power** | 201.190 | **214.676** | **16.460** |
| **Min Crank Power** | 6.762 | **7.545** | **1.092** |
| **Difference** | 194.428 | **207.130202** | **17.07036081** |
| | | | |
| **Ground velocity** | 3.461 | **3.634** | **0.306** |
| **Force on roller** | 26.743 | **17.425** | **11.162** |
| **Horiz force from pedal** | 15.516 | **20.818** | **2.764** |
| **Horiz force from other** | 11.226 | **-3.393** | **12.932** |
| | | | |
| **Max Front bracket force** | 248.938 | **251.582** | **4.553** |
| **Min Front bracket force** | -343.030 | **-353.437** | **12.614** |
| **Front bracket power** | 92.557 | **61.208** | **39.595** |
| **Max Front bracket power** | 903.545 | **915.470** | **21.448** |
| **Min Front bracket power** | -1239.582 | **-1276.522** | **48.880** |

**Roller Rig RMS results for the hardtail bike**

**Roller Rig RMS results for the hardtail bike (continued)**

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 | Subject 6 | Mean of all subjects | sd of all subjects |
|---|---|---|---|---|---|---|---|---|
| **RMS acc hb** | 0.5567189 | 0.3606906 | 0.4816939 | 0.5785291 | 0.6184565 | 0.3361851 | **0.489** | **0.118** |
| **RMS acc seat** | 1.789445 | 1.313479 | 1.630649 | 1.727443 | 1.849721 | 1.265435 | **1.596** | **0.249** |
| **RMS vel hb** | 0.1022832 | 0.0652056 | 0.06849719 | 0.1094143 | 0.1064376 | 0.04964699 | **0.084** | **0.026** |
| **RMS vel seat** | 0.2685074 | 0.1774216 | 0.2096365 | 0.2401229 | 0.2635176 | 0.1772229 | **0.223** | **0.041** |
| **RMS dist hb** | 0.004140077 | 0.003165505 | 0.002720435 | 0.004666297 | 0.003905051 | 0.001864038 | **0.003** | **0.001** |
| **RMS dist seat** | 0.00777643 | 0.004777784 | 0.004803884 | 0.006518986 | 0.007070794 | 0.004419894 | **0.006** | **0.001** |
| **Pedal force mean** | 129.8028 | 100.7805 | 126.4102 | 153.647 | 135.0487 | 123.9633 | **128.275** | **17.146** |
| **Pedal force max** | 216.533 | 207.4141 | 214.427 | 233.2572 | 228.1175 | 214.8532 | **219.100** | **9.641** |
| **Pedal force min** | 7.399145 | 6.981442 | 5.747619 | 5.902222 | 6.729149 | 6.736195 | **6.583** | **0.637** |
| **Pedal power mean** | 132.8344 | 151.88192 | 163.3782 | 155.8426 | 154.9645 | 153.1244 | **152.004** | **10.214** |
| **Pedal power max** | 228.6392 | 186.3639 | 229.1414 | 254.1059 | 246.3279 | 237.6081 | **230.364** | **23.713** |
| **Pedal power min** | 7.571955201 | 10.5214284 | 7.428480032 | 5.986564152 | 7.721504985 | 8.320816061 | **7.925** | **1.488** |
| **Pedal force min2** | -9.314249 | -16.03382 | -13.47398 | -5.901133 | -1.208099 | 4.764853 | **-6.861** | **7.771** |
| **Pedal power min2** | -9.531785 | -8.254232 | -17.41439 | -5.985459 | -1.386259 | 5.885734 | **-6.114** | **7.878** |
| **Velocity** | 1.023355428 | 1.507056623 | 1.292444755 | 1.014289898 | 1.147471246 | 1.235239785 | **1.203** | **0.186** |

**Roller Rig RMS results for the hardtail bike - the fully suspended bike**

| **NULL HYPOTHESIS** | **n** | **average** | **% Improvement** | **sum** | **sum of squares** | **sd** | **sd(mean)** | **t** |
|---|---|---|---|---|---|---|---|---|
| **RMS acc hb** | 6 | 0.152736317 | 31.25% | 0.916 | 0.184 | 0.094 | 0.038 | 3.984 |
| **RMS acc seat** | 6 | 0.317433233 | 19.89% | 1.905 | 0.821 | 0.208 | 0.085 | 3.736 |
| **RMS vel hb** | 6 | 0.041835302 | 50.05% | 0.251 | 0.013 | 0.023 | 0.009 | 4.527 |
| **RMS vel seat** | 6 | 0.085662517 | 38.46% | 0.514 | 0.052 | 0.040 | 0.016 | 5.302 |
| **RMS dist hb** | 6 | 0.001497399 | 43.91% | 0.009 | 0.000 | 0.001 | 0.000 | 4.325 |
| **RMS dist seat** | 6 | 0.001934838 | 32.82% | 0.012 | 0.000 | 0.002 | 0.001 | 3.130 |
| **Pedal force mean** | 6 | 35.90909 | 27.99% | 215.455 | 10594.004 | 23.905 | 9.759 | 3.680 |
| **Pedal force max** | 6 | 13.36623333 | 6.10% | 80.197 | 1761.659 | 11.745 | 4.795 | 2.788 |
| **Pedal force min** | 6 | -0.130461 | -1.98% | -0.783 | 0.611 | 0.319 | 0.130 | 1.002 |
| **Pedal power mean** | 6 | 48.19704167 | 31.71% | 289.182 | 15757.633 | 19.078 | 7.789 | 6.188 |
| **Pedal power max** | 6 | 10.66881667 | 4.63% | 64.013 | 1687.958 | 14.178 | 5.788 | 1.843 |
| **Pedal power min** | 6 | 0.379743471 | 4.79% | 2.278 | 7.484 | 1.151 | 0.470 | 0.808 |
| **Pedal force min2** | 6 | -8.6572241 | 126.18% | -51.943 | 1847.640 | 16.721 | 6.826 | 1.268 |
| **Pedal power min2** | 6 | -9.282723983 | 151.82% | -55.696 | 2953.339 | 22.074 | 9.012 | 1.030 |
| **Velocity** | 6 | 0.076193675 | 6.33% | 0.457 | 0.169 | 0.164 | 0.067 | 1.141 |

**Roller Rig RMS results for the hardtail bike - the fully suspended bike (cont)**

| **NULL HYPOTHESIS** | | | **95% CONFIDENCE LIMITS** | | **% Improvement by fitting suspension** | |
|---|---|---|---|---|---|---|
| | | | | | **= 100*(average diff. / HT mean)** | |
| | **p** | **Cv** | **Upper** | **Lower** | **HT mean** | **% improvement** |
| **RMS acc hb** | 1.049% | 0.615 | 0.153 | 0.153 | 0.1527 | 31.3% |
| **RMS acc seat** | 1.349% | 0.656 | 0.317 | 0.317 | 0.3174 | 19.9% |
| **RMS vel hb** | 0.625% | 0.541 | 0.042 | 0.042 | 0.0418 | 50.1% |
| **RMS vel seat** | 0.319% | 0.462 | 0.086 | 0.086 | 0.0857 | 38.5% |
| **RMS dist hb** | 0.754% | 0.566 | 0.001 | 0.001 | 0.0015 | 43.9% |
| **RMS dist seat** | 2.597% | 0.783 | 0.002 | 0.002 | 0.0019 | 32.8% |
| **Pedal force mean** | 1.430% | 0.666 | 35.909 | 35.909 | 35.9091 | 28.0% |
| **Pedal force max** | 3.855% | 0.879 | 13.366 | 13.366 | 13.3662 | 6.1% |
| **Pedal force min** | 36.243% | -2.445 | -0.130 | -0.130 | **-0.1305** | **-2.0%** |
| **Pedal power mean** | 0.161% | 0.396 | 48.197 | 48.197 | 48.1970 | 31.7% |
| **Pedal power max** | 12.462% | 1.329 | 10.669 | 10.669 | 10.6688 | 4.6% |
| **Pedal power min** | 45.555% | 3.030 | 0.380 | 0.380 | **0.3797** | **4.8%** |
| **Pedal force min2** | 26.056% | -1.931 | -8.657 | -8.657 | -8.6572 | 126.2% |
| **Pedal power min2** | 35.020% | -2.378 | -9.283 | -9.283 | -9.2827 | 151.8% |
| **Velocity** | 30.549% | 2.146 | 0.076 | 0.076 | 0.0762 | 6.3% |

**Roller Rig RMS results for the fully suspended bike**

| | **Subject 1** | **Subject 2** | **Subject 3** | **Subject 4** | **Subject 5** | **Subject 6** | **Mean of all subjects** | **sd of all subjects** |
|---|---|---|---|---|---|---|---|---|
| **RMS acc hb** | 0.2837445 | 0.3272582 | 0.342016 | 0.4048825 | 0.3841959 | 0.2737591 | **0.336** | **0.053** |
| **RMS acc seat** | 1.234403 | 1.34046 | 1.411776 | 1.325659 | 1.378586 | 0.9806886 | **1.279** | **0.158** |
| **RMS vel hb** | 0.03182286 | 0.04021579 | 0.04285707 | 0.06136209 | 0.04145236 | 0.0327629 | **0.042** | **0.011** |
| **RMS vel seat** | 0.1327562 | 0.1412222 | 0.1478592 | 0.1377381 | 0.1429258 | 0.1199523 | **0.137** | **0.010** |
| **RMS dist hb** | 0.001320629 | 0.001870092 | 0.00202408 | 0.003228104 | 0.001786211 | 0.001247894 | **0.002** | **0.001** |
| **RMS dist seat** | 0.003833421 | 0.004162709 | 0.004684042 | 0.003682051 | 0.004140923 | 0.0032556 | **0.004** | **0.000** |
| **Pedal force mean** | 66.06692 | 89.52171 | 110.492 | 100.5032 | 79.62033 | 107.9938 | **92.366** | **17.327** |
| **Pedal force max** | 180.0189 | 195.1142 | 210.8997 | 225.9696 | 217.7644 | 204.6378 | **205.734** | **16.469** |
| **Pedal force min** | 7.390989 | 6.954234 | 5.737585 | 6.682507 | 6.753455 | 6.759768 | **6.713** | **0.543** |
| **Pedal power mean** | 78.71504 | 111.7654 | 147.0832 | 90.02244 | 87.23229 | 108.0254 | **103.807** | **24.691** |
| **Pedal power max** | 194.8421 | 188.5041 | 235.3831 | 240.3835 | 235.3869 | 223.6738 | **219.696** | **22.480** |
| **Pedal power min** | 8.805950009 | 8.682170445 | 7.637678403 | 5.985636134 | 7.39910705 | 6.761745972 | **7.545** | **1.092** |
| **Pedal force min2** | 0.6051185 | -6.114453 | 26.63012 | -8.46097 | -0.6747999 | -1.208099 | **1.796** | **12.658** |
| **Pedal power min2** | 0.7209648 | -7.633726 | 35.44912 | -7.57864 | -0.7393129 | -1.208453 | **3.168** | **16.215** |
| **Velocity** | 1.191444069 | 1.248472577 | 1.331166057 | 0.895717151 | 1.095603221 | 1.000292609 | **1.127** | **0.162** |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the Rough track

| | | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (m/s^2) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | **137.26043** | **-533.5248** | **938.96145** | **109.09642** | **-690.6152** | **1092.8352** | **-0.002929** | **-4.160792** | **2.4531533** |
| | **No data points** | | 250 | 273 | | 209 | 250 | | 321 | 205 |
| | **Max** | 1340.3185 | | | 1370.7854 | | | 6.4535714 | | |
| | **Min** | -731.8014 | | | -944.3683 | | | -8.825 | | |
| | **Difference** | 1472.4863 | | | 1783.4504 | | | 6.6139455 | | |
| **Subject 2** | **Average** | **156.10877** | **-621.9469** | **969.92826** | **98.877104** | **-731.361** | **1073.757** | **-0.002461** | **-3.69661** | **2.7513489** |
| | **No data points** | | 256 | 218 | | 266 | 270 | | 375 | 233 |
| | **Max** | 1553.7614 | | | 1603.2158 | | | 11.65 | | |
| | **Min** | -918.7297 | | | -1041.367 | | | -7.671429 | | |
| | **Difference** | 1591.8751 | | | 1805.118 | | | 6.4479584 | | |
| **Subject 3** | **Average** | **138.62621** | **-590.8655** | **863.42401** | **135.40647** | **-744.4361** | **1015.1185** | **-0.004444** | **-4.291885** | **2.4315762** |
| | **No data points** | | 289 | 298 | | 214 | 220 | | 283 | 208 |
| | **Max** | 1230.2827 | | | 1398.2378 | | | 9.7642857 | | |
| | **Min** | -1138.801 | | | -1273.797 | | | -9.696429 | | |
| | **Difference** | 1454.2895 | | | 1759.5546 | | | 6.7234616 | | |
| **Subject 4** | **Average** | **168.59696** | **-600.7652** | **974.34338** | **167.0636** | **-733.0938** | **1062.4579** | **-0.003534** | **-4.810714** | **2.3100889** |
| | **No data points** | | 251 | 200 | | 193 | 268 | | 266 | 217 |
| | **Max** | 1262.1002 | | | 1469.6141 | | | 3.9571429 | | |
| | **Min** | -873.6548 | | | -969.9906 | | | -7.360714 | | |
| | **Difference** | 1575.1085 | | | 1795.5517 | | | 7.1208032 | | |
| **Subject 5** | **Average** | **112.68988** | **-566.8643** | **970.6303** | **-17.5741** | **-714.4521** | **913.18371** | **-0.002104** | **-3.180229** | **2.6744609** |
| | **No data points** | | 233 | 208 | | 305 | 298 | | 306 | 212 |
| | **Max** | 1392.022 | | | 1594.065 | | | 3.9071429 | | |
| | **Min** | -821.9512 | | | -1149.346 | | | -8.282143 | | |
| | **Difference** | 1537.4946 | | | 1627.6358 | | | 5.8546897 | | |
| **Subject 6** | **Average** | **122.99149** | **-572.4156** | **885.35157** | **87.450873** | **-720.8038** | **1010.2121** | **-0.004028** | **-3.930233** | **2.4223036** |
| | **No data points** | | 267 | 303 | | 212 | 232 | | 301 | 200 |
| | **Max** | 1197.1393 | | | 1218.882 | | | 3.4892857 | | |
| | **Min** | -828.5799 | | | -969.9906 | | | -6.485714 | | |
| | **Difference** | 1457.7672 | | | 1731.0159 | | | 6.3525361 | | |
| **Subject 7** | **Average** | **137.38651** | **-572.2201** | **983.48499** | **99.253391** | **-689.5041** | **1065.6027** | **-0.003467** | **-3.699596** | **2.7894876** |
| | **No data points** | | 266 | 232 | | 256 | 278 | | 292 | 230 |
| | **Max** | 1463.6116 | | | 1460.4633 | | | 4.3428571 | | |
| | **Min** | -873.6548 | | | -1006.594 | | | -7.639286 | | |
| | **Difference** | 1555.7051 | | | 1755.1069 | | | 6.489084 | | |
| **Subject 8** | **Average** | **182.4721** | **-583.6091** | **1050.8635** | **123.75277** | **-736.061** | **1044.0009** | **-0.003463** | **-4.179544** | **2.5456633** |
| | **No data points** | | 302 | 131 | | 282 | 227 | | 393 | 322 |
| | **Max** | 1340.3185 | | | 1343.333 | | | 5.4071429 | | |
| | **Min** | -886.9121 | | | -1068.819 | | | -8.825 | | |
| | **Difference** | 1634.4726 | | | 1780.0618 | | | 6.7252071 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the Rough track (continued)

| | | Channel 5 Force (On crank) | | | Channel 6 Crank speed | | | Channel 7 Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | **199.42043** | **163.67405** | **245.35125** | **0.3593333** | **0.2632161** | **0.5362513** | **1.7712082** | **1.5824726** | **1.9648717** |
| | **No data points** | | 223 | 141 | | 90 | 62 | | 226 | 196 |
| | **Max** | 297.8767 | | | 0.6535986 | | | 2.1346889 | | |
| | **Min** | 102.00041 | | | 0.0979398 | | | 1.3154998 | | |
| | **Difference** | 81.677196 | | | 0.2730352 | | | 0.3823991 | | |
| **Subject 2** | **Average** | **193.52139** | **161.43221** | **224.43478** | **0.3734786** | **0.2794887** | **0.5406776** | **1.8411689** | **1.7123955** | **1.9589301** |
| | **No data points** | | 253 | 193 | | 106 | 103 | | 290 | 268 |
| | **Max** | 264.69371 | | | 0.6446041 | | | 2.1254638 | | |
| | **Min** | 123.90763 | | | 0.0929429 | | | 1.5756477 | | |
| | **Difference** | 63.002572 | | | 0.2611889 | | | 0.2465346 | | |
| **Subject 3** | **Average** | **183.0541** | **130.27039** | **233.78735** | **0.3603848** | **0.2503252** | **0.5558986** | **1.7739151** | **1.5738112** | **1.9387057** |
| | **No data points** | | 86 | 90 | | 119 | 75 | | 216 | 202 |
| | **Max** | 323.81098 | | | 0.6585955 | | | 2.0719582 | | |
| | **Min** | 97.973351 | | | 0.043973 | | | 0.0276753 | | |
| | **Difference** | 103.51697 | | | 0.3055733 | | | 0.3648945 | | |
| **Subject 4** | **Average** | **207.4894** | **166.05557** | **247.40213** | **0.3541999** | **0.2532889** | **0.5472889** | **1.7489648** | **1.621685** | **1.9221666** |
| | **No data points** | | 272 | 156 | | 108 | 40 | | 272 | 246 |
| | **Max** | 288.37284 | | | 0.6096256 | | | 2.0369028 | | |
| | **Min** | 127.12928 | | | 0.0929429 | | | 1.3782305 | | |
| | **Difference** | 81.346558 | | | 0.294 | | | 0.3004816 | | |
| **Subject 5** | **Average** | **148.48206** | **97.072295** | **209.50579** | **0.366763** | **0.3019895** | **0.5524148** | **1.8114056** | **1.6863858** | **1.9429111** |
| | **No data points** | | 288 | 211 | | 80 | 122 | | 250 | 230 |
| | **Max** | 264.69371 | | | 0.6446041 | | | 2.0719582 | | |
| | **Min** | 53.997835 | | | 0.1169282 | | | 1.4686365 | | |
| | **Difference** | 112.43349 | | | 0.2504253 | | | 0.2565253 | | |
| **Subject 6** | **Average** | **185.50504** | **149.03897** | **243.3473** | **0.3524766** | **0.2411494** | **0.5309297** | **1.7403029** | **1.5956446** | **1.9070288** |
| | **No data points** | | 260 | 162 | | 121 | 43 | | 266 | 240 |
| | **Max** | 288.37284 | | | 0.5906372 | | | 2.0276777 | | |
| | **Min** | 105.06098 | | | 0.0929429 | | | 1.3874556 | | |
| | **Difference** | 94.308328 | | | 0.2897803 | | | 0.3113841 | | |
| **Subject 7** | **Average** | **198.1212** | **160.55826** | **247.19184** | **0.3780013** | **0.3103305** | **0.5472041** | **1.8532702** | **1.7009165** | **2.000705** |
| | **No data points** | | 203 | 155 | | 71 | 137 | | 297 | 281 |
| | **Max** | 289.17825 | | | 0.6535986 | | | 2.1808145 | | |
| | **Min** | 94.107371 | | | 0.1369159 | | | 1.5221421 | | |
| | **Difference** | 86.633585 | | | 0.2368735 | | | 0.2997885 | | |
| **Subject 8** | **Average** | **185.52826** | **130.163** | **238.55003** | **0.384123** | **0.2782332** | **0.5585244** | **1.8990931** | **1.7194812** | **2.056691** |
| | **No data points** | | 150 | 190 | | 99 | 166 | | 189 | 262 |
| | **Max** | 274.19758 | | | 0.7315507 | | | 2.2066447 | | |
| | **Min** | 90.885722 | | | 0.1219251 | | | 1.5405923 | | |
| | **Difference** | 108.38703 | | | 0.2802913 | | | 0.3372099 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the Rough track (continued)

| | | Channel 8<br>Force (Vertical Right Handlebar) | | | Channel 9<br>Force (On seat) | | | Channel 11<br>Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (N) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | **85.806847** | **-47.93615** | **193.91659** | **200.09091** | **-214.98** | **648.55715** | **57.608172** | **-90.44521** | **168.61446** |
| | **No data points** | | 218 | 232 | | 276 | 295 | | 236 | 285 |
| | **Max** | 271.61993 | | | 1039.1685 | | | 264.68549 | | |
| | **Min** | -112.969 | | | -298.2299 | | | -163.9782 | | |
| | **Difference** | 241.85274 | | | 863.53714 | | | 259.05967 | | |
| **Subject 2** | **Average** | **103.63323** | **-60.68308** | **215.45097** | **189.3427** | **-239.7412** | **764.4506** | **83.878748** | **-111.6779** | **214.56788** |
| | **No data points** | | 206 | 226 | | 249 | 275 | | 228 | 261 |
| | **Max** | 305.33166 | | | 1138.0845 | | | 311.81267 | | |
| | **Min** | -123.2889 | | | -337.5253 | | | -186.5734 | | |
| | **Difference** | 276.13404 | | | 1004.1918 | | | 326.24574 | | |
| **Subject 3** | **Average** | **57.357164** | **-51.19613** | **163.68202** | **386.23434** | **0.5472858** | **891.66154** | **27.57358** | **-86.17056** | **143.58885** |
| | **No data points** | | 251 | 245 | | 203 | 286 | | 292 | 216 |
| | **Max** | 251.3241 | | | 1369.7918 | | | 226.5964 | | |
| | **Min** | -138.4248 | | | -99.04287 | | | -163.9782 | | |
| | **Difference** | 214.87815 | | | 891.11426 | | | 229.75941 | | |
| **Subject 4** | **Average** | **52.666639** | **-47.53741** | **138.24693** | **277.25963** | **-82.28445** | **638.11146** | **33.165911** | **-86.23105** | **142.44472** |
| | **No data points** | | 229 | 274 | | 223 | 201 | | 251 | 208 |
| | **Max** | 177.36469 | | | 793.91106 | | | 207.87465 | | |
| | **Min** | -97.83311 | | | -131.5632 | | | -135.5727 | | |
| | **Difference** | 185.78434 | | | 720.39592 | | | 228.67576 | | |
| **Subject 5** | **Average** | **102.05926** | **-31.54914** | **239.30111** | **268.8323** | **-81.36782** | **706.76439** | **61.250738** | **-100.7389** | **196.33428** |
| | **No data points** | | 240 | 244 | | 276 | 257 | | 283 | 242 |
| | **Max** | 333.88344 | | | 2051.3636 | | | 296.31881 | | |
| | **Min** | -106.433 | | | -899.8559 | | | -195.6115 | | |
| | **Difference** | 270.85025 | | | 788.13221 | | | 297.07319 | | |
| **Subject 6** | **Average** | **69.724044** | **-48.06241** | **160.29135** | **253.08487** | **-112.4414** | **639.02215** | **28.663786** | **-99.19896** | **118.89999** |
| | **No data points** | | 199 | 261 | | 277 | 237 | | 242 | 230 |
| | **Max** | 253.04408 | | | 959.22271 | | | 226.5964 | | |
| | **Min** | -118.1289 | | | -178.9887 | | | -167.206 | | |
| | **Difference** | 208.35377 | | | 751.46351 | | | 218.09896 | | |
| **Subject 7** | **Average** | **110.03362** | **-13.79605** | **227.19936** | **483.99247** | **-75.08973** | **1138.3621** | **72.544812** | **-127.7413** | **204.04372** |
| | **No data points** | | 257 | 245 | | 217 | 205 | | 214 | 258 |
| | **Max** | 368.97116 | | | 1608.2742 | | | 311.81267 | | |
| | **Min** | -163.5366 | | | -185.7637 | | | -198.8394 | | |
| | **Difference** | 240.99541 | | | 1213.4518 | | | 331.78506 | | |
| **Subject 8** | **Average** | **56.885622** | **-80.9641** | **207.1853** | **221.78115** | **-83.32869** | **575.22171** | **15.953624** | **-126.2037** | **182.71881** |
| | **No data points** | | 157 | 122 | | 273 | 303 | | 197 | 119 |
| | **Max** | 283.31584 | | | 913.15225 | | | 258.22972 | | |
| | **Min** | -171.7925 | | | -178.9887 | | | -186.5734 | | |
| | **Difference** | 288.1494 | | | 658.55039 | | | 308.92248 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the Rough track (continued)

| | | Channel 12<br>Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|---|
| | | (m/s^2) | | | (W) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | **-0.016521** | **-7.164521** | **10.790804** | 71.658408 | 43.081649 | 131.56992 |
| | **No data points** | | 269 | 370 | | | |
| | **Max** | 27.390244 | | | 194.69179 | | |
| | **Min** | -31.7439 | | | 9.9899049 | | |
| | **Difference** | 17.955325 | | | 88.488276 | | |
| **Subject 2** | **Average** | **-0.010523** | **-7.222416** | **9.5054384** | 72.276091 | 45.118481 | 121.34687 |
| | **No data points** | | 210 | 296 | | | |
| | **Max** | 47.512195 | | | 170.62265 | | |
| | **Min** | -27.92683 | | | 11.516336 | | |
| | **Difference** | 16.727854 | | | 76.228385 | | |
| **Subject 3** | **Average** | **-0.010334** | **-6.870817** | **11.245209** | 65.969912 | 32.609967 | 129.96206 |
| | **No data points** | | 285 | 392 | | | |
| | **Max** | 31.02439 | | | 213.26046 | | |
| | **Min** | -58.65854 | | | 4.3081815 | | |
| | **Difference** | 18.116026 | | | 97.352092 | | |
| **Subject 4** | **Average** | **-0.016629** | **-7.003669** | **11.554426** | 73.492731 | 42.060029 | 135.40043 |
| | **No data points** | | 236 | 324 | | | |
| | **Max** | 34.597561 | | | 175.79946 | | |
| | **Min** | -25.2439 | | | 11.815766 | | |
| | **Difference** | 18.558095 | | | 93.340402 | | |
| **Subject 5** | **Average** | **-0.015605** | **-6.482982** | **9.4965648** | 54.45772 | 29.314817 | 115.7341 |
| | **No data points** | | 177 | 213 | | | |
| | **Max** | 22.865854 | | | 170.62265 | | |
| | **Min** | -27.86585 | | | 6.3138689 | | |
| | **Difference** | 15.979547 | | | 86.419285 | | |
| **Subject 6** | **Average** | **-0.011904** | **-6.912024** | **11.329047** | 65.386194 | 35.940661 | 129.20032 |
| | **No data points** | | 257 | 331 | | | |
| | **Max** | 30.073171 | | | 170.32374 | | |
| | **Min** | -23.04878 | | | 9.7646739 | | |
| | **Difference** | 18.241072 | | | 93.259656 | | |
| **Subject 7** | **Average** | **-0.011847** | **-6.87561** | **8.1306058** | 74.890076 | 49.826129 | 135.26438 |
| | **No data points** | | 195 | 186 | | | |
| | **Max** | 43.890244 | | | 189.00649 | | |
| | **Min** | -23.40244 | | | 12.884796 | | |
| | **Difference** | 15.006216 | | | 85.438252 | | |
| **Subject 8** | **Average** | **-0.020502** | **-6.905062** | **10.69645** | 71.265669 | 36.215662 | 133.23602 |
| | **No data points** | | 265 | 450 | | | |
| | **Max** | 38.646341 | | | 200.58943 | | |
| | **Min** | -28.28049 | | | 11.081252 | | |
| | **Difference** | 17.601512 | | | 97.020358 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the Rough track

| | | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (m/s^2) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | **158.85774** | **-419.9007** | **790.25645** | **136.65857** | **-540.0248** | **865.28758** | **-0.00355** | **-1.882023** | **1.7320807** |
| | **No data points** | | 240 | 204 | | 210 | 250 | | 119 | 115 |
| | **Max** | 1093.7322 | | | 1209.7312 | | | 2.9464286 | | |
| | **Min** | -608.5083 | | | -783.3142 | | | -11.03929 | | |
| | **Difference** | 1210.1572 | | | 1405.3123 | | | 3.6141036 | | |
| **Subject 2** | **Average** | **126.00413** | **-482.2788** | **757.90387** | **97.216803** | **-601.0234** | **839.62941** | **-0.006849** | **-2.422837** | **1.9724181** |
| | **No data points** | | 242 | 222 | | 217 | 237 | | 213 | 231 |
| | **Max** | 1023.4684 | | | 1182.2788 | | | 8.7178571 | | |
| | **Min** | -743.733 | | | -907.7651 | | | -12.46786 | | |
| | **Difference** | 1240.1827 | | | 1440.6528 | | | 4.3952551 | | |
| **Subject 3** | **Average** | **161.79686** | **-529.9303** | **771.26049** | **122.23636** | **-640.7622** | **878.26037** | **-0.00284** | **-2.088743** | **1.7796908** |
| | **No data points** | | 269 | 287 | | 292 | 268 | | 270 | 201 |
| | **Max** | 1093.7322 | | | 1262.8059 | | | 3.6464286 | | |
| | **Min** | -848.4659 | | | -969.9906 | | | -4.760714 | | |
| | **Difference** | 1301.1908 | | | 1519.0225 | | | 3.8684342 | | |
| **Subject 4** | **Average** | **155.03919** | **-469.8006** | **734.97513** | **147.35025** | **-783.774** | **814.26** | **-0.004061** | **-1.944481** | **1.9542602** |
| | **No data points** | | 228 | 172 | | 199 | 234 | | 143 | 140 |
| | **Max** | 913.4326 | | | 1057.8278 | | | 8.5785714 | | |
| | **Min** | -783.505 | | | -892.8705 | | | -8.021429 | | |
| | **Difference** | 1204.7757 | | | 1598.034 | | | 3.8987407 | | |
| **Subject 5** | **Average** | **167.29719** | **-508.7751** | **770.89378** | **167.73142** | **-619.4722** | **847.1535** | **-0.004103** | **-1.914996** | **1.7171659** |
| | **No data points** | | 306 | 323 | | 258 | 329 | | 176 | 62 |
| | **Max** | 1055.286 | | | 1182.2788 | | | 2.8607143 | | |
| | **Min** | -783.505 | | | -926.0667 | | | -4.307143 | | |
| | **Difference** | 1279.6689 | | | 1466.6257 | | | 3.6321618 | | |
| **Subject 6** | **Average** | **109.01404** | **-459.8351** | **745.50455** | **65.415085** | **-588.2262** | **820.59415** | **-0.002514** | **-1.935627** | **1.7304989** |
| | **No data points** | | 326 | 229 | | 307 | 245 | | 164 | 189 |
| | **Max** | 983.69642 | | | 1138.3549 | | | 2.5821429 | | |
| | **Min** | -776.8763 | | | -872.9921 | | | -2.860714 | | |
| | **Difference** | 1205.3397 | | | 1408.8203 | | | 3.666126 | | |
| **Subject 8** | **Average** | **154.43281** | **-462.3955** | **771.88214** | **113.02348** | **-569.31** | **860.77673** | **-0.00304** | **-2.041263** | **1.8927062** |
| | **No data points** | | 357 | 337 | | 323 | 323 | | 224 | 213 |
| | **Max** | 1028.7713 | | | 1200.5804 | | | 6.5928571 | | |
| | **Min** | -808.6939 | | | -979.1414 | | | -3.503571 | | |
| | **Difference** | 1234.2776 | | | 1430.0867 | | | 3.933969 | | |
| **Subject 7** | **Average** | **177.9439** | **-439.8761** | **788.85407** | **166.58231** | **-542.9959** | **865.14072** | **-0.003927** | **-2.374647** | **1.9201773** |
| | **No data points** | | 261 | 263 | | 242 | 292 | | 243 | 274 |
| | **Max** | 1093.7322 | | | 1182.2788 | | | 3.9428571 | | |
| | **Min** | -815.3225 | | | -827.238 | | | -6.314286 | | |
| | **Difference** | 1228.7302 | | | 1408.1366 | | | 4.2948245 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the Rough track (continued)

| | | Channel 5 Force (On crank) | | | Channel 6 Crank speed | | | Channel 7 Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | **196.06762** | **154.56922** | **232.65236** | **0.3553065** | **0.2832894** | **0.5414972** | **1.7515391** | **1.6045176** | **1.9263429** |
| | **No data points** | | 193 | 126 | | 123 | 47 | | 261 | 235 |
| | **Max** | 285.15119 | | | 0.6046287 | | | 2.1346889 | | |
| | **Min** | 112.95402 | | | 0.1069343 | | | 1.3505551 | | |
| | **Difference** | 78.083143 | | | 0.2582078 | | | 0.3218253 | | |
| **Subject 2** | **Average** | **166.01342** | **119.07912** | **232.2981** | **0.3118492** | **0.2248619** | **0.5517145** | **1.5160116** | **1.5991955** | **1.9460014** |
| | **No data points** | | 244 | 134 | | 88 | 75 | | 291 | 216 |
| | **Max** | 288.37284 | | | 0.6585955 | | | 2.0996335 | | |
| | **Min** | -167.0073 | | | 0.0389761 | | | -0.009225 | | |
| | **Difference** | 113.21899 | | | 0.3268526 | | | 0.3468059 | | |
| **Subject 3** | **Average** | **193.17879** | **162.98036** | **226.51607** | **0.3781498** | **0.2923506** | **0.5585903** | **1.8648112** | **1.7246262** | **1.9816347** |
| | **No data points** | | 252 | 147 | | 83 | 150 | | 268 | 246 |
| | **Max** | 261.63314 | | | 0.6535986 | | | 2.1254638 | | |
| | **Min** | 112.14861 | | | 0.131919 | | | 1.603323 | | |
| | **Difference** | 63.535713 | | | 0.2662397 | | | 0.2570085 | | |
| **Subject 4** | **Average** | **182.21875** | **145.8911** | **218.10291** | **0.3565964** | **0.2565832** | **0.5346341** | **1.7575964** | **1.6350391** | **1.920697** |
| | **No data points** | | 169 | 140 | | 81 | 80 | | 263 | 242 |
| | **Max** | 269.52619 | | | 0.6146225 | | | 2.0719582 | | |
| | **Min** | 109.89345 | | | 0.0929429 | | | 1.3690054 | | |
| | **Difference** | 72.211809 | | | 0.278051 | | | 0.2856579 | | |
| **Subject 5** | **Average** | **207.38827** | **158.94946** | **245.79571** | **0.3461654** | **0.2430232** | **0.5356488** | **1.7110603** | **1.5386129** | **1.8899417** |
| | **No data points** | | 252 | 229 | | 116 | 45 | | 206 | 314 |
| | **Max** | 287.56742 | | | 0.6046287 | | | 2.0276777 | | |
| | **Min** | 106.6718 | | | 0.0979398 | | | 1.3505551 | | |
| | **Difference** | 86.846253 | | | 0.2926256 | | | 0.3513287 | | |
| **Subject 6** | **Average** | **186.1055** | **145.54459** | **233.97883** | **0.356615** | **0.2683289** | **0.5368925** | **1.7608463** | **1.6428205** | **1.9205685** |
| | **No data points** | | 211 | 177 | | 79 | 72 | | 341 | 207 |
| | **Max** | 272.58675 | | | 0.6246164 | | | 2.0442829 | | |
| | **Min** | 105.86639 | | | 0.1169282 | | | 1.422511 | | |
| | **Difference** | 88.43424 | | | 0.2685636 | | | 0.277748 | | |
| **Subject 8** | **Average** | **203.50381** | **167.50057** | **237.51611** | **0.3817075** | **0.3073031** | **0.5594393** | **1.8783117** | **1.7137008** | **2.0159553** |
| | **No data points** | | 152 | 135 | | 61 | 152 | | 251 | 280 |
| | **Max** | 292.23881 | | | 0.6735863 | | | 2.2158698 | | |
| | **Min** | 115.37026 | | | 0.1559042 | | | 1.5221421 | | |
| | **Difference** | 70.015541 | | | 0.2521362 | | | 0.3022545 | | |
| **Subject 7** | **Average** | **181.57678** | **130.21943** | **230.23357** | **0.3786352** | **0.286666** | **0.5603897** | **1.8751403** | **1.7164061** | **2.0438** |
| | **No data points** | | 147 | 154 | | 76 | 124 | | 244 | 149 |
| | **Max** | 277.41923 | | | 0.6735863 | | | 2.1900396 | | |
| | **Min** | 99.584175 | | | 0.1369159 | | | 1.5313672 | | |
| | **Difference** | 100.01414 | | | 0.2737237 | | | 0.3273939 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the Rough track (continued)

| | | Channel 8 Force (Vertical Right Handlebar) | | | Channel 9 Force (On seat) | | | Channel 11 Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (N) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | **67.621655** | **-32.00961** | **161.03293** | **182.79043** | **-53.05907** | **355.62413** | **37.280152** | **-104.4397** | **148.59729** |
| | **No data points** | | 321 | 212 | | 344 | 226 | | 191 | 223 |
| | **Max** | 248.22812 | | | 509.35821 | | | 239.50796 | | |
| | **Min** | -114.689 | | | -204.7339 | | | -391.2215 | | |
| | **Difference** | 193.04254 | | | 408.6832 | | | 253.03695 | | |
| **Subject 2** | **Average** | **60.889865** | **-39.35747** | **171.22448** | **315.29077** | **-152.2494** | **726.92517** | **33.173295** | **-109.7998** | **165.08008** |
| | **No data points** | | 265 | 246 | | 274 | 326 | | 193 | 232 |
| | **Max** | 249.60411 | | | 1230.2254 | | | 258.22972 | | |
| | **Min** | -101.2731 | | | -449.9914 | | | -160.7503 | | |
| | **Difference** | 210.58195 | | | 879.17458 | | | 274.87988 | | |
| **Subject 3** | **Average** | **93.093253** | **-60.05238** | **194.3776** | **280.06042** | **-119.6008** | **642.95179** | **66.485486** | **-101.4005** | **209.06195** |
| | **No data points** | | 210 | 276 | | 297 | 277 | | 268 | 230 |
| | **Max** | 258.20404 | | | 899.60211 | | | 296.31881 | | |
| | **Min** | -123.2889 | | | -264.3545 | | | -163.9782 | | |
| | **Difference** | 254.42998 | | | 762.55254 | | | 310.46242 | | |
| **Subject 4** | **Average** | **53.055385** | **-51.20359** | **149.37623** | **446.52945** | **196.18729** | **683.34896** | **22.108643** | **-91.2534** | **126.87533** |
| | **No data points** | | 250 | 229 | | 283 | 232 | | 229 | 312 |
| | **Max** | 209.35643 | | | 899.60211 | | | 239.50796 | | |
| | **Min** | -114.689 | | | 26.973388 | | | -6415.108 | | |
| | **Difference** | 200.57983 | | | 487.16167 | | | 218.12873 | | |
| **Subject 5** | **Average** | **48.828031** | **-46.19804** | **129.71595** | **281.53786** | **4.6359892** | **520.00475** | **36.572007** | **-81.85144** | **156.95763** |
| | **No data points** | | 223 | 235 | | 200 | 189 | | 210 | 193 |
| | **Max** | 179.08467 | | | 648.92461 | | | 226.5964 | | |
| | **Min** | -101.2731 | | | -85.49274 | | | -148.4843 | | |
| | **Difference** | 175.91399 | | | 515.36876 | | | 238.80907 | | |
| **Subject 6** | **Average** | **74.687337** | **-31.38025** | **156.63719** | **255.00585** | **-22.77642** | **503.37188** | **25.547448** | **-97.04674** | **143.08252** |
| | **No data points** | | 297 | 310 | | 267 | 201 | | 198 | 146 |
| | **Max** | 219.67635 | | | 727.51539 | | | 204.64676 | | |
| | **Min** | -86.1372 | | | -145.1133 | | | -158.168 | | |
| | **Difference** | 188.01744 | | | 526.1483 | | | 240.12926 | | |
| **Subject 8** | **Average** | **98.645598** | **-52.92071** | **225.35047** | **529.6748** | **83.722765** | **991.87039** | **74.07974** | **-108.2095** | **243.62235** |
| | **No data points** | | 232 | 281 | | 269 | 266 | | 223 | 276 |
| | **Max** | 311.86761 | | | 1535.1035 | | | 377.66161 | | |
| | **Min** | -173.5125 | | | -126.1431 | | | -173.6618 | | |
| | **Difference** | 278.27118 | | | 908.14762 | | | 351.83185 | | |
| **Subject 7** | **Average** | **53.893262** | **-71.0208** | **178.46884** | **277.94115** | **35.042432** | **460.65262** | **34.373976** | **-119.9333** | **185.12879** |
| | **No data points** | | 159 | 205 | | 222 | 199 | | 102 | 150 |
| | **Max** | 278.15588 | | | 734.29046 | | | 273.72358 | | |
| | **Min** | -136.7048 | | | -52.97241 | | | -160.7503 | | |
| | **Difference** | 249.48963 | | | 425.61019 | -426.2786 | -154.3073 | 305.06209 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the Rough track (continued)

| | | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|---|
| | | (m/s^2) | | | (W) | | |
| | | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | **-0.010608** | **-6.485216** | **11.401926** | 69.664107 | 43.787825 | 125.98061 |
| | **No data points** | | 179 | 214 | | | |
| | **Max** | 25.304878 | | | 172.41058 | | |
| | **Min** | -21.08537 | | | 12.078662 | | |
| | **Difference** | 17.887142 | | | 82.192781 | | |
| **Subject 2** | **Average** | **-0.006094** | **-6.467068** | **10.319371** | 51.771158 | 26.776356 | 128.16223 |
| | **No data points** | | 227 | 260 | | | |
| | **Max** | 28.52439 | | | 189.92105 | | |
| | **Min** | -20.90244 | | | -6.509288 | | |
| | **Difference** | 16.786439 | | | 101.38587 | | |
| **Subject 3** | **Average** | **-0.013413** | **-6.526911** | **8.7867431** | 73.050516 | 47.6474 | 126.52967 |
| | **No data points** | | 150 | 232 | | | |
| | **Max** | 44.365854 | | | 171.00305 | | |
| | **Min** | -22.09756 | | | 14.79453 | | |
| | **Difference** | 15.313654 | | | 78.882271 | | |
| **Subject 4** | **Average** | **-0.015754** | **-6.828057** | **11.095395** | 64.978545 | 37.433198 | 116.60526 |
| | **No data points** | | 151 | 259 | | | |
| | **Max** | 25.365854 | | | 165.65686 | | |
| | **Min** | -25.18293 | | | 10.213818 | | |
| | **Difference** | 17.923452 | | | 79.172063 | | |
| **Subject 5** | **Average** | **-0.015425** | **-7.07387** | **12.41232** | 71.790633 | 38.628399 | 131.66018 |
| | **No data points** | | 122 | 195 | | | |
| | **Max** | 30.426829 | | | 173.8715 | | |
| | **Min** | -28.40244 | | | 10.44742 | | |
| | **Difference** | 19.486191 | | | 93.031779 | | |
| **Subject 6** | **Average** | **-0.065854** | **-6.69341** | **10.136511** | 66.368008 | 39.053816 | 125.62148 |
| | **No data points** | | 152 | 198 | | | |
| | **Max** | 0 | | | 170.26215 | | |
| | **Min** | -0.658537 | | | 12.378765 | | |
| | **Difference** | 16.829921 | | | 86.567659 | | |
| **Subject 8** | **Average** | **-0.011625** | **-6.662778** | **7.2199545** | 77.678936 | 51.47344 | 132.87585 |
| | **No data points** | | 115 | 193 | | | |
| | **Max** | 32.512195 | | | 196.84806 | | |
| | **Min** | -27.45122 | | | 17.986713 | | |
| | **Difference** | | | | 81.40241 | | |
| **Subject 7** | **Average** | **-0.015199** | **-6.636947** | **9.6748546** | 68.751361 | 37.329489 | 129.02052 |
| | **No data points** | | 135 | 281 | | | |
| | **Max** | 22.036585 | | | 186.86579 | | |
| | **Min** | -24.12195 | | | 13.634658 | | |
| | **Difference** | 16.311801 | | | 91.69103 | | |

## The Rolling Road Rig

## Mean of the combined subjects average results for the hardtail bike on the Rough track

| | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 144.5 | -580.3 | 954.6 | 100.4 | -720.0 | 1034.6 | 0.0 | -4.0 | 2.5 |
| Mean sd | 23.21 | 26.11 | 58.96 | 53.96 | 20.63 | 56.65 | 0.00 | 0.49 | 0.17 |
| Max | 1347.4 | | | 1432.3 | | | 6.1 | | |
| Max sd | 120.57 | | | 128.71 | | | 3.03 | | |
| Min | -884.3 | | | -1053.0 | | | -8.1 | | |
| Min sd | 117.37 | | | 110.94 | | | 1.01 | | |
| Average Diffrence | 1534.9 | | | 1754.7 | | | 6.5 | | |
| Avg Diffrence sd | 67.15 | | | 56.58 | | | 0.36 | | |
| Average no data points | | 264.3 | 232.9 | | 242.1 | 255.4 | | 317.1 | 228.4 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike on the Rough track (Continued)

| | Channel 5 Force (On crank) | | | Channel 6 Crank speed | | | Channel 7 Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 |
| mean | 187.6 | 144.8 | 236.2 | 0.366 | 0.272 | 0.546 | 1.805 | 1.649 | 1.962 |
| Mean sd | 17.89 | 24.07 | 13.33 | 0.012 | 0.025 | 0.010 | 0.056 | 0.062 | 0.048 |
| Max | 286.4 | | | 0.6483518 | | | 2.107 | | |
| Max sd | 19.41 | | | 0.0413017 | | | 0.066 | | |
| Min | 99.4 | | | 0.0995639 | | | 1.277 | | |
| Min sd | 22.59 | | | 0.0278291 | | | 0.513 | | |
| Average Diffrence | 91.4 | | | 0.274 | | | 0.312 | | |
| Avg Diffrence sd | 16.52 | | | 0.023 | | | 0.048 | | |
| Average no data points | | 216.9 | 162.3 | | 99.3 | 93.5 | | 250.8 | 240.6 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike on the Rough track (Continued)

| | Channel 8 Force (Vertical Right Handlebar) | | | Channel 9 Force (On seat) | | | Channel 11 Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 79.8 | -47.7 | 193.2 | 285.1 | -111.1 | 750.3 | 47.6 | -103.6 | 171.4 |
| Mean sd | 23.54 | 19.63 | 35.75 | 101.10 | 78.91 | 184.64 | 24.48 | 16.75 | 33.92 |
| Max | 280.6 | | | 1234.1 | | | 263.0 | | |
| Max sd | 58.09 | | | 421.88 | | | 40.69 | | |
| Min | -129.1 | | | -288.7 | | | -174.8 | | |
| Min sd | 26.73 | | | 259.48 | | | 21.11 | | |
| Average Diffrence | 240.9 | | | 861.4 | | | 275.0 | | |
| Avg Diffrence sd | 36.15 | | | 178.77 | | | 46.56 | | |
| Average no data points | | 219.6 | 231.1 | | 249.3 | 257.4 | | 242.9 | 227.4 |

## The Rolling Road Rig

### Mean of the combined subjects average results for the hardtail bike on the Rough track (Continued)

| | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | -6.9 | 10.3 | 68.7 | 39.3 | 129.0 |
| Mean sd | 0.00 | 0.22 | 1.19 | 6.66 | 6.89 | 6.97 |
| Max | 34.5 | | | 185.6 | | |
| Max sd | 8.39 | | | 16.31 | | |
| Min | -30.8 | | | 9.7 | | |
| Min sd | 11.62 | | | 2.94 | | |
| Average Diffrence | 17.3 | | | 89.7 | | |
| Avg Diffrence sd | 1.25 | | | 7.07 | | |
| Average no data points | | 236.8 | 320.3 | | | |

**The Rolling Road Rig**

**Mean of the combined subjects average results for the full suspension bike on the Rough track (Continued)**

| | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 151.3 | -471.6 | 766.4 | 127.0 | -610.7 | 848.9 | 0.0 | -2.1 | 1.8 |
| Mean sd | 22.63 | 35.46 | 19.43 | 35.11 | 78.22 | 22.76 | 0.00 | 0.21 | 0.11 |
| Max | 1035.7 | | | 1177.0 | | | 5.0 | | |
| Max sd | 63.63 | | | 59.48 | | | 2.58 | | |
| Min | -771.1 | | | -894.9 | | | -6.7 | | |
| Min sd | 72.59 | | | 67.0 | | | 3.55 | | |
| Average Diffrence | 1238.0 | | | 1459.6 | | | 3.9 | | |
| Avg Diffrence sd | 35.42 | | | 67.77 | | | 0.30 | | |
| Average no data points | | 278.6 | 254.6 | | 256.0 | 272.3 | | 194.0 | 178.1 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the full suspension bike on the Rough track (Continued)

| | Channel 5 Force (On crank) (N) | | | Channel 6 Crank speed (m/s) | | | Channel 7 Road Speed (m/s) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 | 8.000 |
| mean | 189.5 | 148.1 | 232.1 | 0.358 | 0.270 | 0.547 | 1.764 | 1.647 | 1.956 |
| Mean sd | 13.37 | 16.61 | 8.03 | 0.023 | 0.027 | 0.011 | 0.120 | 0.067 | 0.053 |
| Max | 279.3 | | | 0.6384829 | | | 2.114 | | |
| Max sd | 10.75 | | | 0.0296439 | | | 0.067 | | |
| Min | 74.4 | | | 0.1098076 | | | 1.268 | | |
| Min sd | 97.68 | | | 0.0355568 | | | 0.524 | | |
| Average Diffrence | 84.0 | | | 0.277 | | | 0.309 | | |
| Avg Diffrence sd | 16.59 | | | 0.024 | | | 0.034 | | |
| Average no data points | | 202.5 | 155.3 | | 88.4 | 93.1 | | 265.6 | 236.1 |

## The Rolling Road Rig

## Mean of the combined subjects average results for the full suspension bike on the Rough track (Continued)

| | Channel 8 Force (Vertical Right Handlebar) | | | Channel 9 Force (On seat) | | | Channel 11 Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 68.8 | -48.0 | 170.8 | 321.1 | -3.5 | 610.6 | 41.2 | -101.7 | 172.3 |
| Mean sd | 18.70 | 13.73 | 29.36 | 112.05 | 111.78 | 197.28 | 18.81 | 11.79 | 38.49 |
| Max | 244.3 | | | 898.1 | | | 264.5 | | |
| Max sd | 41.45 | | | 334.93 | | | 53.73 | | |
| Min | -118.9 | | | -162.7 | | | -971.5 | | |
| Min sd | 26.86 | | | 146.51 | | | 2201.03 | | |
| Average Diffrence | 218.8 | | | 614.1 | | | 274.0 | | |
| Avg Diffrence sd | 37.03 | | | 203.57 | | | 45.20 | | |
| Average no data points | | 244.6 | 249.3 | | 269.5 | 239.5 | | 201.8 | 220.3 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the full suspension bike on the Rough track (Continued)

| | Channel 12<br>Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | -6.7 | 10.1 | 79.6 | 40.3 | 127.1 |
| Mean sd | 0.02 | 0.20 | 1.62 | 7.67 | 7.51 | 4.97 |
| Max | 26.1 | | | 178.4 | | |
| Max sd | 12.53 | | | 11.24 | | |
| Min | -21.2 | | | 10.6 | | |
| Min sd | 8.77 | | | 7.36 | | |
| Average Diffrence | 17.2 | | | 86.8 | | |
| Avg Diffrence sd | 1.35 | | | 7.99 | | |
| Average no data points | | 153.9 | 229.0 | | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - full suspension bike on the Rough track

| HT - SUS | Channel 0 | | | Channel 3 | | | Channel 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Force (Horizontal Right Handlebar) | | | | | | Handlebar Acceleration | | |
| NULL HYPOTHESIS | | | | Force (Horizontal Left handlebar) | | | | | |
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | -6.8 | -108.7 | 188.2 | -26.6 | -109.3 | 185.8 | 0.0 | -1.9 | 0.7 |
| **sum** | -54.3 | -869.4 | 1505.5 | -212.9 | -874.7 | 1486.1 | 0.0 | -15.3 | 5.7 |
| **sum of squares** | 7701.9 | 101538.8 | 308022.4 | 40796.5 | 128850.7 | 300997.1 | 0.0 | 31.8 | 4.3 |
| **sd** | 32.37 | 31.74 | 59.43 | 70.84 | 68.87 | 59.70 | 0.00 | 0.58 | 0.18 |
| **sd(mean)** | 11.44 | 11.22 | 21.01 | 25.05 | 24.35 | 21.11 | 0.00 | 0.21 | 0.06 |
| **t** | 0.59 | 9.68 | 8.96 | 1.06 | 4.49 | 8.80 | 0.81 | 9.35 | 11.23 |
| **p** | 57.209% | 0.003% | 0.004% | 32.331% | 0.283% | 0.005% | 44.633% | 0.003% | 0.001% |
| **Cv** | -4.77 | -0.29 | 0.32 | -2.66 | -0.63 | 0.32 | 3.51 | -0.30 | 0.25 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | -6.8 | -108.7 | 188.2 | -26.6 | -109.3 | 185.8 | 0.0 | -1.9 | 0.7 |
| **Lower** | -6.8 | -108.7 | 188.2 | -26.6 | -109.3 | 185.8 | 0.0 | -1.9 | 0.7 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 144.5 | -580.3 | 954.6 | 100.4 | -720.0 | 1034.6 | 0.0 | -4.0 | 2.5 |
| **% improvement** | -4.7% | 18.7% | 19.7% | -26.5% | 15.2% | 18.0% | -16.9% | 48.0% | 27.9% |
| **Ht-Sus** | **Channel 0** | | | **Channel 3** | | | **Channel 4** | | |
| **Difference** | **Force (Horizontal Right Handlebar)** | | | **Force (Horizontal Left handlebar)** | | | **Handlebar Acceleration** | | |
| **n** | 8 | | | 8 | | | 8 | | |
| **average** | 296.9 | | | 295.1 | | | 2.6 | | |
| **sum** | 2374.9 | | | 2360.8 | | | 21.0 | | |
| **sum of squares** | 751226.0 | | | 746392.9 | | | 56.3 | | |
| **sd** | 81.26 | | | 84.28 | | | 0.39 | | |
| **sd(mean)** | 28.73 | | | 29.80 | | | 0.14 | | |
| **t** | 10.33 | | | 9.90 | | | 18.87 | | |
| **p** | 0.002% | | | 0.002% | | | 0.000% | | |
| **Cv** | 0.27 | | | 0.29 | | | 0.15 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 296.9 | | | 295.1 | | | 2.6 | | |
| **Lower** | 296.9 | | | 295.1 | | | 2.6 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 1534.9 | | | 1754.7 | | | 6.5 | | |
| **% improvement** | 19.34% | | | 16.82% | | | 40.18% | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - full suspension bike on the Rough track (continued)

| | Channel 5<br>Force (On crank) | | | Channel 6<br>Crank speed | | | Channel 7<br>Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 | 8 | 8 | 8 |
| **average** | -1.9 | -3.3 | 4.1 | 0.008 | 0.002 | -0.001 | 0.0 | 0.0 | 0.0 |
| **sum** | -14.9 | -26.5 | 32.5 | 0.064 | 0.016 | -0.010 | 0.3 | 0.0 | 0.0 |
| **sum of squares** | 5576.2 | 9508.8 | 2827.8 | 0.005 | 0.011 | 0.001 | 0.1 | 0.1 | 0.0 |
| **sd** | 28.15 | 36.69 | 19.62 | 0.024 | 0.039 | 0.011 | 0.13 | 0.09 | 0.04 |
| **sd(mean)** | 9.95 | 12.97 | 6.94 | 0.009 | 0.014 | 0.004 | 0.04 | 0.03 | 0.01 |
| **t** | 0.19 | 0.26 | 0.59 | 0.934 | 0.141 | 0.319 | 0.90 | 0.07 | 0.45 |
| **p** | 85.658% | 80.599% | 57.685% | 38.145% | 89.195% | 75.922% | 39.668% | 94.772% | 66.875% |
| **Cv** | -15.08 | -11.09 | 4.83 | 3.029 | 20.081 | -8.874 | 3.13 | 41.62 | 6.34 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | -1.9 | -3.3 | 4.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **Lower** | -1.9 | -3.3 | 4.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 187.6 | 144.8 | 236.2 | 0.4 | 0.3 | 0.5 | 1.8 | 1.6 | 2.0 |
| **% improvement** | -1.0% | -2.3% | 1.7% | 2.2% | 0.7% | -0.2% | 2.2% | 0.1% | 0.3% |
| **Ht-Sus Difference** | **Channel 5 Force (On crank)** | | | **Channel 6 Crank speed** | | | **Channel 7 Road Speed** | | |
| **n** | 8 | | | 8.000 | | | 8 | | |
| **average** | 7.4 | | | -0.003 | | | 0.0 | | |
| **sum** | 58.9 | | | -0.025 | | | 0.0 | | |
| **sum of squares** | 5252.0 | | | 0.009 | | | 0.0 | | |
| **sd** | 26.23 | | | 0.035 | | | 0.07 | | |
| **sd(mean)** | 9.28 | | | 0.013 | | | 0.03 | | |
| **t** | 0.79 | | | 0.252 | | | 0.14 | | |
| **p** | 45.305% | | | 0.808 | | | 88.915% | | |
| **Cv** | 3.56 | | | -11.216 | | | 19.57 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 7.4 | | | -0.003 | | | 0.0 | | |
| **Lower** | 7.4 | | | -0.003 | | | 0.0 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 91.4 | | | 0.3 | | | 0.3 | | |
| **% improvement** | 8.06% | | | -1.15% | | | 1.17% | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - full suspension bike on the Rough track (continued)

| | Channel 8<br>Force (Vertical Right Handlebar) | | | Channel 9<br>Force (On seat) | | | Channel 11<br>Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | 10.9 | 0.3 | 22.4 | -36.0 | -107.6 | 139.7 | 6.4 | -1.8 | -0.9 |
| **sum** | 87.5 | 2.4 | 179.1 | -288.2 | -860.6 | 1117.4 | 51.0 | -14.5 | -7.2 |
| **sum of squares** | 11188.7 | 5354.3 | 18830.3 | 193508.2 | 181327.0 | 837287.3 | 10075.1 | 1202.7 | 13581.2 |
| **sd** | 38.23 | 27.65 | 46.01 | 161.74 | 112.60 | 311.96 | 37.32 | 12.96 | 44.04 |
| **sd(mean)** | 13.52 | 9.78 | 16.27 | 57.18 | 39.81 | 110.29 | 13.19 | 4.58 | 15.57 |
| **t** | 0.81 | 0.03 | 1.38 | 0.63 | 2.70 | 1.27 | 0.48 | 0.39 | 0.06 |
| **p** | 44.531% | 97.620% | 21.121% | 54.870% | 3.054% | 24.588% | 64.362% | 70.481% | 95.556% |
| **Cv** | 3.50 | 91.48 | 2.06 | -4.49 | -1.05 | 2.23 | 5.85 | -7.17 | -48.98 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 10.9 | 0.3 | 22.4 | -36.0 | -107.6 | 139.7 | 6.4 | -1.8 | -0.9 |
| **Lower** | 10.9 | 0.3 | 22.4 | -36.0 | -107.6 | 139.7 | 6.4 | -1.8 | -0.9 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 79.8 | -47.7 | 193.2 | 285.1 | -111.1 | 750.3 | 47.6 | -103.6 | 171.4 |
| **% improvement** | 13.7% | -0.6% | 11.6% | -12.6% | 96.8% | 18.6% | 13.4% | 1.7% | -0.5% |
| **Ht-Sus**<br>**Difference** | **Channel 8**<br>**Force (Vertical Right Handlebar)** | | | **Channel 9**<br>**Force (On seat)** | | | **Channel 11**<br>**Force (Vertical Left Handlebar)** | | |
| **n** | 8 | | | 8 | | | 8 | | |
| **average** | 22.1 | | | 247.2 | | | 0.9 | | |
| **sum** | 176.7 | | | 1978.0 | | | 7.3 | | |
| **sum of squares** | 20773.3 | | | 566086.4 | | | 13595.8 | | |
| **sd** | 49.09 | | | 104.90 | | | 44.06 | | |
| **sd(mean)** | 17.36 | | | 37.09 | | | 15.58 | | |
| **t** | 1.27 | | | 6.67 | | | 0.06 | | |
| **p** | 24.390% | | | 0.029% | | | 95.505% | | |
| **Cv** | 2.22 | | | 0.42 | | | 48.42 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 22.1 | | | 247.2 | | | 0.9 | | |
| **Lower** | 22.1 | | | 247.2 | | | 0.9 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 240.9 | | | 861.4 | | | 275.0 | | |
| **% improvement** | 9.17% | | | 28.70% | | | 0.33% | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - full suspension bike on the Rough track (continued)

| | Channel 12<br>Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | 0.0 | -0.3 | 0.2 | 0.7 | -1.0 | 1.9 |
| **sum** | 0.0 | -2.1 | 1.7 | 5.3 | -8.0 | 15.3 |
| **sum of squares** | 0.0 | 1.7 | 31.7 | 862.5 | 684.9 | 732.7 |
| **sd** | 0.02 | 0.41 | 2.12 | 11.08 | 9.83 | 10.03 |
| **sd(mean)** | 0.01 | 0.14 | 0.75 | 3.92 | 3.48 | 3.54 |
| **t** | 0.70 | 1.79 | 0.28 | 0.17 | 0.29 | 0.54 |
| **p** | 50.594% | 11.654% | 78.435% | 86.941% | 78.295% | 60.719% |
| **Cv** | 4.03 | -1.58 | 9.95 | 16.58 | -9.88 | 5.26 |
| **95% CONFIDENCE LIMITS** | | | | | | |
| **Upper** | 0.0 | -0.3 | 0.2 | 0.7 | -1.0 | 1.9 |
| **Lower** | 0.0 | -0.3 | 0.2 | 0.7 | -1.0 | 1.9 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | |
| **HT mean** | 0.0 | -6.9 | 10.3 | 68.7 | 39.3 | 129.0 |
| **% improvement** | -35.2% | 3.7% | 2.1% | 1.0% | -2.5% | 1.5% |
| **Ht-Sus** | **Channel 12** | | | **Channel 12** | | |
| **Difference** | **Seat Acceleration** | | | **Seat Acceleration** | | |
| **n** | 8 | | | 8 | | |
| **average** | 2.2 | | | 2.9 | | |
| **sum** | 17.6 | | | 23.2 | | |
| **sum of squares** | 249.4 | | | 1347.6 | | |
| **sd** | 5.48 | | | 13.52 | | |
| **sd(mean)** | 1.94 | | | 4.78 | | |
| **t** | 1.14 | | | 0.61 | | |
| **p** | 29.263% | | | 56.297% | | |
| **Cv** | 2.49 | | | 4.66 | | |
| **95% CONFIDENCE LIMITS** | | | | | | |
| **Upper** | 2.2 | | | 2.9 | | |
| **Lower** | 2.2 | | | 2.9 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | |
| **HT mean** | 17.3 | | | 89.7 | | |
| **% improvement** | 12.77% | | | 3.24% | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the Rough track

| | | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 7.26E-08 | 0.0139361 | -0.0182717 | 1.33E-07 | 0.04457778 | -0.0584117 | -6.48E-06 | 0.6701633 | -0.2851353 | -2.02E-05 | 2.27363814 | -0.983298 |
| | **No data points** | | 450 | 421 | | 557 | 484 | | 344 | 607 | | 348 | 585 |
| | **Max** | 0.03651241 | | | 0.1246782 | | | 1.064998 | | | 3.636593 | | |
| | **Min** | -0.0308241 | | | -0.1052681 | | | -0.5107694 | | | -1.7441 | | |
| | **Difference** | 0.03220776 | | | 0.10298946 | | | 0.95529859 | | | 3.2569361 | | |
| **Subject 2** | **Average** | -4.92E-07 | 0.01219002 | -0.0171633 | -1.77E-06 | 0.03803588 | -0.0552823 | -3.00E-05 | 0.65487281 | -0.2634585 | -0.0001022 | 2.22572425 | -0.9137638 |
| | **No data points** | | 241 | 369 | | 388 | 421 | | 349 | 600 | | 352 | 560 |
| | **Max** | 0.0190938 | | | 0.06519805 | | | 1.030911 | | | 3.520169 | | |
| | **Min** | -0.0503136 | | | -0.1718044 | | | -0.6720769 | | | -2.294747 | | |
| | **Difference** | 0.02935334 | | | 0.09331813 | | | 0.91833127 | | | 3.13948803 | | |
| **Subject 3** | **Average** | 1.15E-07 | 0.01342643 | -0.0182561 | 3.67E-07 | 0.04218128 | -0.0586715 | -2.22E-06 | 0.65699539 | -0.2790768 | -9.54E-06 | 2.23256206 | -0.9652896 |
| | **No data points** | | 393 | 395 | | 536 | 449 | | 336 | 560 | | 339 | 533 |
| | **Max** | 0.03087762 | | | 0.1054117 | | | 0.9535812 | | | 3.256086 | | |
| | **Min** | -0.02956 | | | -0.1009287 | | | -0.5695721 | | | -1.944854 | | |
| | **Difference** | 0.03168248 | | | 0.10085283 | | | 0.93607217 | | | 3.19785166 | | |
| **Subject 4** | **Average** | -2.63E-07 | 0.01242335 | -0.0175985 | -7.82E-07 | 0.03973215 | -0.0558675 | 1.57E-05 | 0.67222817 | -0.2737987 | 5.33E-05 | 2.28757535 | -0.9523778 |
| | **No data points** | | 351 | 366 | | 472 | 430 | | 325 | 572 | | 327 | 532 |
| | **Max** | 0.02102178 | | | 0.07177185 | | | 0.9344748 | | | 3.191007 | | |
| | **Min** | -0.0266202 | | | -0.0908882 | | | -0.4582888 | | | -1.564783 | | |
| | **Difference** | 0.03002187 | | | 0.09559965 | | | 0.94602685 | | | 3.23995318 | | |
| **Subject 5** | **Average** | -2.90E-07 | 0.01180694 | -0.0166343 | -1.02E-06 | 0.0374193 | -0.0554339 | 6.26E-07 | 0.58164557 | -0.2536736 | 2.78E-06 | 1.98609728 | -0.8793547 |
| | **No data points** | | 210 | 327 | | 323 | 346 | | 335 | 457 | | 335 | 423 |
| | **Max** | 0.02069717 | | | 0.07067518 | | | 0.9502824 | | | 3.244918 | | |
| | **Min** | -0.026333 | | | -0.0899224 | | | -0.4300649 | | | -1.468484 | | |
| | **Difference** | 0.02844121 | | | 0.09285324 | | | 0.83531922 | | | 2.86545199 | | |
| **Subject 6** | **Average** | -1.13E-07 | 0.01217658 | -0.0169992 | -3.30E-07 | 0.03845788 | -0.0544431 | 7.55E-06 | 0.65008344 | -0.2654253 | 2.40E-05 | 2.21979316 | -0.9246096 |
| | **No data points** | | 319 | 400 | | 472 | 463 | | 321 | 563 | | 321 | 517 |
| | **Max** | 0.01970795 | | | 0.06730175 | | | 0.8743101 | | | 2.985527 | | |
| | **Min** | -0.0246437 | | | -0.0841438 | | | -0.4275284 | | | -1.459665 | | |
| | **Difference** | 0.02917575 | | | 0.09290096 | | | 0.91550878 | | | 3.14440274 | | |
| **Subject 7** | **Average** | 6.55E-07 | 0.01203821 | -0.0154036 | 2.18E-06 | 0.03818858 | -0.0499717 | -1.56E-06 | 0.62658926 | -0.2531705 | -6.73E-06 | 2.13320072 | -0.8788939 |
| | **No data points** | | 182 | 355 | | 271 | 406 | | 349 | 405 | | 351 | 372 |
| | **Max** | 0.02293965 | | | 0.07834042 | | | 0.8530201 | | | 2.912634 | | |
| | **Min** | -0.0257852 | | | -0.0880502 | | | -0.4655679 | | | -1.589672 | | |
| | **Difference** | 0.02744183 | | | 0.08816028 | | | 0.8797598 | | | 3.01209466 | | |
| **Subject 8** | **Average** | -1.24E-08 | 0.01331188 | -0.0199184 | -7.34E-08 | 0.04096139 | -0.0652405 | -2.82E-06 | 0.73701246 | -0.2926538 | -1.01E-05 | 2.50808644 | -1.0204173 |
| | **No data points** | | 283 | 374 | | 426 | 405 | | 348 | 533 | | 350 | 497 |
| | **Max** | 0.0439627 | | | 0.1501399 | | | 1.143625 | | | 3.905138 | | |
| | **Min** | -0.0294548 | | | -0.1005801 | | | -0.6048046 | | | -2.065177 | | |
| | **Difference** | 0.0332303 | | | 0.10620188 | | | 1.02966622 | | | 3.52850378 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the Rough track

| | | Distance (Handlebar) (m) | | | Distance (Seat) (m) | | | Velocity (Handlebar) (m/s) | | | Velocity (Seat) (m/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 6.91E-08 | 0.01411721 | -1.43E-02 | 2.81E-07 | 0.04615326 | -4.57E-02 | 3.14E-06 | 0.35543661 | -2.43E-01 | 1.14E-05 | 1.19586071 | -0.8482483 |
| | **No data points** | | 347 | 488 | | 397 | 601 | | 158 | 270 | | 173 | 238 |
| | **Max** | 0.03657738 | | | 0.1249016 | | | 0.5542924 | | | 1.892698 | | |
| | **Min** | -0.0228426 | | | -0.0779976 | | | -0.5539111 | | | -1.891402 | | |
| | **Difference** | 0.02844343 | | | 0.09189094 | | | 0.59874085 | | | 2.04410897 | | |
| **Subject 2** | **Average** | 1.42E-07 | 0.01360999 | -0.0139974 | 4.49E-07 | 0.04265118 | -0.0451106 | 2.27E-06 | 0.35944117 | -0.2634923 | 5.40E-06 | 1.21227155 | -0.9169883 |
| | **No data points** | | 303 | 466 | | 409 | 561 | | 177 | 330 | | 190 | 303 |
| | **Max** | 0.02137483 | | | 0.07299507 | | | 0.5756723 | | | 1.965505 | | |
| | **Min** | -0.0242386 | | | -0.0827637 | | | -0.4770518 | | | -1.629014 | | |
| | **Difference** | 0.02760738 | | | 0.08776174 | | | 0.62293344 | | | 2.12925985 | | |
| **Subject 3** | **Average** | -1.05E-06 | 0.01425769 | -0.0140764 | -3.56E-06 | 0.04579943 | -0.045307 | 7.68E-08 | 0.34734892 | -0.2498706 | 3.02E-08 | 1.17495413 | -0.8697551 |
| | **No data points** | | 215 | 318 | | 260 | 384 | | 85 | 207 | | 91 | 205 |
| | **Max** | 0.03010529 | | | 0.1027846 | | | 0.5159238 | | | 1.761541 | | |
| | **Min** | -0.025897 | | | -0.0884366 | | | -0.4954668 | | | -1.691774 | | |
| | **Difference** | 0.02833405 | | | 0.09110648 | | | 0.59721948 | | | 2.04470926 | | |
| **Subject 4** | **Average** | -1.20E-07 | 0.01256045 | -0.0132145 | -5.46E-07 | 0.03988918 | -0.0419318 | -5.03E-06 | 0.36577372 | -0.2569414 | -1.69E-05 | 1.24186396 | -0.8915445 |
| | **No data points** | | 258 | 365 | | 342 | 465 | | 130 | 355 | | 134 | 328 |
| | **Max** | 0.01809414 | | | 0.0618 | | | 0.5529003 | | | 1.887813 | | |
| | **Min** | -0.0207647 | | | -0.0709 | | | -0.4462092 | | | -1.523498 | | |
| | **Difference** | 0.02577498 | | | 0.08182101 | | | 0.62271513 | | | 2.13340844 | | |
| **Subject 5** | **Average** | -3.42E-07 | 0.01439406 | -0.0145639 | -1.17E-06 | 0.04508269 | -0.0471856 | 2.14E-05 | 0.34826826 | -0.2596925 | 7.34E-05 | 1.17189213 | -0.8972828 |
| | **No data points** | | 467 | 610 | | 610 | 713 | | 121 | 335 | | 134 | 316 |
| | **Max** | 0.02994119 | | | 0.1022429 | | | 0.4760596 | | | 1.625384 | | |
| | **Min** | -0.0315395 | | | -0.1077015 | | | -0.4552072 | | | -1.554293 | | |
| | **Difference** | 0.02895796 | | | 0.09226826 | | | 0.60796079 | | | 2.06917489 | | |
| **Subject 6** | **Average** | 4.45E-07 | 1.30E-02 | -0.0123286 | 2.60E-06 | 2.45E-02 | -0.0524305 | -2.03E-05 | 4.01E-01 | -0.261615 | -6.95E-05 | 1.37E+00 | -0.881112 |
| | **No data points** | | 410 | 430 | | 409 | 542 | | 330 | 341 | | 330 | 312 |
| | **Max** | 0.02279 | | | 0.0698243 | | | 0.4415 | | | 2.221345 | | |
| | **Min** | -0.031298 | | | -0.0765398 | | | -0.510778 | | | -1.675567 | | |
| | **Difference** | 0.02530492 | | | 0.07689927 | | | 0.66259759 | | | 2.24674188 | | |
| **Subject 7** | **Average** | 1.34E-07 | 0.0178573 | -0.0180375 | 4.75E-07 | 0.0588301 | -0.0590802 | 6.63E-06 | 0.38151905 | -0.2801614 | 2.14E-05 | 1.28529422 | -0.9731555 |
| | **No data points** | | 832 | 886 | | 899 | 968 | | 396 | 786 | | 421 | 738 |
| | **Max** | 0.03405866 | | | 0.1162938 | | | 0.6652483 | | | 2.271527 | | |
| | **Min** | -0.0367255 | | | -0.1254022 | | | -0.5798698 | | | -1.979846 | | |
| | **Difference** | 0.03589481 | | | 0.11791033 | | | 0.66168047 | | | 2.25844976 | | |
| **Subject 8** | **Average** | 7.60E-07 | 1.36E-02 | -0.0151159 | 2.60E-06 | 4.34E-02 | -0.0492305 | -2.03E-05 | 4.01E-01 | -0.2569266 | -6.95E-05 | 1.36E+00 | -0.8925363 |
| | **No data points** | | 331 | 550 | | 419 | 626 | | 348 | 357 | | 359 | 328 |
| | **Max** | 0.02090279 | | | 0.0713743 | | | 0.6496215 | | | 2.218122 | | |
| | **Min** | -0.0242631 | | | -0.0828398 | | | -0.4909838 | | | -1.676567 | | |
| | **Difference** | 0.02874987 | | | 0.09267738 | | | 0.6579525 | | | 2.25083511 | | |

**The Rolling Road Rig**

**Mean of the combined subjects average results for displacement and velocity of the hardtail bike on the Rough track**

| | Distance (Handlebar) (m) | | | Distance (Seat) (m) | | | Velocity (Handlebar) (m/s) | | | Velocity (Seat) (m/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | 0.0127 | -0.0175 | 0.0000 | 0.0399 | -0.0567 | 0.0000 | 0.6562 | -0.2708 | 0.0000 | 2.2333 | -0.9398 |
| sd | 0.00 | 0.0008 | 0.0013 | 0.0000 | 0.0025 | 0.0044 | 0.0000 | 0.0438 | 0.0144 | 0.0000 | 0.1471 | 0.0500 |
| difference | 0.03019432 | | | 0.09660955 | | | 0.92699786 | | | 3.17308527 | | |
| sd | 0.00199678 | | | 0.00611589 | | | 0.05685783 | | | 0.19307498 | | |

**The Rolling Road Rig**
**Mean of the combined subjects average results for displacement and velocity of the full suspension bike on the Rough track**

| | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0000 | 0.0142 | -0.0145 | 0.0000 | 0.0433 | -0.0483 | 0.0000 | 0.3700 | -0.2590 | 0.0000 | 1.2508 | -0.8963 |
| sd | 0.0000 | 0.0016 | 0.0017 | 0.0000 | 0.0095 | 0.0054 | 0.0000 | 0.0220 | 0.0108 | 0.0000 | 0.0779 | 0.0371 |
| difference | 0.02863342 | | | 0.09154193 | | | 0.62897503 | | | 2.14708602 | | |
| sd | 0.0032354 | | | 0.01207485 | | | 0.02797862 | | | 0.09316446 | | |

**The Rolling Road Rig** **Mean of the combined subjects average results for displacement and velocity of the hardtail bike - the full suspension bike on the Rough track**

| | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HT - SUS** | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| **NULL HYPOTHESIS** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | -4.57E-08 | -1.51E-03 | -3.07E-03 | -3.02E-07 | -3.35E-03 | -8.41E-03 | -8.74E-07 | 2.86E-01 | -1.18E-02 | -3.06E-06 | 9.83E-01 | -4.34E-02 |
| **sum** | -3.65E-07 | -1.21E-02 | -2.46E-02 | -2.42E-06 | -2.68E-02 | -6.73E-02 | -6.99E-06 | 2.29E+00 | -9.44E-02 | -2.44E-05 | 7.86E+00 | -3.47E-01 |
| **sum of squares** | 2.96E-12 | 4.41E-05 | 1.18E-04 | 3.91E-11 | 7.24E-04 | 1.05E-03 | 3.15E-09 | 6.66E-01 | 4.94E-03 | 3.56E-08 | 7.83E+00 | 5.85E-02 |
| **sd** | 6.48E-07 | 1.92E-03 | 2.47E-03 | 2.34E-06 | 9.52E-03 | 8.30E-03 | 2.12E-05 | 3.82E-02 | 2.34E-02 | 7.13E-05 | 1.26E-01 | 7.88E-02 |
| **sd(mean)** | 2.29E-07 | 6.78E-04 | 8.75E-04 | 8.28E-07 | 3.36E-03 | 2.93E-03 | 7.49E-06 | 1.35E-02 | 8.27E-03 | 2.52E-05 | 4.44E-02 | 2.79E-02 |
| **t** | 1.99E-01 | 2.23E+00 | 3.51E+00 | 3.65E-01 | 9.94E-01 | 2.87E+00 | 1.17E-01 | 2.12E+01 | 1.43E+00 | 1.21E-01 | 2.21E+01 | 1.56E+00 |
| **p** | 8.48E-01 | 6.10E-02 | 9.81E-03 | 7.26E-01 | 3.53E-01 | 2.41E-02 | 9.10E-01 | 1.30E-07 | 1.97E-01 | 9.07E-01 | 9.77E-08 | 1.63E-01 |
| **Cv** | -1.42E+01 | -1.27E+00 | -8.05E-01 | -7.74E+00 | -2.84E+00 | -9.86E-01 | -2.42E+01 | 1.33E-01 | -1.98E+00 | -2.33E+01 | 1.28E-01 | -1.81E+00 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | | | | |
| **Upper** | -4.57E-08 | -1.51E-03 | -3.07E-03 | -3.02E-07 | -3.35E-03 | -8.41E-03 | -8.74E-07 | 2.86E-01 | -1.18E-02 | -3.06E-06 | 9.83E-01 | -4.34E-02 |
| **Lower** | -4.57E-08 | -1.51E-03 | -3.07E-03 | -3.02E-07 | -3.35E-03 | -8.41E-03 | -8.74E-07 | 2.86E-01 | -1.18E-02 | -3.06E-06 | 9.83E-01 | -4.34E-02 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | | | | |
| **HT mean** | -4.57E-08 | -1.51E-03 | -3.07E-03 | -3.02E-07 | -3.35E-03 | -8.41E-03 | -8.74E-07 | 2.86E-01 | -1.18E-02 | -3.06E-06 | 9.83E-01 | -4.34E-02 |
| **% improvement** | 111.6% | -11.9% | 17.5% | 187.3% | -8.4% | 14.8% | 36.5% | 43.6% | 4.4% | 35.6% | 44.0% | 4.6% |
| **HT - SUS** | | | | | | | | | | | | |
| **NULL HYPOTHESIS** | | | | | | | | | | | | |
| **Diffrence** | | | | | | | | | | | | |
| **n** | 8 | | | 8 | | | 8 | | | 8 | | |
| **average** | 0.0016 | | | 0.0051 | | | 0.2980 | | | 1.0260 | | |
| **sum** | 0.0125 | | | 0.0405 | | | 2.3842 | | | 8.2080 | | |
| **sum of squares** | 0.0002 | | | 0.0018 | | | 0.7351 | | | 8.6860 | | |
| **sd** | 0.2997 | | | 0.2566 | | | 0.3219 | | | 0.3206 | | |
| **sd(mean)** | 0.1060 | | | 0.0907 | | | 0.1138 | | | 0.1134 | | |
| **t** | 1.0100 | | | 0.9608 | | | 14.2222 | | | 14.9271 | | |
| **p** | 34.6132% | | | 36.8650% | | | 0.0002% | | | 0.0001% | | |
| **Cv** | 192.0166 | | | 50.6295 | | | 1.0800 | | | 0.3125 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | | | | |
| **Upper** | 0.0016 | | | 0.0051 | | | 0.2980 | | | 1.0260 | | |
| **Lower** | 0.0016 | | | 0.0051 | | | 0.2980 | | | 1.0260 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | | | | |
| **HT mean** | 0.0016 | | | 0.0051 | | | 0.2980 | | | 1.0260 | | |
| **% improvement** | 5.2% | | | 5.2% | | | 32.1% | | | 32.3% | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the smooth track

| | | Channel 0 | | | Channel 3 | | | Channel 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Handlebar Acceleration | | |
| | | Force (Horizontal Right Handlebar) | | | Force (Horizontal Left handlebar) | | | | | |
| | | (N) | | | (N) | | | (m/s^2) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 112.03064 | -141.26123 | 406.83991 | 90.603287 | -186.32919 | 431.97112 | -0.0031597 | -0.70006 | 0.7030864 |
| | **No data points** | | 207 | 293 | | 270 | 345 | | 238 | 243 |
| | **Max** | 543.55324 | | | 646.04161 | | | 2.0928571 | | |
| | **Min** | -233.32599 | | | -345.90568 | | | -2.1607143 | | |
| | **Difference** | 548.10114 | | | 618.30031 | | | 1.4031464 | | |
| **Subject 2** | **Average** | 118.68902 | -126.62256 | 347.3883 | 80.237674 | -190.78542 | 352.46501 | -0.0042275 | -0.6821334 | 0.6780894 |
| | **No data points** | | 294 | 244 | | 227 | 273 | | 376 | 326 |
| | **Max** | 556.81056 | | | 565.51452 | | | 1.1857143 | | |
| | **Min** | -233.32599 | | | -371.52794 | | | -2.0392857 | | |
| | **Difference** | 474.01086 | | | 543.25043 | | | 1.3602228 | | |
| **Subject 3** | **Average** | 106.667 | -176.76956 | 356.74257 | 99.463592 | -191.00449 | 366.80406 | -0.0034377 | -0.6698858 | 0.6545142 |
| | **No data points** | | 271 | 124 | | 221 | 252 | | 294 | 322 |
| | **Max** | 615.14279 | | | 636.89081 | | | 1.5178571 | | |
| | **Min** | -285.02955 | | | -380.67874 | | | -2.6142857 | | |
| | **Difference** | 533.51212 | | | 557.80855 | | | 1.3244 | | |
| **Subject 4** | **Average** | 150.52645 | -142.59754 | 477.52529 | 138.84896 | -195.36377 | 520.80486 | -0.0043749 | -0.7440698 | 0.7633075 |
| | **No data points** | | 181 | 287 | 48000 | 246 | 361 | 48000 | 268 | 230 |
| | **Max** | 588.62814 | | | 664.34322 | | | 2.9642857 | | |
| | **Min** | -258.5149 | | | -345.90568 | | | -2.9464286 | | |
| | **Difference** | 620.12284 | | | 716.16863 | | | 1.5073773 | | |
| **Subject 5** | **Average** | 96.433614 | -150.88488 | 338.99223 | -83.143663 | -398.93828 | 295.09669 | -0.0036331 | -0.6778259 | 0.6041361 |
| | **No data points** | | 259 | 273 | | 261 | 238 | | 206 | 234 |
| | **Max** | 1068.5433 | | | 1325.0314 | | | 5.2142857 | | |
| | **Min** | -258.5149 | | | -541.73291 | | | -11.753571 | | |
| | **Difference** | 489.87711 | | | 694.03497 | | | 1.2819621 | | |
| **Subject 6** | **Average** | 131.18686 | -145.70654 | 395.93231 | 127.64929 | -164.09341 | 425.05875 | -0.0052906 | -0.6310525 | 0.7039783 |
| | **No data points** | | 208 | 214 | | 225 | 302 | | 226 | 237 |
| | **Max** | 556.81056 | | | 664.34322 | | | 3.8535714 | | |
| | **Min** | -245.25758 | | | -309.30246 | | | -4.1142857 | | |
| | **Difference** | 541.63885 | | | 589.15217 | | | 1.3350308 | | |
| **Subject 7** | **Average** | 168.83302 | -64.495702 | 385.12438 | 135.59044 | -111.10754 | 420.02172 | -0.002278 | -0.632489 | 0.6203151 |
| | **No data points** | | 152 | 173 | | 143 | 183 | | 227 | 433 |
| | **Max** | 938.62151 | | | 933.3769 | | | 3.925 | | |
| | **Min** | -220.06866 | | | -1890.5616 | | | -2.4928571 | | |
| | **Difference** | 449.62008 | | | 531.12926 | | | 1.2528041 | | |
| **Subject 8** | **Average** | 149.94819 | -79.665308 | 365.40469 | 137.59443 | -103.39497 | 443.37438 | -0.0038184 | -0.5621186 | 0.5819739 |
| | **No data points** | | 160 | 204 | | 191 | 198 | | 529 | 465 |
| | **Max** | 550.1819 | | | 673.49403 | | | 2.8964286 | | |
| | **Min** | -245.25758 | | | -281.85004 | | | -2.0571429 | | |
| | **Difference** | 445.07 | | | 546.76935 | | | 1.1440924 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the smooth track (continued)

| | | Channel 5<br>Force (On crank) | | | Channel 6<br>Crank speed | | | Channel 7<br>Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 198.2955 | 151.62358 | 236.98976 | 0.3528033 | 0.3318587 | 0.3628771 | 1.7390477 | 1.6450383 | 1.8892318 |
| | **No data points** | | 99 | 72 | | 16 | 10 | | 269 | 266 |
| | **Max** | 275.8084 | | | 0.5026913 | | | 1.9557219 | | |
| | **Min** | 132.60608 | | | 0.1998772 | | | 1.4501863 | | |
| | **Difference** | 85.366186 | | | 0.0310185 | | | 0.2441935 | | |
| **Subject 2** | **Average** | 179.44909 | 146.6456 | 203.45936 | 0.3679162 | 0.3396175 | 0.3635949 | 1.8166955 | 1.694215 | 1.94331 |
| | **No data points** | | 89 | 42 | | 46 | 11 | | 224 | 231 |
| | **Max** | 245.04165 | | | 0.5176821 | | | 2.0811833 | | |
| | **Min** | 121.65247 | | | 0.2098711 | | | 1.5405923 | | |
| | **Difference** | 56.813763 | | | 0.0239774 | | | 0.249095 | | |
| **Subject 3** | **Average** | 185.41831 | 148.7266 | 219.33749 | 0.3661609 | 0.2751354 | 0.3545156 | 1.8094475 | 1.6865393 | 1.9414321 |
| | **No data points** | | 105 | 49 | | 46 | 15 | | 281 | 204 |
| | **Max** | 344.26845 | | | 0.5076882 | | | 2.0369028 | | |
| | **Min** | 120.84706 | | | 0.0389761 | | | 0.0276753 | | |
| | **Difference** | 70.610886 | | | 0.0793802 | | | 0.2548927 | | |
| **Subject 4** | **Average** | 183.12884 | 140.45838 | 217.96849 | 0.3425989 | 0.2167274 | 0.3129429 | 1.6922183 | 1.5084098 | 1.8453803 |
| | **No data points** | 48000 | 170 | 57 | 48000 | 43 | 37 | 48000 | 359 | 590 |
| | **Max** | 297.07129 | | | 0.5126851 | | | 1.9557219 | | |
| | **Min** | 61.085464 | | | 0.0389761 | | | 0 | | |
| | **Difference** | 77.510111 | | | 0.0962156 | | | 0.3369705 | | |
| **Subject 5** | **Average** | 185.02611 | 143.35446 | 225.04764 | 0.3566374 | 0.2975232 | 0.3628541 | 1.7646215 | 1.6528801 | 1.9152645 |
| | **No data points** | | 135 | 57 | | 17 | 13 | | 207 | 222 |
| | **Max** | 348.93985 | | | 0.5126851 | | | 2.053508 | | |
| | **Min** | 61.085464 | | | 0.0389761 | | | -0.0092251 | | |
| | **Difference** | 81.693181 | | | 0.0653309 | | | 0.2623844 | | |
| **Subject 6** | **Average** | 187.22495 | 148.48364 | 221.64551 | 0.3530626 | 0.3400988 | 0.3667747 | 1.7511119 | 1.6488776 | 1.8983936 |
| | **No data points** | | 81 | 37 | | 13 | 5 | | 265 | 292 |
| | **Max** | 274.19758 | | | 0.5026913 | | | 2.0000024 | | |
| | **Min** | 123.90763 | | | 0.1998772 | | | 1.422511 | | |
| | **Difference** | 73.161865 | | | 0.0266759 | | | 0.249516 | | |
| **Subject 7** | **Average** | 216.34742 | 193.85693 | 241.03537 | 0.3760465 | 0.3435668 | 0.3627772 | 1.853972 | 1.7121004 | 1.9830847 |
| | **No data points** | | 106 | 62 | | 27 | 15 | | 234 | 242 |
| | **Max** | 289.17825 | | | 0.5176821 | | | 2.1162387 | | |
| | **Min** | 151.45273 | | | 0.2048742 | | | 1.5405923 | | |
| | **Difference** | 47.178439 | | | 0.0192104 | | | 0.2709843 | | |
| **Subject 8** | **Average** | 172.5728 | 135.94993 | 206.90157 | 0.3749253 | 0.3404576 | 0.3655255 | 1.8618049 | 1.7241751 | 1.9817171 |
| | **No data points** | | 116 | 53 | | 12 | 16 | | 279 | 235 |
| | **Max** | 260.82773 | | | 0.5266765 | | | 2.1088586 | | |
| | **Min** | 110.53778 | | | 0.219865 | | | 1.603323 | | |
| | **Difference** | 70.951642 | | | 0.0250679 | | | 0.257542 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the smooth track (continued)

| | | Channel 8 Force (Vertical Right Handlebar) | | | Channel 9 Force (On seat) | | | Channel 11 Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (N) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 81.423448 | 30.530317 | 132.90886 | 99.549946 | 25.658822 | 219.69275 | 34.328382 | -16.227153 | 102.76791 |
| | **No data points** | | 282 | 266 | | 67 | 119 | | 187 | 232 |
| | **Max** | 192.50057 | | | 297.9761 | | | 138.15225 | | |
| | **Min** | -30.753646 | | | -231.8342 | | | -60.040136 | | |
| | **Difference** | 102.37855 | | | 194.03393 | | | 118.99506 | | |
| **Subject 2** | **Average** | 106.86185 | 60.281976 | 155.00196 | 339.52327 | 288.56232 | 388.12016 | 75.727066 | 42.15728 | 134.001 |
| | **No data points** | | 217 | 237 | | 114 | 114 | | 316 | 251 |
| | **Max** | 233.09224 | | | 502.58314 | | | 182.69711 | | |
| | **Min** | -19.05774 | | | 151.63463 | | | -69.723802 | | |
| | **Difference** | 94.719989 | | | 99.557838 | | | 91.843721 | | |
| **Subject 3** | **Average** | 69.18887 | 10.453157 | 132.6779 | 302.25052 | 250.84978 | 376.16764 | 31.707807 | -12.223161 | 99.325777 |
| | **No data points** | | 203 | 178 | | 77 | 112 | | 219 | 218 |
| | **Max** | 165.66878 | | | 509.35821 | | | 132.34205 | | |
| | **Min** | -49.329498 | | | -19.097073 | | | -72.951691 | | |
| | **Difference** | 122.22474 | | | 125.31786 | | | 111.54894 | | |
| **Subject 4** | **Average** | 64.579415 | 30.630902 | 109.29341 | 336.99922 | 333.7781 | 404.68981 | 34.714101 | 5.9435902 | 86.206441 |
| | **No data points** | 48000 | 254 | 274 | 48000 | 64 | 106 | 48000 | 273 | 153 |
| | **Max** | 147.43693 | | | 575.75388 | | | 112.97471 | | |
| | **Min** | -37.633591 | | | 158.4097 | | | -60.040136 | | |
| | **Difference** | 78.662506 | | | 70.91171 | | | 80.262851 | | |
| **Subject 5** | **Average** | 85.070958 | 25.893439 | 141.84468 | 417.28645 | 331.02665 | 502.5284 | 24.694962 | -49.378386 | 111.69673 |
| | **No data points** | | 364 | 300 | | 92 | 297 | | 299 | 196 |
| | **Max** | 184.24463 | | | 800.68612 | | | 169.78556 | | |
| | **Min** | -55.865445 | | | -46.197344 | | | -252.42232 | | |
| | **Difference** | 115.95124 | | | 171.50175 | | | 161.07512 | | |
| **Subject 6** | **Average** | 81.333213 | 36.339478 | 123.23174 | 212.12346 | 189.10923 | 286.33892 | 32.986293 | -2.2442846 | 76.277854 |
| | **No data points** | | 277 | 214 | | 32 | 34 | | 194 | 198 |
| | **Max** | 169.10875 | | | 371.14683 | | | 97.480846 | | |
| | **Min** | 7.7740454 | | | 79.818916 | | | -66.495913 | | |
| | **Difference** | 86.892261 | | | 97.229695 | | | 78.522138 | | |
| **Subject 7** | **Average** | 105.9965 | 42.46333 | 163.50473 | 439.29436 | 354.03646 | 556.49113 | 75.571401 | 21.607522 | 154.70903 |
| | **No data points** | | 297 | 220 | | 102 | 176 | | 288 | 297 |
| | **Max** | 216.23638 | | | 846.75659 | | | 233.05218 | | |
| | **Min** | -52.76947 | | | -99.042873 | | | -908.32935 | | |
| | **Difference** | 121.0414 | | | 202.45466 | | | 133.10151 | | |
| **Subject 8** | **Average** | 68.731927 | 10.023387 | 137.20139 | 163.14378 | 128.11547 | 237.75574 | 50.271194 | -13.154553 | 119.97576 |
| | **No data points** | | 206 | 159 | | 42 | 61 | | 163 | 251 |
| | **Max** | 197.66053 | | | 377.9219 | | | 166.55767 | | |
| | **Min** | -51.049484 | | | -32.647209 | | | -51.002046 | | |
| | **Difference** | 127.178 | | | 109.64027 | | | 133.13031 | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the smooth track (continued)

| | | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|---|
| | | (m/s^2) | | | (W) | | |
| | | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | -0.0155447 | -1.3754146 | 1.3233796 | 69.959298 | 50.3176 | 85.998166 |
| | **No data points** | | 250 | 292 | | | |
| | **Max** | 5.6585366 | | | 138.64647 | | |
| | **Min** | -8.8780488 | | | 26.504938 | | |
| | **Difference** | 2.6987942 | | | 35.680565 | | |
| **Subject 2** | **Average** | -0.0163826 | -1.5318177 | 1.4870455 | 66.022221 | 49.803411 | 73.97678 |
| | **No data points** | | 243 | 273 | | | |
| | **Max** | 3.1585366 | | | 126.85366 | | |
| | **Min** | -3.9268293 | | | 25.531339 | | |
| | **Difference** | 3.0188632 | | | 24.173368 | | |
| **Subject 3** | **Average** | -0.0131481 | -1.2504796 | 1.2269602 | 67.892943 | 40.919949 | 77.758562 |
| | **No data points** | | 267 | 298 | | | |
| | **Max** | 6.2560976 | | | 174.78103 | | |
| | **Min** | -6.195122 | | | 4.7101426 | | |
| | **Difference** | 2.4774398 | | | 36.838613 | | |
| **Subject 4** | **Average** | -0.0130305 | -1.3244215 | 1.3578397 | 62.739732 | 30.441173 | 68.211699 |
| | **No data points** | 48000 | 156 | 210 | | | |
| | **Max** | 5.7804878 | | | 152.30403 | | |
| | **Min** | -5.4756098 | | | 2.3808708 | | |
| | **Difference** | 2.6822612 | | | 37.770525 | | |
| **Subject 5** | **Average** | -0.0201799 | -1.301021 | 1.4213329 | 65.987232 | 42.651271 | 81.659452 |
| | **No data points** | | 215 | 284 | | | |
| | **Max** | 7.804878 | | | 178.89627 | | |
| | **Min** | -8.0365854 | | | 2.3808708 | | |
| | **Difference** | 2.7223539 | | | 39.008181 | | |
| **Subject 6** | **Average** | -0.0201799 | -1.301021 | 1.4213329 | 66.102137 | 50.499111 | 81.293973 |
| | **No data points** | | 215 | 284 | | | |
| | **Max** | 7.804878 | | | 137.83673 | | |
| | **Min** | -8.0365854 | | | 24.766315 | | |
| | **Difference** | 2.7223539 | | | 30.794862 | | |
| **Subject 7** | **Average** | -0.0154167 | -1.274599 | 1.3056794 | 81.356682 | 66.6028 | 87.442136 |
| | **No data points** | | 555 | 487 | | | |
| | **Max** | 7.3780488 | | | 149.70239 | | |
| | **Min** | -9.6463415 | | | 31.028753 | | |
| | **Difference** | 2.5802784 | | | 20.839336 | | |
| **Subject 8** | **Average** | -0.0156941 | -1.1974766 | 1.2703823 | 64.701906 | 46.285183 | 75.627803 |
| | **No data points** | | 347 | 356 | | | |
| | **Max** | 6.4268293 | | | 137.37185 | | |
| | **Min** | -5.2439024 | | | 24.303386 | | |
| | **Difference** | 2.4678589 | | | 29.342619 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the smooth track

| | | Channel 0<br>Force (Horizontal Right Handlebar) | | | Channel 3<br>Force (Horizontal Left handlebar) | | | Channel 4<br>Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (N) | | | (m/s^2) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | 151.10417 | -91.219058 | 429.23386 | 138.20101 | -136.33619 | 428.99026 | -0.0041879 | -0.4536683 | 0.4503139 |
| | **No data points** | | 183 | 225 | | 228 | 382 | | 590 | 512 |
| | **Max** | 588.62814 | | | 592.96694 | | | 2.7535714 | | |
| | **Min** | -193.55401 | | | -265.37859 | | | -10.167857 | | |
| | **Difference** | 520.45291 | | | 565.32644 | | | 0.9039822 | | |
| **Subject 2** | **Average** | 140.858 | -107.35943 | 370.18685 | 123.50703 | -171.56501 | 391.78933 | -0.0036407 | -0.4911346 | 0.48420735 |
| | **No data points** | | 181 | 148 | | 154 | 209 | | 226 | 237 |
| | **Max** | 615.14279 | | | 611.26855 | | | 1.1321429 | | |
| | **Min** | -245.25758 | | | -336.75488 | | | -2.3714286 | | |
| | **Difference** | 477.54627 | | | 563.35435 | | | 0.975342 | | |
| **Subject 3** | **Average** | 115.01635 | -179.86137 | 376.00371 | 114.94382 | -199.59738 | 400.59414 | -0.0036804 | -0.4465233 | 0.41455904 |
| | **No data points** | | 268 | 115 | | 210 | 240 | | 377 | 392 |
| | **Max** | 628.40012 | | | 655.19242 | | | 2.5464286 | | |
| | **Min** | -310.21847 | | | -380.67874 | | | -6.7678571 | | |
| | **Difference** | 555.86508 | | | 600.19151 | | | 0.8610823 | | |
| **Subject 4** | **Average** | 177.71482 | -143.08608 | 581.76932 | 174.90176 | -205.91441 | 619.76908 | -0.0032746 | -0.578729 | 0.58209948 |
| | **No data points** | | 206 | 288 | | 228 | 273 | | 204 | 247 |
| | **Max** | 718.54992 | | | 754.02111 | | | 2.5285714 | | |
| | **Min** | -271.77223 | | | -389.82955 | | | -4.7071429 | | |
| | **Difference** | 724.8554 | | | 825.68349 | | | 1.1608285 | | |
| **Subject 5** | **Average** | 119.01272 | -182.26799 | 403.15296 | -42.896934 | -380.30553 | 378.06074 | -0.0032094 | -0.3179418 | 0.32548518 |
| | **No data points** | | 230 | 229 | | 255 | 299 | | 253 | 265 |
| | **Max** | 783.51082 | | | 825.39739 | | | 1.4464286 | | |
| | **Min** | -310.21847 | | | -560.03452 | | | -7.9857143 | | |
| | **Difference** | 585.42096 | | | 758.36627 | | | 0.643427 | | |
| **Subject 6** | **Average** | 155.75047 | -131.64654 | 414.34488 | 153.19788 | -138.15869 | 437.87089 | -0.0038343 | -0.4237425 | 0.4969182 |
| | **No data points** | | 188 | 236 | | 193 | 317 | | 142 | 124 |
| | **Max** | 595.25681 | | | 710.09725 | | | 2.8071429 | | |
| | **Min** | -233.32599 | | | -291.00085 | | | -3.8 | | |
| | **Difference** | 545.99142 | | | 576.02959 | | | 0.9206607 | | |
| **Subject 7** | **Average** | 180.46113 | -56.982962 | 388.56814 | 176.29818 | -101.97317 | 441.60782 | -0.0034545 | -0.5219196 | 0.53729396 |
| | **No data points** | | 193 | 190 | | 144 | 343 | | 240 | 260 |
| | **Max** | 666.84636 | | | 710.09725 | | | 2.4071429 | | |
| | **Min** | -174.99376 | | | -256.22779 | | | -1.8642857 | | |
| | **Difference** | 445.5511 | | | 543.58099 | | | 1.0592136 | | |
| **Subject 8** | **Average** | 159.12872 | -71.425232 | 382.21241 | 148.01895 | -102.33311 | 439.99072 | -0.0032616 | -0.3966472 | 0.44771557 |
| | **No data points** | | 115 | 163 | | 159 | 203 | | 147 | 111 |
| | **Max** | 556.81056 | | | 700.94644 | | | 2.8607143 | | |
| | **Min** | -226.69732 | | | -300.15165 | | | -3.4 | | |
| | **Difference** | 453.63764 | | | 542.32383 | | | 0.8443628 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the smooth track (continued)

| | | Channel 5<br>Force (On crank) | | | Channel 6<br>Crank speed | | | Channel 7<br>Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | (N) | | | (m/s) | | | (m/s) | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | 205.63125 | 153.97828 | 242.29529 | 0.3550874 | 0.3327956 | 0.3654678 | 1.7540101 | 1.6502527 | 1.9175356 |
| | **No data points** | | 28 | 81 | | 16 | 13 | | 234 | 165 |
| | **Max** | 288.37284 | | | 0.5176821 | | | 2.0719582 | | |
| | **Min** | 138.08289 | | | 0.1998772 | | | 1.4594114 | | |
| | **Difference** | 88.317018 | | | 0.0326722 | | | 0.2672829 | | |
| **Subject 2** | **Average** | 182.08024 | 150.08031 | 206.38186 | 0.3624308 | 0.3417901 | 0.3638765 | 1.7902508 | 1.6670807 | 1.9191984 |
| | **No data points** | | 75 | 56 | | 33 | 20 | | 203 | 328 |
| | **Max** | 261.63314 | | | 0.5176821 | | | 2.0811833 | | |
| | **Min** | 121.65247 | | | 0.2098711 | | | 1.5313672 | | |
| | **Difference** | 56.301546 | | | 0.0220864 | | | 0.2521177 | | |
| **Subject 3** | **Average** | 190.16739 | 150.48454 | 226.47926 | 0.3566624 | 0.2339353 | 0.3162574 | 1.7632306 | 1.5395647 | 1.9156504 |
| | **No data points** | | 95 | 51 | | 38 | 31 | | 158 | 224 |
| | **Max** | 337.18082 | | | 0.4976943 | | | 2.0184526 | | |
| | **Min** | 119.23624 | | | 0.0489699 | | | 0.1623618 | | |
| | **Difference** | 75.994722 | | | 0.0823221 | | | 0.3760857 | | |
| **Subject 4** | **Average** | 191.80699 | 146.77727 | 222.89843 | 0.355975 | 0.3263785 | 0.3621109 | 1.7606393 | 1.6463501 | 1.916636 |
| | **No data points** | | 198 | 129 | | 19 | 21 | | 237 | 233 |
| | **Max** | 264.69371 | | | 0.5176821 | | | 1.9907773 | | |
| | **Min** | 116.98108 | | | 0.1948803 | | | 1.4501863 | | |
| | **Difference** | 76.121156 | | | 0.0357324 | | | 0.2702859 | | |
| **Subject 5** | **Average** | 202.76638 | 158.65679 | 245.11571 | 0.3591204 | 0.3122527 | 0.3587796 | 1.7823891 | 1.6641072 | 1.9346308 |
| | **No data points** | | 202 | 87 | | 9 | 7 | | 200 | 153 |
| | **Max** | 289.98366 | | | 0.5176821 | | | 2.0442829 | | |
| | **Min** | 126.32387 | | | 0.1998772 | | | 1.4870867 | | |
| | **Difference** | 86.458924 | | | 0.046527 | | | 0.2705236 | | |
| **Subject 6** | **Average** | 194.60918 | 149.72945 | 230.89568 | 0.3525139 | 0.3237103 | 0.3673458 | 1.7490295 | 1.6477477 | 1.9088252 |
| | **No data points** | | 53 | 22 | | 11 | 7 | | 307 | 189 |
| | **Max** | 282.09062 | | | 0.5026913 | | | 2.0000024 | | |
| | **Min** | 130.99526 | | | 0.1808889 | | | 1.4317361 | | |
| | **Difference** | 81.166226 | | | 0.0436355 | | | 0.2610775 | | |
| **Subject 7** | **Average** | 222.93402 | 200.84025 | 244.24519 | 0.3693628 | 0.3415402 | 0.3668461 | 1.8225608 | 1.6867558 | 1.9604073 |
| | **No data points** | | 87 | 54 | | 24 | 14 | | 195 | 228 |
| | **Max** | 300.93727 | | | 0.5176821 | | | 2.0627331 | | |
| | **Min** | 157.09062 | | | 0.2048742 | | | 1.4501863 | | |
| | **Difference** | 43.404938 | | | 0.0253059 | | | 0.2736516 | | |
| **Subject 8** | **Average** | 175.70494 | 140.72732 | 206.0818 | 0.3707711 | 0.3501599 | 0.3652757 | 1.8414931 | 1.7208212 | 1.9753187 |
| | **No data points** | | 108 | 51 | | 16 | 10 | | 424 | 140 |
| | **Max** | 264.69371 | | | 0.5266765 | | | 2.0996335 | | |
| | **Min** | 107.47722 | | | 0.214868 | | | 1.5682676 | | |
| | **Difference** | 65.354476 | | | 0.0151157 | | | 0.2544975 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the smooth track (continued)

| | | Channel 8 | | | Channel 9 | | | Channel 11 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Force (Vertical Right Handlebar) | | | Force (On seat) | | | Force (Vertical Left Handlebar) | | |
| | | (N) | | | (N) | | | (N) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject 1** | **Average** | 49.23149 | -8.9902975 | 123.82985 | 81.809036 | -19.184929 | 230.75621 | 6.4339337 | -27.498672 | 70.719467 |
| | **No data points** | | 218 | 163 | | 1203 | 314 | | 327 | 311 |
| | **Max** | 175.9887 | | | 323.72136 | | | 116.2026 | | |
| | **Min** | -54.145459 | | | -131.5632 | | | -69.723802 | | |
| | **Difference** | 132.82015 | | | 249.94114 | | | 98.218138 | | |
| **Subject 2** | **Average** | 101.83774 | 46.842304 | 158.65753 | 395.6383 | 306.14207 | 485.85745 | 62.944061 | 26.36052 | 133.19649 |
| | **No data points** | | 266 | 186 | | 151 | 326 | | 260 | 170 |
| | **Max** | 202.82049 | | | 543.23355 | | | 185.925 | | |
| | **Min** | -52.76947 | | | 224.80537 | | | -81.989781 | | |
| | **Difference** | 111.81522 | | | 179.71538 | | | 106.83597 | | |
| **Subject 3** | **Average** | 65.011576 | 5.802737 | 133.82353 | 296.94169 | 172.50047 | 436.49397 | 31.04613 | -24.265678 | 108.83695 |
| | **No data points** | | 219 | 263 | | 198 | 168 | | 123 | 149 |
| | **Max** | 157.41285 | | | 548.6536 | | | 138.15225 | | |
| | **Min** | -64.465377 | | | -19.097073 | | | -76.17958 | | |
| | **Difference** | 128.02079 | | | 263.9935 | | | 133.10263 | | |
| **Subject 4** | **Average** | 49.543818 | 9.3104032 | 101.57806 | 323.95563 | 189.35724 | 445.32039 | 23.444357 | -23.809527 | 98.447046 |
| | **No data points** | | 281 | 247 | | 280 | 227 | | 165 | 149 |
| | **Max** | 118.88516 | | | 483.61295 | | | 122.65838 | | |
| | **Min** | -52.76947 | | | 151.63463 | | | -53.584358 | | |
| | **Difference** | 92.267653 | | | 255.96315 | | | 122.25657 | | |
| **Subject 5** | **Average** | 79.611328 | 5.2729645 | 162.49561 | 427.25472 | 221.2416 | 729.9719 | 17.113983 | -62.691891 | 122.47343 |
| | **No data points** | | 218 | 254 | | 173 | 155 | | 251 | 185 |
| | **Max** | 236.18822 | | | 1018.8433 | | | 173.01345 | | |
| | **Min** | -59.305418 | | | 139.43951 | | | -129.76254 | | |
| | **Difference** | 157.22265 | | | 508.7303 | | | 185.16532 | | |
| **Subject 6** | **Average** | 70.489968 | 14.783822 | 131.61914 | 216.16094 | 115.24383 | 320.75186 | 31.505943 | -14.418135 | 87.345274 |
| | **No data points** | | 310 | 339 | | 195 | 282 | | 184 | 160 |
| | **Max** | 148.81292 | | | 383.34195 | | | 116.2026 | | |
| | **Min** | -54.145459 | | | 52.718645 | | | -69.723802 | | |
| | **Difference** | 116.83532 | | | 205.50802 | | | 101.76341 | | |
| **Subject 7** | **Average** | 110.49354 | 49.861569 | 191.87466 | 445.28078 | 271.85184 | 661.76302 | 66.923806 | -11.693532 | 168.01857 |
| | **No data points** | | 287 | 205 | | 182 | 297 | | 180 | 232 |
| | **Max** | 268.17996 | | | 780.36092 | | | 229.82429 | | |
| | **Min** | -67.561352 | | | 192.28504 | | | -113.62309 | | |
| | **Difference** | 142.01309 | | | 389.91118 | | | 179.7121 | | |
| **Subject 8** | **Average** | 59.264392 | -1.2226747 | 133.01309 | 187.18627 | 98.199718 | 234.83627 | 44.944478 | -23.919271 | 109.78684 |
| | **No data points** | | 202 | 186 | | 469 | 1425 | | 123 | 242 |
| | **Max** | 185.96462 | | | 364.37176 | | | 157.51958 | | |
| | **Min** | -59.305418 | | | -0.1268835 | | | -56.812247 | | |
| | **Difference** | 134.23576 | | | 136.63655 | | | 133.70611 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the smooth track (continued)

| | | **Channel 12 Seat Acceleration** | | | **Crank Power** | | |
|---|---|---|---|---|---|---|---|
| | | **(m/s^2)** | | | **(W)** | | |
| | | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **Subject 1** | **Average** | -0.0154667 | -1.3930582 | 1.5030647 | 73.017073 | 51.243293 | 88.5511392 |
| | **No data points** | | 195 | 191 | | | |
| | **Max** | 5.8902439 | | | 149.28544 | | |
| | **Min** | -7.8658537 | | | 27.599626 | | |
| | **Difference** | 2.8961229 | | | 37.307846 | | |
| **Subject 2** | **Average** | -0.013328 | -1.2126764 | 1.1463916 | 65.991496 | 51.295961 | 75.097511 |
| | **No data points** | | 223 | 243 | | | |
| | **Max** | 2.6829268 | | | 135.44278 | | |
| | **Min** | -3.2195122 | | | 25.531339 | | |
| | **Difference** | 2.359068 | | | 23.80155 | | |
| **Subject 3** | **Average** | -0.0164548 | -1.3546989 | 1.3905627 | 67.825562 | 35.203642 | 71.6257377 |
| | **No data points** | | 211 | 153 | | | |
| | **Max** | 4.2926829 | | | 167.81298 | | |
| | **Min** | -6.4878049 | | | 5.8389895 | | |
| | **Difference** | 2.7452616 | | | 36.422096 | | |
| **Subject 4** | **Average** | -0.0108981 | -1.4402439 | 1.4711841 | 68.278491 | 47.904945 | 80.7139585 |
| | **No data points** | | 140 | 124 | | | |
| | **Max** | 9.2926829 | | | 137.02718 | | |
| | **Min** | -6.8536585 | | | 22.79731 | | |
| | **Difference** | 2.911428 | | | 32.809013 | | |
| **Subject 5** | **Average** | -0.0103342 | -1.2098687 | 1.1349214 | 72.81754 | 49.541005 | 87.9425283 |
| | **No data points** | | 312 | 210 | | | |
| | **Max** | 7.6011274 | | | 150.11934 | | |
| | **Min** | -6.1453201 | | | 25.249266 | | |
| | **Difference** | 2.3447901 | | | 38.401523 | | |
| **Subject 6** | **Average** | -0.0203887 | -1.3075251 | 1.2384046 | 68.602444 | 48.468963 | 84.8185618 |
| | **No data points** | | 129 | 122 | | | |
| | **Max** | 7.0243902 | | | 141.80449 | | |
| | **Min** | -10.365854 | | | 23.695588 | | |
| | **Difference** | 2.5459297 | | | 36.349599 | | |
| **Subject 7** | **Average** | -0.0151784 | -1.3656011 | 1.2428976 | 82.343531 | 68.595026 | 89.6003996 |
| | **No data points** | | 338 | 267 | | | |
| | **Max** | 5.6585366 | | | 155.78982 | | |
| | **Min** | -8.8170732 | | | 32.18381 | | |
| | **Difference** | 2.6084987 | | | 21.005374 | | |
| **Subject 8** | **Average** | -0.0143067 | -1.217973 | 1.1428846 | 65.146322 | 49.277072 | 75.2766653 |
| | **No data points** | | 206 | 127 | | | |
| | **Max** | 7.5609756 | | | 139.40797 | | |
| | **Min** | -6.0121951 | | | 23.093418 | | |
| | **Difference** | 2.3608576 | | | 25.999594 | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike on a smooth track

| | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 129.3 | -128.5 | 384.2 | 90.9 | -192.6 | 406.9 | 0.0 | -0.7 | 0.7 |
| Mean sd | 25.20 | 37.75 | 44.51 | 73.97 | 91.06 | 68.14 | 0.00 | 0.05 | 0.06 |
| Max | 677.3 | | | 763.6 | | | 3.0 | | |
| Max sd | 205.69 | | | 250.99 | | | 1.35 | | |
| Min | -247.4 | | | -558.4 | | | -3.8 | | |
| Min sd | 20.05 | | | 543.83 | | | 3.30 | | |
| Average Diffrence | 512.7 | | | 599.6 | | | 1.3 | | |
| Avg Difference sd | 59.32 | | | 71.08 | | | 0.11 | | |
| Average no data points | | 216.5 | 226.5 | | 223.0 | 269.0 | | 295.5 | 311.3 |

## The Rolling Road Rig

## Mean of the combined subjects average results for the hardtail bike on a smooth track (continued)

| | Channel 5 Force (On crank) | | | Channel 6 Crank speed | | | Channel 7 Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 |
| mean | 188.4 | 151.1 | 221.5 | 0.3612689 | 0.3106232 | 0.3564828 | 1.786 | 1.659 | 1.925 |
| Mean sd | 13.41 | 17.98 | 13.04 | 0.0118444 | 0.0453293 | 0.0179641 | 0.059 | 0.068 | 0.047 |
| Max | 291.9 | | | 0.5125602 | | | 2.039 | | |
| Max sd | 37.35 | | | 0.0081967 | | | 0.064 | | |
| Min | 110.4 | | | 0.1439116 | | | 0.947 | | |
| Min sd | 32.65 | | | 0.0871245 | | | 0.781 | | |
| Average Diffrence | 70.4 | | | 0.0458596 | | | 0.266 | | |
| Avg Diffrence sd | 12.73 | | | 0.0298761 | | | 0.030 | | |
| Average no data points | | 112.6 | 53.6 | | 27.5 | 15.3 | | 264.8 | 285.3 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike on a smooth track (continued)

| | Channel 8<br>Force (Vertical Right Handlebar) | | | Channel 9<br>Force (On seat) | | | Channel 11<br>Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 82.9 | 30.8 | 137.0 | 288.8 | 237.6 | 371.5 | 45.0 | -2.9 | 110.6 |
| Mean sd | 16.22 | 16.50 | 17.08 | 120.55 | 115.61 | 120.10 | 20.21 | 27.36 | 25.48 |
| Max | 188.2 | | | 535.3 | | | 154.1 | | |
| Max sd | 27.93 | | | 199.59 | | | 43.22 | | |
| Min | -36.1 | | | -4.9 | | | -192.6 | | |
| Min sd | 21.76 | | | 131.69 | | | 296.73 | | |
| Average Diffrence | 106.1 | | | 133.8 | | | 113.6 | | |
| Avg Diffrence sd | 18.09 | | | 49.11 | | | 28.94 | | |
| Average no data points | | 262.5 | 231.0 | | 73.8 | 127.4 | | 242.4 | 224.5 |

## The Rolling Road Rig

## Mean of the combined subjects average results for the hardtail bike on a smooth track (continued)

| | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | -1.3 | 1.4 | 68.1 | 47.2 | 79.0 |
| Mean sd | 0.00 | 0.10 | 0.09 | 5.76 | 10.32 | 6.40 |
| Max | 6.3 | | | 149.5 | | |
| Max sd | 1.52 | | | 18.61 | | |
| Min | -6.9 | | | 17.7 | | |
| Min sd | 2.00 | | | 12.24 | | |
| Average Diffrence | 2.7 | | | 31.8 | | |
| Avg Diffrence sd | 0.17 | | | 6.69 | | |
| Average no data points | | 281.0 | 310.5 | | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the full suspension bike on the smooth track

| | Channel 0 Force (Horizontal Right Handlebar) | | | Channel 3 Force (Horizontal Left handlebar) | | | Channel 4 Handlebar Acceleration | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 149.9 | -120.5 | 418.2 | 123.3 | -179.5 | 442.3 | 0.0 | -0.5 | 0.5 |
| Mean sd | 24.15 | 46.97 | 69.05 | 70.60 | 90.26 | 75.70 | 0.00 | 0.08 | 0.08 |
| Max | 644.1 | | | 695.0 | | | 2.3 | | |
| Max sd | 75.27 | | | 75.58 | | | 0.65 | | |
| Min | -245.8 | | | -347.5 | | | -5.1 | | |
| Min sd | 49.62 | | | 99.06 | | | 2.91 | | |
| Average Diffrence | 538.7 | | | 621.9 | | | 0.9 | | |
| Avg Diffrence sd | 90.37 | | | 108.11 | | | 0.15 | | |
| Average no data points | | 195.5 | 199.3 | | 196.4 | 283.3 | | 272.4 | 268.5 |

## The Rolling Road Rig
## Mean of the combined subjects average results for the full suspension bike on the smooth track (Continued)

| | Channel 5 Force (On crank) | | | Channel 6 Crank speed | | | Channel 7 Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 |
| mean | 195.7 | 156.4 | 228.0 | 0.3602405 | 0.3203203 | 0.358245 | 1.783 | 1.653 | 1.931 |
| Mean sd | 14.75 | 18.68 | 15.79 | 0.0067339 | 0.0369032 | 0.0171893 | 0.034 | 0.052 | 0.024 |
| Max | 286.2 | | | 0.514434 | | | 2.046 | | |
| Max sd | 25.02 | | | 0.0094168 | | | 0.040 | | |
| Min | 127.2 | | | 0.1817634 | | | 1.318 | | |
| Min sd | 15.19 | | | 0.0546197 | | | 0.469 | | |
| Average Diffrence | 71.6 | | | 0.0379247 | | | 0.278 | | |
| Avg Diffrence sd | 15.58 | | | 0.0208411 | | | 0.040 | | |
| Average no data points | | 105.8 | 66.4 | | 20.8 | 15.4 | | 244.8 | 207.5 |

**The Rolling Road Rig**
**Mean of the combined subjects average results for the full suspension bike on the smooth track (Continued)**

| | Channel 8<br>Force (Vertical Right Handlebar) | | | Channel 9<br>Force (On seat) | | | Channel 11<br>Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 73.2 | 15.2 | 142.1 | 296.8 | 169.4 | 443.2 | 35.5 | -20.2 | 112.4 |
| Mean sd | 22.85 | 21.64 | 27.79 | 127.79 | 104.10 | 183.39 | 21.36 | 24.42 | 29.78 |
| Max | 186.8 | | | 555.8 | | | 154.9 | | |
| Max sd | 48.34 | | | 236.19 | | | 40.05 | | |
| Min | -58.1 | | | 76.3 | | | -81.4 | | |
| Min sd | 5.62 | | | 121.82 | | | 26.87 | | |
| Average Diffrence | 126.9 | | | 273.8 | | | 132.6 | | |
| Avg Diffrence sd | 19.88 | | | 120.70 | | | 33.57 | | |
| Average no data points | | 250.1 | 230.4 | | 356.4 | 399.3 | | 201.6 | 199.8 |

## The Rolling Road Rig

## Mean of the combined subjects average results for the full suspension bike on the smooth track (Continued)

| | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | -1.3 | 1.3 | 70.5 | 50.2 | 81.7 |
| Mean sd | 0.00 | 0.09 | 0.15 | 5.56 | 9.06 | 7.02 |
| Max | 6.3 | | | 147.1 | | |
| Max sd | 2.09 | | | 10.97 | | |
| Min | -7.0 | | | 23.2 | | |
| Min sd | 2.13 | | | 7.67 | | |
| Average Diffrence | 2.6 | | | 31.5 | | |
| Avg Diffrence sd | 0.24 | | | 6.87 | | |
| Average no data points | | 219.3 | 179.6 | | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - the fully suspended bike on the smooth track

| HT - SUS | Channel 0 | | | Channel 3 | | | Channel 4 | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Handlebar Acceleration | | |
| NULL HYPOTHESIS | Force (Horizontal Right Handlebar) | | | Force (Horizontal Left handlebar) | | | | | |
| | (N) | | | (N) | | | (m/s^2) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| average | -20.6 | -8.0 | -33.9 | -32.4 | -13.1 | -35.4 | 0.0 | -0.2 | 0.2 |
| sum | -164.7 | -64.2 | -271.5 | -259.3 | -104.8 | -283.1 | 0.0 | -1.7 | 1.6 |
| sum of squares | 4159.8 | 4192.0 | 17009.1 | 9715.5 | 4158.2 | 20015.6 | 0.0 | 0.4 | 0.3 |
| sd | 10.47 | 22.92 | 33.37 | 13.68 | 19.94 | 37.79 | 0.00 | 0.07 | 0.06 |
| sd(mean) | 3.70 | 8.10 | 11.80 | 4.84 | 7.05 | 13.36 | 0.00 | 0.03 | 0.02 |
| t | 5.56 | 0.99 | 2.88 | 6.70 | 1.86 | 2.65 | 0.62 | 7.99 | 8.64 |
| p | 0.085% | 35.534% | 2.375% | 0.028% | 10.546% | 3.303% | 55.234% | 0.009% | 0.006% |
| Cv | -0.51 | -2.86 | -0.98 | -0.42 | -1.52 | -1.07 | -4.53 | -0.35 | 0.33 |
| 95% CONFIDENCE LIMITS | | | | | | | | | |
| Upper | -20.6 | -8.0 | -33.9 | -32.4 | -13.1 | -35.4 | 0.0 | -0.2 | 0.2 |
| Lower | -20.6 | -8.0 | -33.9 | -32.4 | -13.1 | -35.4 | 0.0 | -0.2 | 0.2 |
| % Improvement by fitting suspension = 100*(average diff. / HT mean) | | | | | | | | | |
| HT mean | 129.3 | -128.5 | 384.2 | 90.9 | -192.6 | 406.9 | 0.0 | -0.7 | 0.7 |
| % improvement | -15.9% | 6.2% | -8.8% | -35.7% | 6.8% | -8.7% | 5.5% | 31.5% | 29.6% |
| DIFFERENCE ANALYSIS (HT - SU) | | | | | | | | | |
| ht | Channel 0 | | | Channel 3 | | | Channel 4 | | |
| | Force (Horizontal Right Handlebar) | | | Force (Horizontal Left handlebar) | | | Handlebar Acceleration | | |
| | Difference (max - Min) | | | Difference (max - Min) | | | Difference (max - Min) | | |
| n | 8 | | | 8 | | | 8 | | |
| average | -25.9 | | | -22.3 | | | 0.4 | 0.77972 | 2.17282 |
| sum | -207.4 | | | -178.2 | | | 3.2 | | 1.3931 |
| sum of squares | 21483.0 | | | 21485.7 | | | 1.4 | | |
| sd | 47.97 | | | 50.02 | | | 0.13 | | |
| sd(mean) | 16.96 | | | 17.68 | | | 0.05 | | |
| t | 1.53 | | | 1.26 | | | 8.52 | | |
| p | 17.027% | | | 24.810% | | | 0.006% | | |
| Cv | -1.85 | | | -2.25 | | | 0.33 | | |
| 95% CONFIDENCE LIMITS | | | | | | | | | |
| Upper | -25.9 | | | -22.3 | | | 0.4 | | |
| Lower | -25.9 | | | -22.3 | | | 0.4 | | |
| % Improvement by fitting suspension = 100*(average diff. / HT mean) | | | | | | | | | |
| HT mean | 512.7 | | | 599.6 | | | 1.3 | 2.17282 | |
| % improvement | -5.1% | | | -3.7% | | | 30.5% | 35.9% | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - the fully suspended bike on the smooth track (continued)

| | Channel 5<br>Force (On crank) | | | Channel 6<br>Crank speed | | | Channel 7<br>Road Speed | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8.000 | 8.000 | 8.000 |
| **average** | -7.3 | -5.3 | -6.5 | 0.001 | -0.010 | -0.002 | 0.003 | 0.006 | -0.006 |
| **sum** | -58.2 | -42.2 | -52.0 | 0.008 | -0.078 | -0.014 | 0.025 | 0.050 | -0.050 |
| **sum of squares** | 581.0 | 367.7 | 611.3 | 0.000 | 0.014 | 0.004 | 0.009 | 0.042 | 0.008 |
| **sd** | 4.74 | 4.56 | 6.25 | 0.007 | 0.044 | 0.024 | 0.037 | 0.077 | 0.033 |
| **sd(mean)** | 1.67 | 1.61 | 2.21 | 0.003 | 0.016 | 0.008 | 0.013 | 0.027 | 0.012 |
| **t** | 4.35 | 3.27 | 2.94 | 0.403 | 0.623 | 0.211 | 0.245 | 0.227 | 0.532 |
| **p** | 0.337% | 1.363% | 2.161% | 69.886% | 55.289% | 83.871% | 81.385% | 82.725% | 61.111% |
| **Cv** | -0.65 | -0.86 | -0.96 | 7.016 | -4.538 | -13.389 | 11.568 | 12.485 | -5.315 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | -7.3 | -5.3 | -6.5 | 0.001 | -0.010 | -0.002 | 0.003 | 0.006 | -0.006 |
| **Lower** | -7.3 | -5.3 | -6.5 | 0.001 | -0.010 | -0.002 | 0.003 | 0.006 | -0.006 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 188.4 | 151.1 | 221.5 | 0.4 | 0.3 | 0.4 | 1.8 | 1.7 | 1.9 |
| **% improvement** | -3.9% | -3.5% | -2.9% | 0.3% | -3.1% | -0.5% | 0.2% | 0.4% | -0.3% |
| **DIFFERENCE ANALYSIS (HT - SU)** | | | | | | | | | |
| **ht** | **Channel 5<br>Force (On crank)<br>Difference (max - Min)** | | | **Channel 6<br>Crank speed<br>Difference (max - Min)** | | | **Channel 7<br>Road Speed<br>Difference (max - Min)** | | |
| **n** | 8 | | | 8 | | | 8 | | |
| **average** | 0.1594 | | | 0.008 | | | 0.0 | | |
| **sum** | -9.8 | | | 0.1 | | | -0.1 | | |
| **sum of squares** | 172.2 | | | 0.0 | | | 0.0 | | |
| **sd** | 4.78 | | | 0.02 | | | 0.05 | | |
| **sd(mean)** | 1.69 | | | 0.01 | | | 0.02 | | |
| **t** | 0.73 | | | 0.95 | | | 0.68 | | |
| **p** | 49.092% | | | 37.605% | | | 51.557% | | |
| **Cv** | 30.01 | | | 2.99 | | | -4.13 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 0.2 | | | 0.0 | | | 0.0 | | |
| **Lower** | 0.2 | | | 0.0 | | | 0.0 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 70.4 | | | 0.0 | | | 0.3 | | |
| **% improvement** | 0.2% | | | 17.3% | | | -4.7% | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - the fully suspended bike on the smooth track (continued)

| | Channel 8 Force (Vertical Right Handlebar) | | | Channel 9 Force (On seat) | | | Channel 11 Force (Vertical Left Handlebar) | | |
|---|---|---|---|---|---|---|---|---|---|
| | (N) | | | (N) | | | (N) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | 9.7 | 15.6 | -5.2 | -8.0 | 68.2 | -71.7 | 9.5 | 17.3 | -1.7 |
| **sum** | 77.7 | 125.0 | -41.2 | -64.1 | 545.8 | -574.0 | 75.6 | 138.4 | -13.9 |
| **sum of squares** | 1562.3 | 3289.8 | 1475.8 | 4391.5 | 54474.1 | 78970.6 | 1231.8 | 2957.1 | 1787.6 |
| **sd** | 10.74 | 13.83 | 13.43 | 23.54 | 49.63 | 73.48 | 8.59 | 8.96 | 15.87 |
| **sd(mean)** | 3.80 | 4.89 | 4.75 | 8.32 | 17.55 | 25.98 | 3.04 | 3.17 | 5.61 |
| **t** | 2.56 | 3.20 | 1.08 | 0.96 | 3.89 | 2.76 | 3.11 | 5.46 | 0.31 |
| **p** | 3.768% | 1.516% | 31.388% | 36.804% | 0.599% | 2.802% | 1.700% | 0.095% | 76.646% |
| **Cv** | 1.11 | 0.89 | -2.61 | -2.94 | 0.73 | -1.02 | 0.91 | 0.52 | -9.16 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | 9.7 | 15.6 | -5.2 | -8.0 | 68.2 | -71.7 | 9.5 | 17.3 | -1.7 |
| **Lower** | 9.7 | 15.6 | -5.2 | -8.0 | 68.2 | -71.7 | 9.5 | 17.3 | -1.7 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 82.9 | 30.8 | 137.0 | 288.8 | 237.6 | 371.5 | 45.0 | -2.9 | 110.6 |
| **% improvement** | 11.7% | 50.7% | -3.8% | -2.8% | 28.7% | -19.3% | 21.0% | -588.5% | -1.6% |
| **DIFFERENCE ANALYSIS (HT - SU)** | | | | | | | | | |
| **ht** | **Channel 8<br>Force (Vertical Right Handlebar)<br>Difference (max - Min)** | | | **Channel 9<br>Force (On seat)<br>Difference (max - Min)** | | | **Channel 11<br>Force (Vertical Left Handlebar)<br>Difference (max - Min)** | | |
| **n** | 8 | | | 8 | | | 8 | | |
| **average** | -20.8 | | | -140.0 | | | -19.0 | | |
| **sum** | -166.2 | | | -1119.8 | | | -152.3 | | |
| **sum of squares** | 4527.2 | | | 224341.9 | | | 6177.9 | | |
| **sd** | 12.39 | | | 98.28 | | | 21.64 | | |
| **sd(mean)** | 4.38 | | | 34.75 | | | 7.65 | | |
| **t** | 4.74 | | | 4.03 | | | 2.49 | | |
| **p** | 0.211% | | | 0.501% | | | 4.175% | | |
| **Cv** | -0.60 | | | -0.70 | | | -1.14 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | |
| **Upper** | -20.8 | | | -140.0 | | | -19.0 | | |
| **Lower** | -20.8 | | | -140.0 | | | -19.0 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | |
| **HT mean** | 106.1 | | | 133.8 | | | 113.6 | | |
| **% improvement** | -19.6% | | | -104.6% | | | -16.8% | | |

## The Rolling Road Rig
## Mean of the combined subjects average results for the hardtail bike - the fully suspended bike on the smooth track (continued)

| | Channel 12 Seat Acceleration | | | Crank Power | | |
|---|---|---|---|---|---|---|
| | (m/s^2) | | | (W) | | |
| | | Average Min | Average Max | | Average Min | Average Max |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | 0.0 | 0.0 | 0.1 | -2.4 | -3.0 | -2.7 |
| **sum** | 0.0 | -0.1 | 0.5 | -19.3 | -24.0 | -21.7 |
| **sum of squares** | 0.0 | 0.1 | 0.3 | 94.1 | 405.3 | 258.4 |
| **sd** | 0.00 | 0.14 | 0.20 | 2.61 | 6.90 | 5.34 |
| **sd(mean)** | 0.00 | 0.05 | 0.07 | 0.92 | 2.44 | 1.89 |
| **t** | 1.22 | 0.14 | 0.95 | 2.61 | 1.23 | 1.43 |
| **p** | 26.022% | 89.640% | 37.387% | 3.504% | 25.830% | 19.484% |
| **Cv** | -2.31 | -20.95 | 2.98 | -1.08 | -2.30 | -1.97 |
| **95% CONFIDENCE LIMITS** | | | | | | |
| **Upper** | 0.0 | 0.0 | 0.1 | -2.4 | -3.0 | -2.7 |
| **Lower** | 0.0 | 0.0 | 0.1 | -2.4 | -3.0 | -2.7 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | |
| **HT mean** | 0.0 | -1.3 | 1.4 | 68.1 | 47.2 | 79.0 |
| **% improvement** | 10.2% | 0.5% | 5.0% | -3.5% | -6.4% | -3.4% |
| **DIFFERENCE ANALYSIS (HT - SU)** | | | | | | |
| **ht** | **Channel 12 Seat Acceleration Difference (max - Min)** | | | **Crank Power Difference (max - Min)** | | |
| **n** | 8 | | | 8 | | |
| **average** | 0.1 | | | 0.2939345 | | |
| **sum** | 0.6 | | | 2.4 | | |
| **sum of squares** | 0.8 | | | 70.0 | | |
| **sd** | 0.33 | | | 3.15 | | |
| **sd(mean)** | 0.11 | | | 1.11 | | |
| **t** | 0.65 | | | 0.26 | | |
| **p** | 53.603% | | | 79.923% | | |
| **Cv** | 4.35 | | | 10.71 | | |
| **95% CONFIDENCE LIMITS** | | | | | | |
| **Upper** | 0.1 | | | 0.3 | | |
| **Lower** | 0.1 | | | 0.3 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | |
| **HT mean** | 2.7 | | | 31.8 | | |
| **% improvement** | 2.8% | | | 0.9% | | |

## The Rolling Road Rig
## Individual subjects average results for the hardtail bike on the smooth track

| | | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject1** | **Average** | -2.13E-07 | 0.00706165 | -0.0072956 | -7.55E-07 | 0.02233106 | -0.0255892 | 5.70E-06 | 0.14587166 | -0.1480549 | 2.15E-05 | 0.49162354 | -0.4987087 |
| | **No data points** | | 462 | 533 | | 591 | 488 | | 428 | 496 | | 460 | 530 |
| | **Max** | 0.01542412 | | | 0.05266806 | | | 0.2721795 | | | 0.9293764 | | |
| | **Min** | -0.0188978 | | | -0.0645234 | | | -0.2467028 | | | -0.8423903 | | |
| | **Difference** | 0.0143572 | | | 0.04792031 | | | 0.29392656 | | | 0.99033219 | | |
| **Subject2** | **Average** | -1.43E-07 | 0.00401327 | -0.0040838 | -4.50E-07 | 0.01347886 | -0.0136833 | -3.54E-08 | 0.11695223 | -0.1160128 | -7.03E-07 | 0.40697449 | -0.4046169 |
| | **No data points** | | 372 | 466 | | 397 | 500 | | 345 | 357 | | 302 | 304 |
| | **Max** | 0.00891313 | | | 0.03043393 | | | 0.1732974 | | | 0.5916613 | | |
| | **Min** | -0.0113863 | | | -0.0388835 | | | -0.2100371 | | | -0.7173146 | | |
| | **Difference** | 0.00809703 | | | 0.02716217 | | | 0.232965 | | | 0.81159136 | | |
| **Subject 3** | **Average** | -2.24E-07 | 0.00382718 | -0.0039078 | -7.96E-07 | 0.01276812 | -0.0130743 | 4.22E-06 | 0.11389145 | -0.1144556 | 1.43E-05 | 0.39541239 | -0.3982267 |
| | **No data points** | | 370 | 397 | | 412 | 433 | | 177 | 151 | | 154 | 128 |
| | **Max** | 0.00847637 | | | 0.02894114 | | | 0.1676794 | | | 0.5725331 | | |
| | **Min** | -0.0095496 | | | -0.0326103 | | | -0.1791599 | | | -0.61178 | | |
| | **Difference** | 0.00773497 | | | 0.02584238 | | | 0.2283471 | | | 0.79363909 | | |
| **Subject 4** | **Average** | -3.51E-07 | 0.00809567 | -0.0081986 | -1.25E-06 | 0.02613126 | -0.0287351 | -3.42E-07 | 0.16073755 | -0.1605611 | -1.52E-06 | 0.53909673 | -0.5407782 |
| | **No data points** | | 864 | 863 | | 993 | 806 | | 938 | 931 | | 1006 | 980 |
| | **Max** | 0.01836568 | | | 0.06271202 | | | 0.3020123 | | | 1.031218 | | |
| | **Min** | -0.0185216 | | | -0.0632536 | | | -0.2913525 | | | -0.9948546 | | |
| | **Difference** | 0.01629431 | | | 0.05486638 | | | 0.32129861 | | | 1.07987495 | | |
| **Subject 8** | **Average** | 2.90E-08 | 0.00387695 | -0.0031143 | 1.31E-07 | 0.00904158 | -0.0112771 | -1.57E-06 | 0.08799843 | -0.0832876 | -6.03E-06 | 0.28987926 | -0.3061142 |
| | **No data points** | | 364 | 321 | | 283 | 280 | | 224 | 210 | | 259 | 264 |
| | **Max** | 0.012654 | | | 0.04611296 | | | 0.21942635 | | | 0.7119625 | | |
| | **Min** | -0.0131211 | | | -0.0428773 | | | -0.2181132 | | | -0.7194531 | | |
| | **Difference** | 0.00699124 | | | 0.0203187 | | | 0.17128608 | | | 0.59599349 | | |
| **Subject 6** | **Average** | -8.85E-08 | 0.00687298 | -0.0071165 | -3.81E-07 | 0.02163687 | -0.0253719 | 4.71E-06 | 0.14617674 | -0.1470581 | 1.66E-05 | 0.48890753 | -0.4940663 |
| | **No data points** | | 377 | 387 | | 500 | 334 | | 299 | 323 | | 335 | 350 |
| | **Max** | 0.01752803 | | | 0.0598595 | | | 0.3428437 | | | 1.170719 | | |
| | **Min** | -0.0205189 | | | -0.0700532 | | | -0.4153998 | | | -1.418472 | | |
| | **Difference** | 0.0139895 | | | 0.04700878 | | | 0.29323486 | | | 0.98297378 | | |
| **Subject 7** | **Average** | -2.35E-07 | 0.00397059 | -0.0040717 | -8.62E-07 | 0.01338912 | -0.0136637 | 4.45E-07 | 0.1180839 | -0.1159331 | 1.42E-06 | 0.40904653 | -0.4044916 |
| | **No data points** | | 521 | 622 | | 548 | 664 | | 87 | 184 | | 79 | 155 |
| | **Max** | 0.010369 | | | 0.0354033 | | | 0.2427749 | | | 0.8288638 | | |
| | **Min** | -0.0142268 | | | -0.0485845 | | | -0.2071161 | | | -0.7074212 | | |
| | **Difference** | 0.00804229 | | | 0.02705287 | | | 0.23401701 | | | 0.81353815 | | |
| **Subject 8** | **Average** | 3.97E-08 | 0.00295056 | -0.0029301 | 1.03E-07 | 0.01074158 | -0.0105712 | -1.67E-06 | 0.09432571 | -0.0947681 | -5.98E-06 | 0.29705554 | -0.294625 |
| | **No data points** | | 329 | 338 | | 256 | 270 | | 143 | 132 | | 242 | 242 |
| | **Max** | 0.01316692 | | | 0.04495941 | | | 0.2346221 | | | 0.8011457 | | |
| | **Min** | -0.0127375 | | | -0.0434925 | | | -0.2176391 | | | -0.7431032 | | |
| | **Difference** | 0.00588066 | | | 0.02131279 | | | 0.18909378 | | | 0.59168056 | | |

## The Rolling Road Rig
## Individual subjects average results for the full suspension bike on the smooth track (continued)

| | | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| | | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| **Subject1** | **Average** | 1.60E-08 | 0.00651586 | -0.0065146 | 4.10E-08 | 0.02033768 | -0.02295 | -5.79E-08 | 0.12151833 | -0.1215366 | -1.34E-08 | 0.37901649 | -0.3758574 |
| | **No data points** | | 208 | 255 | | 300 | 222 | | 265 | 232 | | 426 | 383 |
| | **Max** | 0.03109176 | | | 0.1061714 | | | 0.5127371 | | | 1.750716 | | |
| | **Min** | -0.0124999 | | | -0.04268 | | | -0.4527939 | | | -1.546233 | | |
| | **Difference** | 0.01303051 | | | 0.04328768 | | | 0.2430549 | | | 0.75487392 | | |
| **Subject2** | **Average** | -1.09E-07 | 0.00382198 | -0.0038307 | -3.99E-07 | 0.01276839 | -0.0147988 | -4.73E-07 | 0.09377008 | -0.0939989 | -9.38E-07 | 0.31799948 | -0.2963866 |
| | **No data points** | | 282 | 349 | | 312 | 191 | | 296 | 224 | | 310 | 374 |
| | **Max** | 0.0084804 | | | 0.02895551 | | | 0.1533351 | | | 0.5235784 | | |
| | **Min** | -0.0076559 | | | -0.0261427 | | | -0.1674916 | | | -0.5719441 | | |
| | **Difference** | 0.00765271 | | | 0.02756723 | | | 0.187769 | | | 0.61438603 | | |
| **Subject 3** | **Average** | -1.40E-07 | 0.00407479 | -0.0040989 | -5.00E-07 | 0.01371488 | -0.0156249 | -1.34E-06 | 0.09422935 | -0.0963186 | -4.99E-06 | 0.31990695 | -0.3043469 |
| | **No data points** | | 465 | 491 | | 491 | 313 | | 261 | 183 | | 271 | 279 |
| | **Max** | 0.01833089 | | | 0.06259778 | | | 0.3624728 | | | 1.237703 | | |
| | **Min** | -0.0142299 | | | -0.0485908 | | | -0.2799479 | | | -0.9559311 | | |
| | **Difference** | 0.00817373 | | | 0.02933979 | | | 0.19054795 | | | 0.62425388 | | |
| **Subject 4** | **Average** | 4.48E-07 | 0.00420628 | -0.0044467 | 1.55E-06 | 0.01410816 | -0.0164073 | -6.76E-06 | 0.10083778 | -0.097598 | -2.30E-05 | 0.34147231 | -0.3140968 |
| | **No data points** | | 704 | 764 | | 749 | 585 | | 541 | 450 | | 563 | 611 |
| | **Max** | 0.0131054 | | | 0.04475543 | | | 0.2147924 | | | 0.7334242 | | |
| | **Min** | -0.0093196 | | | -0.0318225 | | | -0.2854907 | | | -0.9748453 | | |
| | **Difference** | 0.00865296 | | | 0.03051541 | | | 0.19843579 | | | 0.65556907 | | |
| **Subject 8** | **Average** | 4.78E-08 | 0.00281593 | -0.0035563 | 1.35E-07 | 0.01118231 | -0.011457 | -1.12E-06 | 0.06117651 | -0.0561426 | -4.13E-06 | 0.19144328 | -0.1954662 |
| | **No data points** | | 337 | 389 | | 301 | 298 | | 311 | 345 | | 397 | 354 |
| | **Max** | 0.01432108 | | | 0.03712867 | | | 0.18911238 | | | 0.5998205 | | |
| | **Min** | -0.0103249 | | | -0.0321142 | | | -0.1781437 | | | -0.5629177 | | |
| | **Difference** | 0.00637219 | | | 0.02263934 | | | 0.11731906 | | | 0.38690947 | | |
| **Subject 6** | **Average** | -3.91E-07 | 0.00431978 | -0.0042552 | -1.31E-06 | 0.01444844 | -0.0160497 | -2.49E-06 | 0.09815154 | -0.1007862 | -8.61E-06 | 0.33180134 | -0.3190368 |
| | **No data points** | | 312 | 374 | | 334 | 260 | | 143 | 112 | | 151 | 158 |
| | **Max** | 0.01376695 | | | 0.04700789 | | | 0.2309312 | | | 0.7886721 | | |
| | **Min** | -0.0181086 | | | -0.0618299 | | | -0.2868082 | | | -0.9792134 | | |
| | **Difference** | 0.00857494 | | | 0.03049812 | | | 0.19893777 | | | 0.65083818 | | |
| **Subject 7** | **Average** | 5.36E-07 | 0.00702717 | -0.0069717 | 1.85E-06 | 0.02598334 | -0.0257936 | -1.28E-05 | 0.1208364 | -0.1211084 | -4.39E-05 | 0.37809893 | -0.4205076 |
| | **No data points** | | 751 | 783 | | 548 | 567 | | 370 | 489 | | 590 | 441 |
| | **Max** | 0.01534999 | | | 0.05241534 | | | 0.2111765 | | | 0.7209858 | | |
| | **Min** | -0.0167868 | | | -0.0573185 | | | -0.2259907 | | | -0.771595 | | |
| | **Difference** | 0.01399892 | | | 0.0517769 | | | 0.24194484 | | | 0.79860648 | | |
| **Subject 8** | **Average** | 5.46E-08 | 0.00271787 | -0.0026634 | 1.66E-07 | 0.01066421 | -0.0103338 | -1.72E-06 | 0.06064202 | -0.0558875 | -5.70E-06 | 0.18449414 | -0.1858458 |
| | **No data points** | | 312 | 376 | | 181 | 219 | | 240 | 291 | | 456 | 331 |
| | **Max** | 0.01075643 | | | 0.03672689 | | | 0.177177 | | | 0.6049806 | | |
| | **Min** | -0.0092813 | | | -0.0316856 | | | -0.1670117 | | | -0.5702896 | | |
| | **Difference** | 0.00538132 | | | 0.02099797 | | | 0.1165295 | | | 0.37033998 | | |

**The Rolling Road Rig**

**Mean of the combined subjects average results for displacement and velocity of the hardtail bike on the smooth track**

| | Distance (Handlebar) (m) | | | Distance (Seat) (m) | | | Velocity (Handlebar) (m/s) | | | Velocity (Seat) (m/s) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0 | 0.0051 | -0.0051 | 0.0000 | 0.0162 | -0.0177 | 0.0000 | 0.1230 | -0.1225 | 0.0000 | 0.4147 | -0.4177 |
| sd | 0.00 | 0.0019 | 0.0021 | 0.0000 | 0.0063 | 0.0075 | 0.0000 | 0.0258 | 0.0272 | 0.0000 | 0.0901 | 0.0893 |
| difference | 0.0101734 | | | 0.03393554 | | | 0.24552112 | | | 0.83245295 | | |
| sd | 0.00401577 | | | 0.01367001 | | | 0.05297135 | | | 0.17927789 | | |

## The Rolling Road Rig

### Mean of the combined subjects average results for displacement and velocity of the full suspension bike on the smooth track (continued)

| | Distance (Handlebar) | | | Distance (Seat) | | | Velocity (Handlebar) | | | Velocity (Seat) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (m) | | | (m) | | | (m/s) | | | (m/s) | | |
| | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max | | Average Min | Average Max |
| n | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| mean | 0.0000 | 0.0044 | -0.0045 | 0.0000 | 0.0154 | -0.0167 | 0.0000 | 0.0939 | -0.0929 | 0.0000 | 0.3055 | -0.3014 |
| sd | 0.0000 | 0.0016 | 0.0015 | 0.0000 | 0.0052 | 0.0053 | 0.0000 | 0.0231 | 0.0252 | 0.0000 | 0.0762 | 0.0800 |
| difference | 0.00897966 | | | 0.03207781 | | | 0.18681735 | | | 0.60697213 | | |
| sd | 0.00302443 | | | 0.01040839 | | | 0.04820908 | | | 0.15476274 | | |

## The Rolling Road Rig

## Mean of the combined subjects average results for displacement and velocity of the hardtail bike - the full suspension bike on the smooth track

| | **Distance (Handlebar)** | | | **Distance (Seat)** | | | **Velocity (Handlebar)** | | | **Velocity (Seat)** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HT - SUS** | **(m)** | | | **(m)** | | | **(m/s)** | | | **(m/s)** | | |
| **NULL HYPOTHESIS** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** | | **Average Min** | **Average Max** |
| **n** | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| **average** | -2.06E-07 | 6.46E-04 | -5.48E-04 | -7.25E-07 | 7.89E-04 | -1.07E-03 | 4.77E-06 | 2.91E-02 | -2.96E-02 | 1.64E-05 | 1.09E-01 | -1.16E-01 |
| **sum** | -1.65E-06 | 5.17E-03 | -4.38E-03 | -5.80E-06 | 6.31E-03 | -8.55E-03 | 3.82E-05 | 2.33E-01 | -2.37E-01 | 1.31E-04 | 8.74E-01 | -9.30E-01 |
| **sum of squares** | 1.39E-12 | 3.26E-05 | 3.17E-05 | 1.68E-11 | 3.65E-04 | 4.01E-04 | 3.32E-10 | 9.27E-03 | 9.90E-03 | 3.99E-09 | 1.13E-01 | 1.42E-01 |
| **sd** | 3.87E-07 | 2.04E-03 | 2.04E-03 | 1.34E-06 | 7.17E-03 | 7.48E-03 | 4.63E-06 | 1.89E-02 | 2.03E-02 | 1.63E-05 | 5.06E-02 | 6.95E-02 |
| **sd(mean)** | 1.37E-07 | 7.22E-04 | 7.23E-04 | 4.75E-07 | 2.53E-03 | 2.64E-03 | 1.64E-06 | 6.67E-03 | 7.19E-03 | 5.75E-06 | 1.79E-02 | 2.46E-02 |
| **t** | 1.51E+00 | 8.94E-01 | 7.58E-01 | 1.53E+00 | 3.11E-01 | 4.04E-01 | 2.92E+00 | 4.36E+00 | 4.12E+00 | 2.85E+00 | 6.11E+00 | 4.73E+00 |
| **p** | 1.76E-01 | 4.01E-01 | 4.73E-01 | 1.70E-01 | 7.65E-01 | 6.98E-01 | 2.24E-02 | 3.31E-03 | 4.47E-03 | 2.48E-02 | 4.88E-04 | 2.13E-03 |
| **Cv** | -1.88E+00 | 3.16E+00 | -3.73E+00 | -1.85E+00 | 9.09E+00 | -7.00E+00 | 9.69E-01 | 6.48E-01 | -6.87E-01 | 9.93E-01 | 4.63E-01 | -5.98E-01 |
| **95% CONFIDENCE LIMITS** | | | | | | | | | | | | |
| **Upper** | -2.06E-07 | 6.46E-04 | -5.48E-04 | -7.25E-07 | 7.89E-04 | -1.07E-03 | 4.77E-06 | 2.91E-02 | -2.96E-02 | 1.64E-05 | 1.09E-01 | -1.16E-01 |
| **Lower** | -2.06E-07 | 6.46E-04 | -5.48E-04 | -7.25E-07 | 7.89E-04 | -1.07E-03 | 4.77E-06 | 2.91E-02 | -2.96E-02 | 1.64E-05 | 1.09E-01 | -1.16E-01 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | | | | |
| **HT mean** | -2.059E-07 | 0.00064615 | -0.0005476 | -7.255E-07 | 0.00078888 | -0.0010689 | 4.7726E-06 | 0.02910946 | -0.0295943 | 1.6365E-05 | 0.10922039 | -0.1162604 |
| **% improvement** | 139.0% | 12.7% | 10.8% | 136.2% | 4.9% | 6.0% | 333.3% | 23.7% | 24.2% | 330.7% | 26.3% | 27.8% |
| **HT - SUS** | | | | | | | | | | | | |
| **NULL HYPOTHESIS** | | | | | | | | | | | | |
| **Diffrence** | | | | | | | | | | | | |
| **n** | 8 | | | 8 | | | 8 | | | 8 | | |
| **average** | 0.0012 | | | 0.0019 | | | 0.0587 | | | 0.2255 | | |
| **sum** | 0.0095 | | | 0.0149 | | | 0.4696 | | | 1.8038 | | |
| **sum of squares** | 0.0001 | | | 0.0015 | | | 0.0383 | | | 0.5063 | | |
| **sd** | 0.0621 | | | 0.0602 | | | 0.0079 | | | 0.0088 | | |
| **sd(mean)** | 0.0219 | | | 0.0213 | | | 0.0028 | | | 0.0031 | | |
| **t** | 0.8346 | | | 0.3603 | | | 4.2432 | | | 5.3474 | | |
| **p** | 43.1513% | | | 72.9233% | | | 0.3825% | | | 0.1067% | | |
| **Cv** | 52.0063 | | | 32.3790 | | | 0.1348 | | | 0.0388 | | |
| **95% CONFIDENCE LIMITS** | | | | | | | | | | | | |
| **Upper** | 0.0012 | | | 0.0019 | | | 0.0587 | | | 0.2255 | | |
| **Lower** | 0.0012 | | | 0.0019 | | | 0.0587 | | | 0.2255 | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | | | | | | | | | |
| **HT mean** | 0.0012 | | | 0.0019 | | | 0.0587 | | | 0.2255 | | |
| **% improvement** | 11.7% | | | 5.5% | | | 23.9% | | | 27.1% | | |

## Individuals reusults for the RMS Values on the rolling road
## Hardtail bike over a rough surface

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 | Subject 6 | Subject 7 | Subject 8 |
|---|---|---|---|---|---|---|---|---|
| **HB dist** | 6.28E-03 | 5.20E-03 | 5.59E-03 | 6.01E-03 | 4.85E-03 | 5.66E-03 | 4.91E-03 | 5.73E-03 |
| **Seat dist** | 2.14E-02 | 1.78E-02 | 1.91E-02 | 2.05E-02 | 1.65E-02 | 1.93E-02 | 1.68E-02 | 1.96E-02 |
| **HB Vel** | 1.39E-01 | 1.25E-01 | 1.31E-01 | 1.33E-01 | 1.10E-01 | 1.28E-01 | 1.12E-01 | 1.35E-01 |
| **Seat Vel** | 4.74E-01 | 4.26E-01 | 4.46E-01 | 4.54E-01 | 3.77E-01 | 4.38E-01 | 3.83E-01 | 4.61E-01 |

## RMS Values for the hardtail bike over a rough surface
## Mean of all subjects

| | Distance (Handlebar) | Distance (seat) | Velocity (handlebar) | Velocity (seat) |
|---|---|---|---|---|
| **Average** | 0.005527656 | 0.018874756 | 0.126585913 | 0.432243613 |
| **Max** | 6.28E-03 | 2.14E-02 | 1.39E-01 | 4.74E-01 |
| **Min** | 4.85E-03 | 1.65E-02 | 1.10E-01 | 3.77E-01 |
| **Difference** | 0.001432111 | 0.0048902 | 0.0286197 | 0.0977262 |
| **n** | **8** | **8** | **8** | **8** |
| **mean** | **0.0055** | **0.0189** | **0.1266** | **0.4322** |
| **sd** | **0.0005** | **0.0017** | **0.0104** | **0.0356** |

## Individuals reusults for the RMS Values on the rolling road
## Full suspension bike over a rough surface

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 | Subject 6 | Subject 7 | Subject 8 |
|---|---|---|---|---|---|---|---|---|
| **HB dist** | 6.17E-03 | 6.58E-03 | 5.34E-03 | 6.34E-03 | 7.49E-03 | 6.36E-03 | 1.12E-02 | 6.36E-03 |
| **Seat dist** | 2.11E-02 | 2.25E-02 | 1.82E-02 | 2.16E-02 | 2.56E-02 | 2.17E-02 | 3.82E-02 | 2.17E-02 |
| **HB vel** | 1.02E-01 | 1.02E-01 | 9.48E-02 | 1.03E-01 | 1.06E-01 | 1.05E-01 | 1.47E-01 | 1.05E-01 |
| **Seat vel** | 3.48E-01 | 3.49E-01 | 3.24E-01 | 3.53E-01 | 3.63E-01 | 3.59E-01 | 5.01E-01 | 3.59E-01 |

## RMS values for the full suspension bike over a rough surface
## Mean of all subjects

| | Distance (Handlebar) | Distance (seat) | Velocity (handlebar) | Velocity (seat) |
|---|---|---|---|---|
| **Average** | 0.006980774 | 0.023836135 | 0.108219405 | 0.3695233 |
| **Max** | 1.12E-02 | 3.82E-02 | 1.47E-01 | 5.01E-01 |
| **Min** | 5.34E-03 | 1.82E-02 | 9.48E-02 | 3.24E-01 |
| **Difference** | 0.005856331 | 0.01999642 | 0.05203096 | 0.1776574 |
| **n** | **8** | **8** | **8** | **8** |
| **mean** | **0.0070** | **0.0238** | **0.1082** | **0.3695** |
| **sd** | **0.0018** | **0.0062** | **0.0160** | **0.0546** |

## Individuals reusults for the RMS Values on the rolling road
## Hardtail bike over a smooth surface

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 | Subject 6 | Subject 7 | Subject 8 |
|---|---|---|---|---|---|---|---|---|
| **HB dist** | 3.29E-03 | 1.65E-03 | 4.61E-03 | 1.60E-03 | 1.29E-03 | 2.93E-03 | 1.94E-03 | 1.29E-03 |
| **Seat dist** | 1.12E-02 | 5.62E-03 | 1.57E-02 | 5.46E-03 | 4.41E-03 | 9.99E-03 | 6.63E-03 | 4.41E-03 |
| **HB Vel** | 6.43E-02 | 4.78E-02 | 8.48E-02 | 4.14E-02 | 3.31E-02 | 5.98E-02 | 3.77E-02 | 3.31E-02 |
| **Seat Vel** | 2.20E-01 | 1.63E-01 | 2.90E-01 | 1.41E-01 | 1.13E-01 | 2.04E-01 | 1.29E-01 | 1.13E-01 |

## RMS Values for the hardtail bike over a smooth surface
## Mean of all subjects

| | Distance (Handlebar) | Distance (seat) | Velocity (handlebar) | Velocity (seat) |
|---|---|---|---|---|
| **Average** | 0.002324395 | 0.007936773 | 0.050234438 | 0.171531025 |
| **Max** | 4.61E-03 | 1.57E-02 | 8.48E-02 | 2.90E-01 |
| **Min** | 1.29E-03 | 4.41E-03 | 3.31E-02 | 1.13E-01 |
| **Difference** | 3.32E-03 | 0.011330879 | 0.05177574 | 0.176794 |
| **n** | **8** | **8** | **8** | **8** |
| **mean** | **0.0023** | **0.0079** | **0.0502** | **0.1715** |
| **sd** | **0.0012** | **0.0040** | **0.0182** | **0.0622** |

## Individuals reusults for the RMS Values on the rolling road
## Full suspension bike over a smooth surface

| | Subject 1 | Subject 2 | Subject 3 | Subject 4 | Subject 5 | Subject 6 | Subject 7 | Subject 8 |
|---|---|---|---|---|---|---|---|---|
| **HB dist** | 2.55E-03 | 1.60E-03 | 2.27E-03 | 1.93E-03 | 1.16E-03 | 1.80E-03 | 4.31E-03 | 1.16E-03 |
| **Seat dist** | 8.72E-03 | 5.46E-03 | 7.76E-03 | 6.58E-03 | 3.97E-03 | 6.15E-03 | 1.47E-02 | 3.97E-03 |
| **HB vel** | 4.50E-02 | 3.42E-02 | 4.26E-02 | 3.55E-02 | 2.12E-02 | 3.26E-02 | 5.56E-02 | 2.12E-02 |
| **Seat vel** | 1.54E-01 | 1.17E-01 | 1.46E-01 | 1.21E-01 | 7.25E-02 | 1.11E-01 | 1.90E-01 | 7.25E-02 |

## RMS values for the full suspension bike over a smooth surface
## Mean of all subjects

| | Distance (Handlebar) | Distance (seat) | Velocity (handlebar) | Velocity (seat) |
|---|---|---|---|---|
| **Average** | 0.002098111 | 0.007164208 | 0.03599923 | 0.122923515 |
| **Max** | 4.31E-03 | 1.47E-02 | 5.56E-02 | 1.90E-01 |
| **Min** | 1.16E-03 | 3.97E-03 | 2.12E-02 | 7.25E-02 |
| **Difference** | 3.15E-03 | 0.010741492 | 0.03438353 | 0.11740444 |
| **n** | **8** | **8** | **8** | **8** |
| **mean** | **0.0021** | **0.0072** | **0.0360** | **0.1229** |
| **sd** | **0.0010** | **0.0035** | **0.0117** | **0.0400** |

## RMS values for the hardtail bike - full suspension bike over a rough surface

| **HT - SUS** | **Distance (Handlebar)** | **Distance (seat)** | **Velocity (handlebar)** | **Velocity (seat)** |
|---|---|---|---|---|
| **NULL HYPOTHESIS** | | | | |
| **n** | 8 | 8 | 8 | 8 |
| **average** | -0.0015 | -0.0050 | 0.0184 | 0.0627 |
| **sum** | -0.0116 | -0.0397 | 0.1469 | 0.5018 |
| **sum of squares** | 0.0000 | 0.0006 | 0.0067 | 0.0777 |
| **sd** | 0.0022 | 0.0074 | 0.0238 | 0.0813 |
| **sd(mean)** | 0.0008 | 0.0026 | 0.0084 | 0.0287 |
| **t** | 1.9024 | 1.9023 | 2.1824 | 2.1827 |
| **p** | 9.8852% | 9.8867% | 6.5410% | 6.5382% |
| **Cv** | -1.4867 | -1.4868 | 1.2960 | 1.2959 |
| **95% CONFIDENCE LIMITS** | | | | |
| **Upper** | -0.0015 | -0.0050 | 0.0184 | 0.0627 |
| **Lower** | -0.0015 | -0.0050 | 0.0184 | 0.0627 |
| | | | | |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | |
| | | | | |
| **HT mean** | 0.0055 | 0.0189 | 0.1266 | 0.4322 |
| **% improvement** | -26.3% | -26.3% | 14.5% | 14.5% |

%

## RMS values for the hardtail bike - full suspension bike over a smooth surface

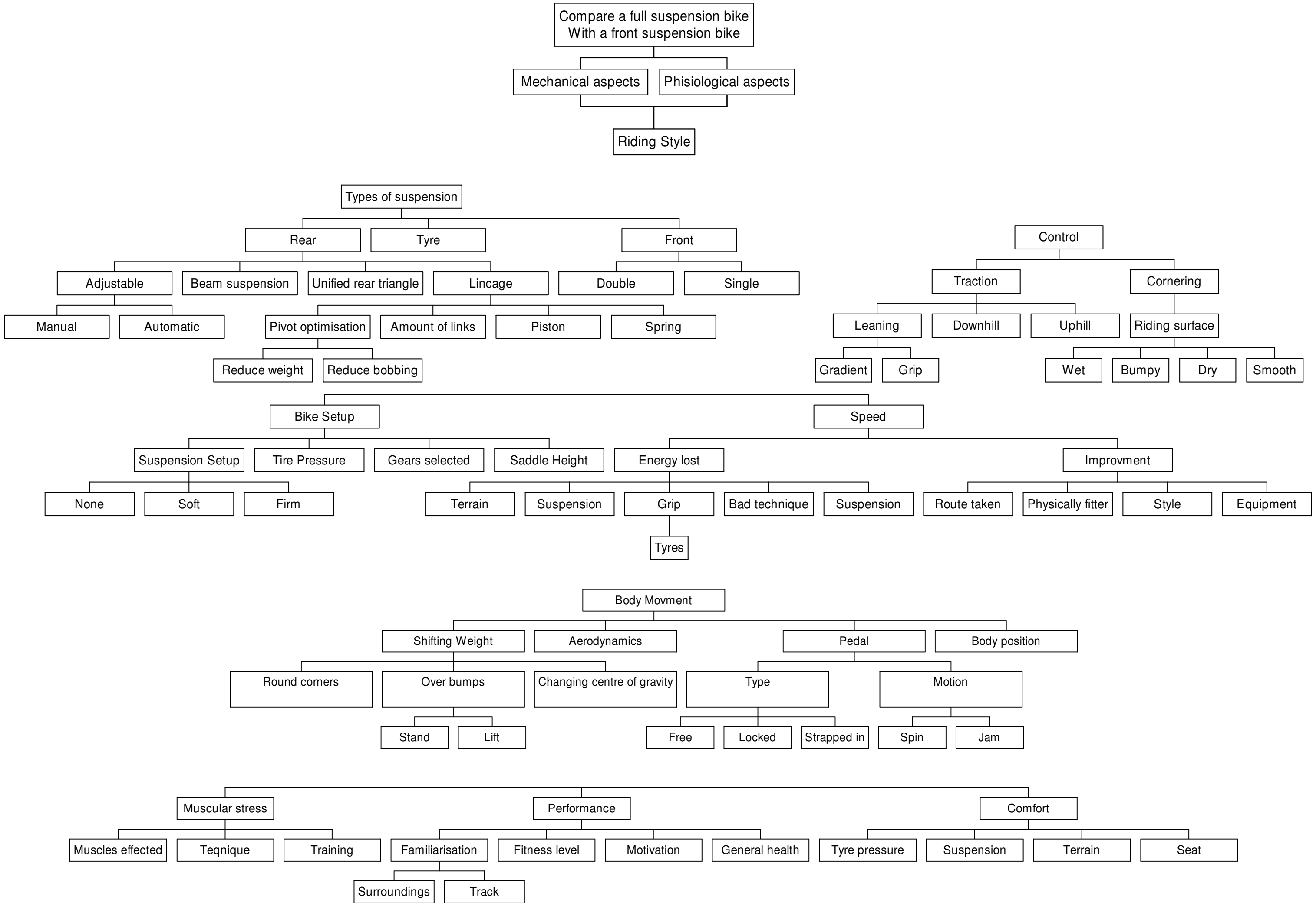
| HT - SUS | Distance (Handlebar) | Distance (seat) | Velocity (handlebar) | Velocity (seat) |
|---|---|---|---|---|
| **NULL HYPOTHESIS** | | | | |
| **n** | 8 | 8 | 8 | 8 |
| **average** | 0.0002 | 0.0008 | 0.0142 | 0.0486 |
| **sum** | 0.0018 | 0.0062 | 0.1139 | 0.3889 |
| **sum of squares** | 0.0000 | 0.0002 | 0.0037 | 0.0434 |
| **sd** | 0.0013 | 0.0046 | 0.0173 | 0.0591 |
| **sd(mean)** | 0.0005 | 0.0016 | 0.0061 | 0.0209 |
| **t** | 0.4771 | 0.4770 | 2.3263 | 2.3263 |
| **p** | 64.7827% | 64.7870% | 5.2900% | 5.2900% |
| **Cv** | 5.9284 | 5.9292 | 1.2158 | 1.2158 |
| **95% CONFIDENCE LIMITS** | | | | |
| **Upper** | 0.0002 | 0.0008 | 0.0142 | 0.0486 |
| **Lower** | 0.0002 | 0.0008 | 0.0142 | 0.0486 |
| **% Improvement by fitting suspension = 100*(average diff. / HT mean)** | | | | |
| Average | 0.0023 | 0.0079 | 0.0502 | 0.1715 |
| **% improvement** | 9.7% | 9.7% | 28.3% | 28.3% |

# Appendix D

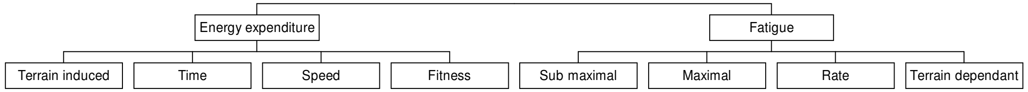
---

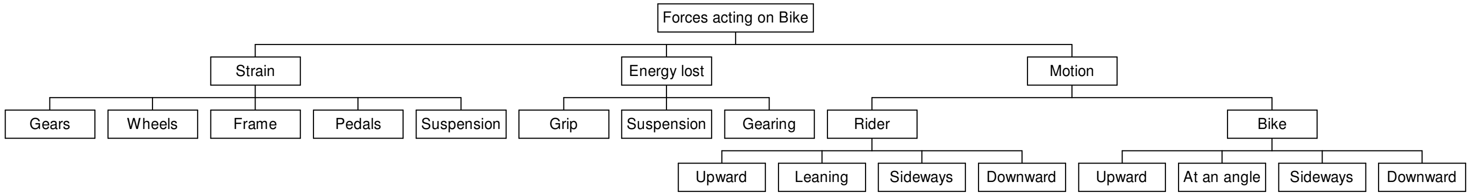
## Tree Chart

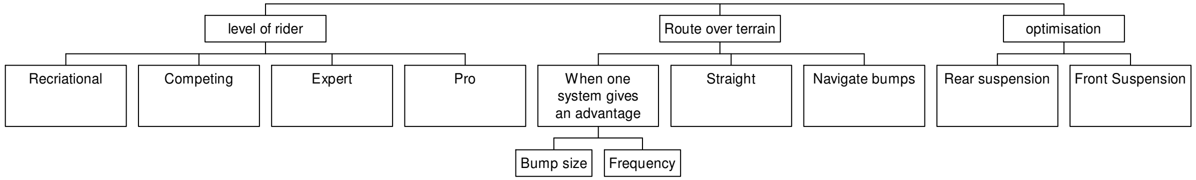
# Decision Matrix Tree



# Decision Matrix Tree (continued)





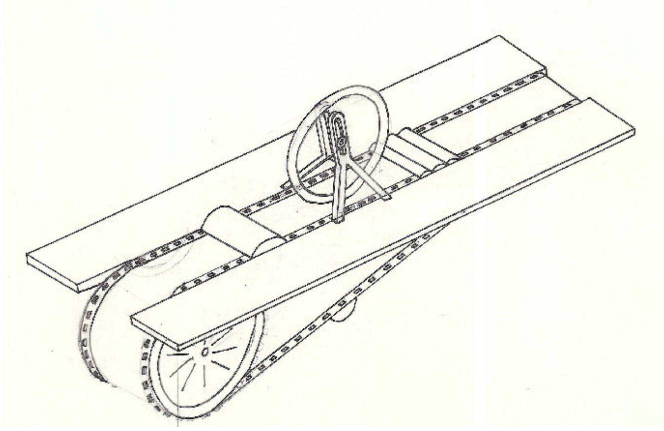


# Appendix E

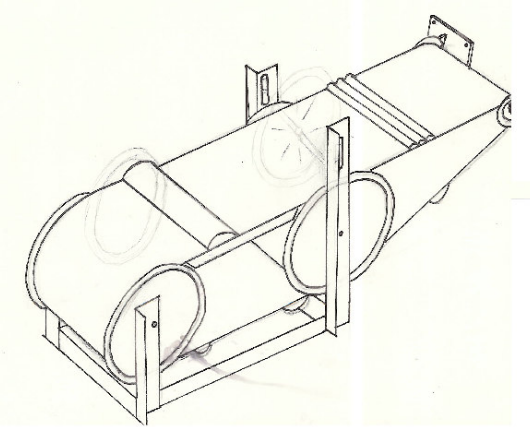
---

## Rolling Road Concepts

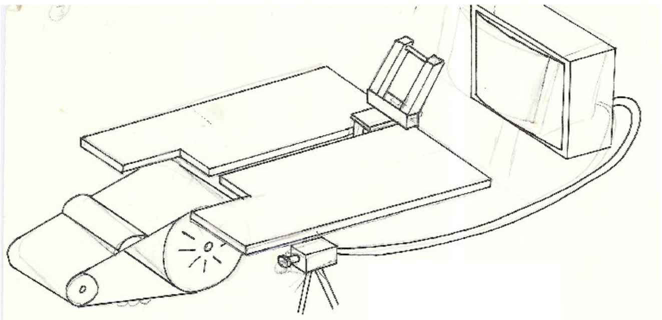
**Concept A**



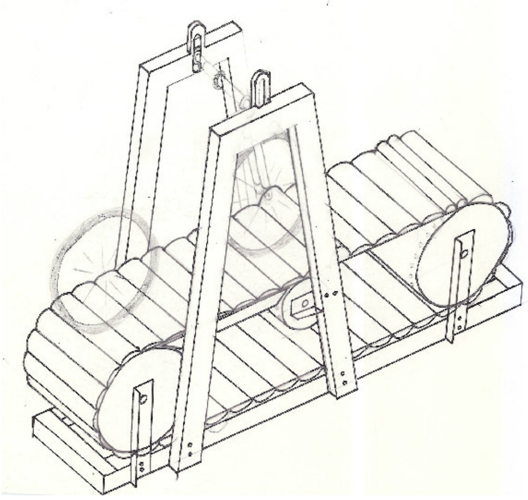
**Concept B**



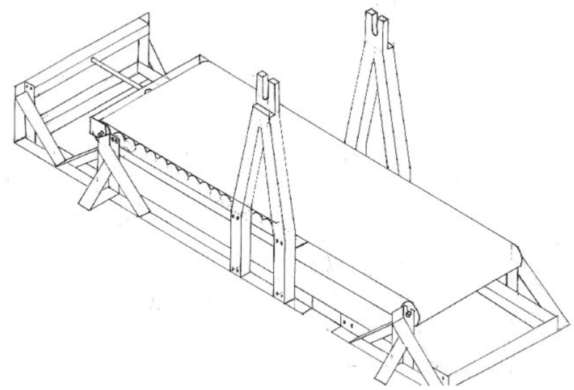
**Concept C**



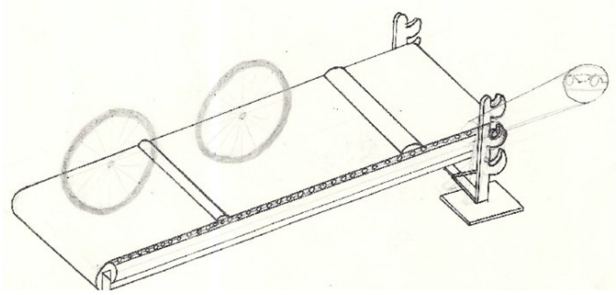
**Concept D**



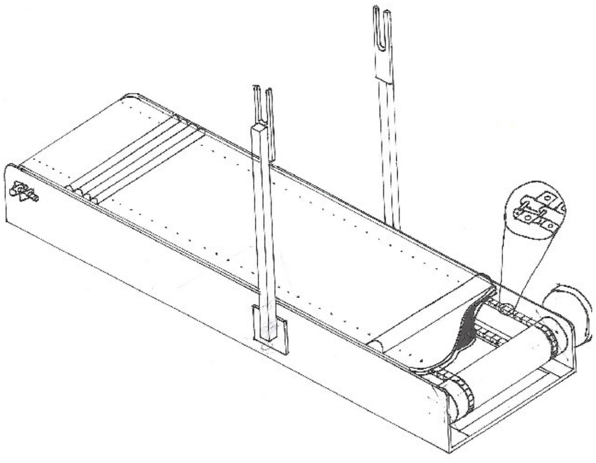
## Concept E



## Concept F



## Concept G



# Appendix F

---

## Inertia Calculations for the Rolling Road Rig

**Inertia calculations for the rig**

To simulate riding outside the rolling road must have the equivalent inertia of a bike and cyclist outside. Energy conservation has been used to determine the required inertia of the rig.

Firstly the equivalent inertia to cycling outside has to be ascertained to establish the inertia requirements of the roller. This calculation determines the additional inertia required to match cycling outside:

$$E_{k\ rig} = 2^* E_{k\ roller\ +} E_{k\ belt}$$

$$½\ m_{bike+rider}\ v^2 = 2^*½\ I_{roller}\ \omega^2 + ½\ m_{belt}\ v^2$$

$$½\ m_{bike+rider}\ v^2 = I_{roller}\ v^2 / r^2 + ½\ m_{belt}\ v^2$$

$$½\ m_{bike+rider} = I_{roller} / r^2 + ½\ m_{belt}$$

$$½\ (12 + 74) = I_{roller} / 0.2304^2 + ½^*11.844$$

$$43 = I_{roller} / 0.053 + 5.922$$

$$37 = I_{roller} / 0.053$$

$$I_{roller} = 1.961\ kg/m^2$$

The next step is to ascertain the inertia of the actual rollers:

$$I_{roller} = (I_{casing}) + 2^*(I_{roller\ ends}) + (I_{bar})$$

$$I_{casing} = mr^2$$

$$I_{casing} = 0.37^*0.125^2$$

$$I_{casing} = 0.0058\ kg/m^2$$

$$I_{roller\ ends} = ½\ mr^2$$

$$I_{roller\ ends} = ½\ (1.9267^*0.125^2)$$

$$I_{roller\ ends} = 0.015\ kg/m^2$$

$$I_{bar} = ½\ mr^2$$

$$I_{bar} = ½\ (0.674^*0.0125^2)$$

$$I_{bar} = 0.000053\ kg/m^2$$

$$I_{rollers} = (I_{casing}) + 2^*(I_{roller\ ends}) + (I_{bar})$$

$$I_{rollers} = (0.0058) + 2^*(0.015) + (0.000053)$$

$$I_{\text{rollers}} = 0.036 \text{ kg/m}^2$$

As the inertia of the rollers has been found this can then be used to determine the additional inertia that is required for the rig to simulate riding outside.

$$I_{\text{total}} = I_{\text{roller}} + I_{\text{disk}}$$

$$I_{\text{disk}} = 1.961 + 0.036$$

$$I_{\text{disk}} = 1.889 \text{ kg/m}^2$$

Therefore two inertia disks of 1.889 kg/m$^2$ are required for the rolling road rig to equate to riding outside. The size of disk required to produce this inertia is calculated below:

$$I_{\text{disk}} = \tfrac{1}{2} mr^2$$

$$1.889 = \tfrac{1}{2} mr^2$$

$$1.889 = \tfrac{1}{2} m{*}0.24^2$$

$$3.778 = m{*}0.0576$$

$$m = 65.6 \text{ kg}$$

Therefore two steel inertia disks are required with a width of 0.0462 m and a radius of 0.24 m.

# Appendix G

---

## Friction Calculation for the Rolling Road Rig

## Rig Friction calculations

The rolling road rig presents a resistance to the rider due to the added friction of the belt; this additional resistance must be quantified to establish the effect this will have on the cyclists' performance.

Firstly the power required to ride on the rig must be established, this can be found via the results of the run down test figure 5-11 and 5-12 (chapter 5). In these run down test the initial velocity of the bike was 10 km/h or 2.78 m/s, the average time taken for the bike to come to rest is 4.6 s, from the average area under the graph a distance of 6.394 m has been calculated.

The deceleration has to then be estblished:

$$v^2 = 2as$$

$$a = v^2/ 2s$$

$$a = 2.78^2/ 2*6.394$$

$$\underline{a = 0.604\ m/s^2}$$

The force that would produce this deceleration is then calculated:

$$F = ma$$

$$F = (75+10)*06604$$

$$\underline{F = 51N}$$

The power can then be obtained:

$$P = Fv$$

$$P = 51*2.78$$

$$\underline{P = 142.8\ W}$$

To find the power required for a bike to go from 2.78m/s to rest with no wind acting on the bike going over a flat surface with no gradient the equations from Martin et al (1998) can be used:

$$P_T = P_{AT} + P_{RR} + P_{WB} + P_{PE} + P_{KE}$$

| | |
|---|---|
| Total Power | $P_T$ |
| Aerodynamic Power | $P_{AT}$ |
| Rolling resistance Power | $P_{RR}$ |
| Wheel Bearing Friction Power | $P_{WB}$ |
| Power Related to changes in Potential Energy | $P_{PE}$ |
| Power Related to changes in Kenetic Energy | $P_{KE}$ |

$$P_{AT} = ½\ \rho\ (C_D A + F_W)\ V_a^2 V_G$$

$$P_{RR} = V_G \operatorname{Cos}[\operatorname{Tan}^{-1}(G_R)]\ C_{RR}\ m_T\ g$$

$$P_{WB} = V_G (91 + 8.7\ V_G)\ 10^{-1}$$

$$P_{PE} = V_G\ m_T\ g \operatorname{Sin}[\operatorname{Tan}^{-1}(G_R)]$$

$$P_{KE} = \Delta KE / \Delta t = ½\ (m_T + I / r^2)\ (V_{GF}^2 - V_{GI}^2) / (t_i - t_f)$$

Firstly find the aerodynamic power ($P_{AT}$) to ride a bike with no wind:

$C_D$ and A were taken from Sunter and Sayers (2001):

| | |
|---|---|
| Drag coefficient | $C_D = 1.15$ |
| Surface area | $A = 0.41 m^2$ |
| Density of air | $\rho = 1.223\ kg/ m^2$ |
| Incremental drag area of the spokes | $F_w = 0.0044 m^2$ |
| Velocity of air, if zero this equals the velocity of the ground | $V_a = 2.78$ m/s |
| Velocity of the ground | $V_G = 2.78$ m/s |

$$P_{AT} = ½\ \rho\ (C_D\ A + F_W)\ V_a^2 V_G$$

$$P_{AT} = ½*1.2234*(1.15*0.41 + 0.0044)*2.78*2.78$$

$$\underline{P_{AT} = 6.255\ W}$$

The power required due to rolling resistance with a road gradient of zero is the calculated ($P_{RR}$):

| | |
|---|---|
| Road gradient | $G_R$ = Rise/Run |
| Coefficient of rolling resistance | = 0.0032 |
| Mass total, rider plus bike | $m_T = 75 + 10 = 85$kg |

$$P_{RR} = V_G \; \text{Cos} \, [\text{Tan}^{-1} \, (G_R)] \, C_{RR} \, m_T \, g$$

$$P_{RR} = 2.78^* \; \text{Cos} \, [\text{Tan}^{-1} \, (0)] \, 0.0032^*85^*9.81$$

$$\underline{P_{RR} = 7.4179\text{W}}$$

Wheel bearing friction power ($P_{WB}$):

$$P_{WB} = V_G \, (91 + 8.7 \, V_G)^*10^{-1}$$

$$P_{WB} = 2.78^*(91 + 8.72.78)^*10^{-1}$$

$$\underline{P_{WB} = 0.9252\text{W}}$$

Potential Energy ($P_{PE}$):

$$P_{PE} = V_G \, m_T \, g \; \text{Sin} \, [\text{Tan}^{-1} \, (G_R)]$$

$$P_{PE} = 2.78^*85^*9.81 \text{Sin} \, [\text{Tan}^{-1}(0)]$$

$$\underline{P_{PE} = 0\text{W}}$$

Kinetic energy ($P_{KE}$):

| | |
|---|---|
| Initial speed | $V_{GF} = 2.87$ m/s |
| Final speed | $V_{GF} = 0$ m/s |
| Initial time | $t_i = 0$s |
| Final time | $t_f = 4.6$s |
| Radius of the wheels | $r = 0.322$m |
| Moment of inertia for two wheels is | $= 0.14$ kgm$^2$ |

$$P_{KE} = \Delta KE/\Delta t = ½ \, (m_T + I/r^2) \, (V_{GF}^2 - V_{GI}^2) \, / \, (t_i - t_f)$$

$$P_{KE} = ½^*(85^*0.14/0.322^2) \, (0^2 - 2.78^2) \, / \, (0 - 4.6)$$

$$\underline{P_{KE} = 29.04 \text{ W}}$$

From these results the total power required can be found:

$$P_T = P_{AT} + P_{RR} + P_{WB} + P_{PE} + P_{KE}$$

$$P_T = 6.255 + 7.4179 + 0.9252 + 0 + 29.04$$

$$\underline{P_T = 43.63W}$$

The power required to travel at 2.78 m/s with no wind resistance on a flat surface is 43.63 W.

Established previously is that it requires 142.8 W to ride on the rig, it now must be established what grade of slope and wind resistance this equates to.

To find the road gradient $G_R$ = Rise / Run the same equation for power is used:

$$P_T = P_{AT} + P_{RR} + P_{WB} + P_{PE} + P_{KE}$$

$$142.8 = 6.255 + V_G \text{ Cos } [\text{Tan}^{-1} (G_R)] \, C_{RR} \, m_T \, g + 0.9252 +$$

$$V_G \, m_T \, g \text{ Sin } [\text{Tan}^{-1} (G_R)] + 29.04$$

$$142.8 = 6.255 + 2.78^* \text{ Cos } [\text{Tan}^{-1} (G_R)] \, 0.0032^*85^*9.81 + 0.9252$$

$$+ 2.78^*85^*9.81 \text{ Sin } [\text{Tan}^{-1}(G_R)] + 29.04$$

$$14.368 = \text{Cos } [\text{Tan}^{-1} (G_R)] + 312.5^* \text{ Sin } [\text{Tan}^{-1} (G_R)]$$

$$\underline{\text{Therefore } G_R = 1/23.355}$$

The rig represents riding up an incline of 1/23.355.

The second consideration is that of the rig represents riding into a head wind, the calculations to ascertain the equivalent head wind are presented below:

$$P_T = P_{AT} + P_{RR} + P_{WB} + P_{PE} + P_{KE}$$

$$142.8 = P_{AT} + 7.4179 + 0.9252 + 0 + 29.04$$

$$P_{AT} = 105.4169 \text{ W}$$

$$P_{AT} = ½ \, \rho \, (C_D \, A + F_W) \, V_a^2 \, V_G$$

If the wind travels directly towards the bike the yaw angle is zero therefore:

$$105.4169 = \tfrac{1}{2} * 1.2234 * (1.15 * 0.41 + 0.0044) * V_a^2 * 2.78$$

$$\underline{V_a = 11.4 \text{ m/s}}$$

This rig is also equivalent to riding into an 11.4 m/s headwind.

# Appendix H

---

## Rig Electronics

## Electronics system Description

### Power supply

The unit comprises of two 1 Farad SUPERCAPS, small inverter IC (LT1303), an inductor and peripheral components. A mains powered external *DC power unit supplies + 4.5 V which is fed via two sprung brushes that run on slip rings mounted on the rear of the chainwheel. The + 4.5 V from the slip rings is supplied to the SUPERCAPS on the power supply PCB. The maximum DC voltage rating (the working voltage) of the SUPERCAPS is 5 V. The inverter IC converts the + 4.5 V to + 8 V. The supply voltage is further regulated by 78L05 IC to + 5 V to supply the remaining instrumentation. The strain bridge is supplied with 1 V DC from a separate LM317 regulator IC fed from the + 8 V supply.

* Part of the FM receiver unit. (This is external to the cycle transmitter system).

### Instrumentation and FM Transmitter PCB on Chainwheel

This PCB accepts the strain signal from a DC four gauge bridge mounted on the torque reaction arm (part of the crank assembly). Signals are fed directly to a standard three op-amp instrumentation amplifier Burr-Brown INA118. The maximum output signal span will be ≈ ± 1.5 V on a ground reference of + 2.5 V. The single ended supply (Vcc) is + 5 V.

The ± 1.5 V analogue signal voltage is applied to the input pin of an Analogue Devices AD654JR voltage to frequency converter IC. The relative square wave output frequency for this input for this input span will be ± 3 KHz, a bandwidth of 6 KHz.

### Propagation

The output frequency of the AD654JR is applied to the input pin of an RF Solutions Radiometrix FM-TX2-433 transmitter module powered from the + 5 V supply. This IC is an integrated FM modulator and transmitter for operation at 433.92 MHz. The

RF output is applied to a small 45 mm long helical antenna via a short length 50 Ω miniature co-axial lead.

The above circuits are constructed using surface mount (SMD) miniaturised electronic components to facilitate space saving requirements for cycle chainwheel mounting.

Receiver

The receiver unit is completely separate from the bike instrumentation and the bike itself. This is an independent mains powered unit with a mains operated power supply Low voltage outputs are available for the internal 433.92 MHz receiver circuits, frequency to voltage converter IC and a connector for the remote slip rings on the bike via an external lead.

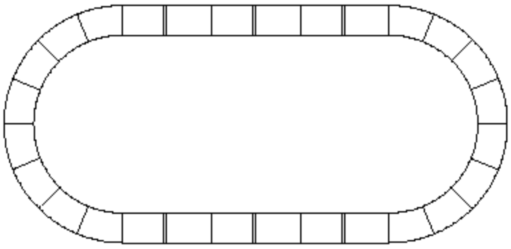
The receiver module is a Radiometrix FM-RX2-433A with RF reception at 433.92 MHz. This unit is powere from + 5V DC. The demodulated output is the restored 6 KHz sweep frequency. This signal is applied to the input of an XR 4152 IC in frequency to voltage converter mode. The output from the XR4151 is a copy of the amplified strain (± 1.5 V on an offset to be restored at a buffer amp to the original transmitted value). This output buffered by a high spec rail-to-rail op-amp for output to a computer or ADC.

# Appendix I

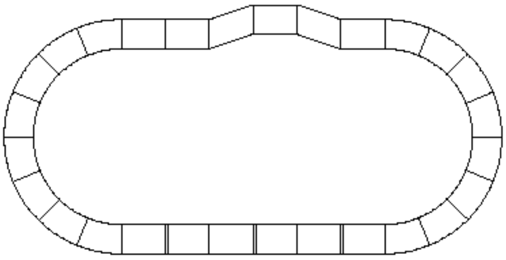
---

## Track Concepts

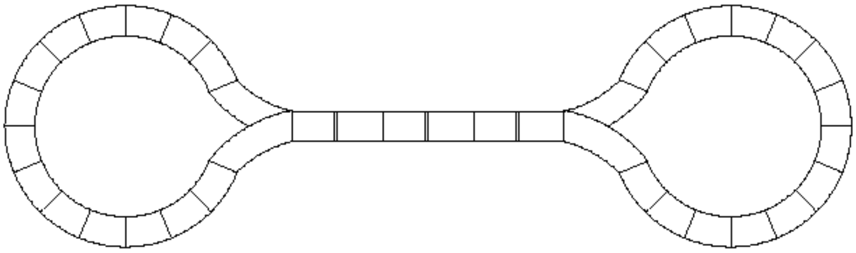
**Concept A**



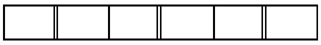
**Concept B**



**Concept C**



**Concept D**



**Concept E**