McMillan, Paul Patrick (2015) *The validity, reliability & sensitivity of global positioning system inertial sensors to monitor training readiness in soccer*. MSc(R) thesis.

http://theses.gla.ac.uk/6505/

Copyright and moral rights for this thesis are retained by the author

A copy can be downloaded for personal non-commercial research or study

This thesis cannot be reproduced or quoted extensively from without first obtaining permission in writing from the Author

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the Author

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given

Glasgow Theses Service
http://theses.gla.ac.uk/
theses@gla.ac.uk

The Validity, Reliability & Sensitivity of Global Positioning System Inertial Sensors to Monitor Training Readiness in Soccer

Paul-Patrick McMillan
BSc (Hons)

Submitted in fulfilment of the requirements for the degree of:

MSc (Research) Sports Science

School of Life Sciences

College of Medical, Veterinary and Life Sciences

University of Glasgow

Dr. Niall MacFarlane

June 2015

Abstract

Over recent decades there has been a progressive change in the volume and frequency of soccer matches at the elite level. Although the relative duration of each match has remained constant, the number of matches played per competitive season and the intensity of match play has increased. With this progressive change in volume of soccer competition from season-to-season at the elite level there now exists a rationale for monitoring player's athletic readiness, with the aim to prevent conditions such as non-functional overreaching (NFOR) and overtraining syndrome (OTS).

Although the literature provides evidence for the utilisation of heart rate (HR) measures, subjective and psychometric questionnaires, hormonal and biochemical markers as well as neuromuscular markers to determine athletic readiness to train and/or compete, each has its respective limitations and all are subject to the extensive requirement of time. However, with technological advances it is now possible to break down temporal patterns of match play and training load to provide a better understanding of the overall physiological demands imposed upon elite soccer players. In light of this, the purpose of this thesis was to consider the current methods available to monitor athletic readiness, and subsequently to investigate the validity, reliability and sensitivity of utilizing a wearable global positioning system (GPS) based inertial measurement unit (IMU) to monitor vertical jump performance. This system could potentially provide an instantaneous marker of an athlete's ballistic performance capacity and therefore aid in the prescription of appropriate loading or recovery strategies.

Three independent studies were conducted to investigate the validity, reliability and sensitivity of the IMU. In study 1, participants underwent a 5-10 minute standard warm-up involving jogging locomotion at an exercise intensity eliciting 40-60% of maximum HR The participants were then required to perform in total 9 jumps on a Just Jump Contact Mat (JJCM) whilst

wearing a Catapult MinimaxX 10Hz S4 GPS device placed on the trunk at the level of thoracic vertebrae 2-3 (T2-3) using a manufacturer issued harness. The JJCM acted as a gold standard reference. The 9 jumps, 3 countermovement jumps to a pre-determined depth (CMJ^{PDD}), 3 countermovement jumps to a self-selected depth (3 CMJ^{SSD}) & 3 squat jumps (SJ) were divided into three bouts. All jumps were performed with the hands positioned on the pelvis and the trunk upright.

In study 2, participants underwent the same warm up as in study 1 and then performed 3 jumps whilst wearing a Catapult MinimaxX 10Hz S4 GPS device placed on the trunk at the level of T2-3 using a manufacturer issued harness. Each participant performed a single CMJ^{PDD}, a single CMJ^{SSD} and a single SJ. Each participant conducted $\geq$2 of 3 jump testing protocols within 7 days. In the event that they did not meet this requirement they were subsequently excluded from analysis. All participants performed their jump protocol at the same time in order to mimic the proposed use for these investigations in the field. Inter-day reliability of jumps was then taken as a marker of system reliability.

In study 3, each participant was required to perform a test battery on two occasions in a repeated-measures protocol, both before and after a short 6-week preparatory period leading into the 2014-2015 youth professional domestic soccer season. The test battery consisted of body mass measurement, 5m-sprint, 10m-sprint, 20m-sprint, free jump (FJ) and CMJ^{PDD} performance measures.

The results of study 1 suggest that the use of Catapult accelerometer power-derived measures are not a valid indicator for vertical jump performance. On the contrary, jump height (H) as well as flight time (FT) appear to provide an accurate and valid measure of vertical jump performance when employing the techniques put forth in this manuscript; FT^{JJCM} (s) was not significantly different from derived IMU FT^{P-T} (s), for CMJ^{SSD} (0.634 $\pm$ 0.046 vs. 0.636 $\pm$

0.042, p>0.05), CMJ^{PDD} (0.625 $\pm$ 0.045 vs. 0.624 $\pm$ 0.043, p>0.05) and SJ (0.616 $\pm$ 0.049 vs. 0.612 $\pm$ 0.004, p>0.05), respectively. $Height^{JJCM}$ (cm) was not significantly different from derived IMU height based on FT^{P-T} (cm), for CMJ^{SSD} (50.40 $\pm$ 7.39 vs. 49.86 $\pm$ 6.71, p>0.05), CMJ^{PDD} (48.60 $\pm$ 7.18 vs. 47.93 $\pm$ 6.73, p>0.05) and SJ (47.16 $\pm$ 7.63 vs. 46.14 $\pm$ 7.31, p>0.05), respectively (Fig 6).

Study 2 suggests that one jump condition has sufficient inter-day reliability with regards to FT and H estimation; the lowest mean coefficient of variation (CV) that we found was for height peak-to-peak (H^{P-P}) for the CMJ^{PDD} condition (CV = 6.46%), with the other conditions up to two times higher and thus not supported in reference to the literature. Although this marker is not valid as shown in study 1 it is the only reliable measure from these investigations and therefore we would suggest that it warrants further research. Furthermore, as the H^{P-P} estimation is shown to be reliable and the height estimation is based on flight-time, we would also suggest that further research for the utilisation of flight-time as a reliable measure when utilizing flight-time peak-to-peak (FT^{P-P}) is warranted to. FT^{P-T} & H^{P-T} for CMJ^{PDD}, CMJ^{SSD} & SJ were not shown to be reliable.

Study 3 revealed that in testing for a change in performance, there was no significant difference between before and after measures for 5m-sprint time (s) (1.08 $\pm$ 0.05 vs. 1.08 $\pm$ 0.05, p=1), 10m-sprint time (s) (1.83 $\pm$ 0.07 vs. 1.81 $\pm$ 0.06, p=0.211), 20-m sprint time (s) (3.08 $\pm$ 0.07 vs. 3.06 $\pm$ 0.08, p=0.355) and FJ (cm) (24.75 $\pm$ 3.27 vs. 24.55 $\pm$ 2.68, p=0.512), although there was a statistical difference for CMJ^{PDD} (s) (0.67 $\pm$ 0.03 vs. 0.64 $\pm$ 0.03, p=0.003). Accordingly, as there was no change in performance shown it was not possible to determine the sensitivity of the Catapult IMU as a means to monitor athletic readiness. Therefore we would advise using caution when implementing the system for the purpose of monitoring vertical jump performance, and suggest a change of 2 standard deviations (SD) as a benchmark for reason to question readiness to train until further more conclusive research can be conducted.

In conclusion, it is clear from these results that IMU flight-time and height measures provide valid markers of vertical jump performance when compared to the gold standard, when employing the techniques put forth in this manuscript; FT^{P-T} & H^{P-T} for CMJ^{PDD}, CMJ^{SSD} & SJ. However, none of these measures were shown to be reliable, and FT^{P-P} & H^{P-P} for CMJ^{PDD} were shown to be the only reliable measures. Additionally, it was not possible to accurately determine the true sensitivity of the IMU system to minute changes in training status for the CMJ^{PDD}, as there was no change shown in the performance markers tested in study 3. Future research should therefore aim to determine the true sensitivity of the Catapult IMU for estimating vertical jump performance, while reinvestigating the sensitivity and reliability of the system.

List of Contents

List of Tables

List of Figures

limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

Figure 6. Bland-Altman plots (n=23) of H^{JJCM} versus IMU derived height (based on FT^{P-T}) for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM height (cm). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

Figure 7. displays the contingency tables for direction and frequency of change for A) FJ vs. 5m-sprint time, 10m-sprint time and 20-m sprint time B) CMJ^{PDD} vs. 5m-sprint time, 10m-sprint time and 20-m sprint time. The green shading highlights the normal trends that would normally be expected.

Figure 8. Jump performance (A) during the 72-hour recovery following LIST (triangles) and soccer (squares). Values are mean and SD. Asterisk signifies significance at $p<0.05$ versus pre-exercise for both exercises (LIST and soccer).

Acknowledgements

Firstly, I am extremely grateful to my supervisor Dr. Niall MacFarlane. Without his knowledge, expertise and insight, the possibility of planning, implementing and executing a research project such as this would not have been feasible. His guidance throughout this master's project has been one of inspiration and education.

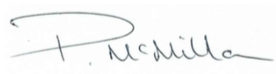
Secondly, I would very much like to thank all of the employees of Celtic Football Club Ltd. particularly the management, coaching and playing staff. I have always felt at home and felt welcome to ask for any help or support that I needed. In this way I would like to express special regards to my supervisor at Celtic Football Club, Bill Styles (First Team Lead Sport Scientist) and Ian Coll (First Team Sport Scientist), as well as Andy Guard (Development Squad Sport Scientist).

Thirdly, gratitude is also expressed to those who have not been mentioned but have provided assistance in any way throughout the progression of this thesis as well as all those who volunteered to take part in this research. Your participation has allowed this work to take fold.

Finally but by no means least I would like to express a special thanks to all of my family, especially my parents Catherine & Paul, Brothers Aidan & Declan and Sister Erin for supporting me over the past 6 years at university. You have encouraged me to always have a positive mentality and to always strive to succeed. For that I'll be forever grateful.

Declaration

I declare, except where explicit reference is made to the contribution of others, that this dissertation is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.

Signature: 

Printed name: Paul McMillan

Abbreviations

ADP	Adenosine Diphosphate
ANS	Autonomic Nervous System
ATP	Adenosine Triphosphate
CK	Creatine Kinase
CO	Cardiac Output
CMJ	Countermovement Jump
CMJ^{PDD}	Countermovement Jump (Pre-Determined Depth)
CMJ^{SSD}	Countermovement Jump (Self Selected Depth)
CV	Coefficient of Variation
FJ	Free Jump
FT	Flight Time
FT^{JJCM}	Flight Time: Just Jump Contact Mat
FT^{P-P}	Flight Time: Peak-to-Peak
FT^{P-T}	Flight Time: Peak-to-Trough
FOR	Functional Overreaching
GCT	Ground Contact Time
GPS	Global Positioning System

H	Height
H^{JJCM}	Height: Just Jump Contact Mat
$H^{P\text{-}P}$	Height: Peak-to-Peak
$H^{P\text{-}T}$	Height: Peak-to-Trough
HF	High Frequency
HPAA	Hypothalamic Pituitary Axis
HR	Heart Rate
HRV	Heart Rate Variability
Hz	Hertz
IgA	Immunoglobulin-A
IMU	Inertial Measurement Unit
JJCM	Just Jump Contact Mat
LIST	Loughborough Intermittent Shuttle Test
LF	Low Frequency
MEMS	Microelectromechanical System
NFOR	Non-Functional Overreaching
NMF	Neuromuscular Fatigue
OTS	Overtraining Syndrome

$Power^{JJCM}$	Derived Power: Just Jump Contact Mat
$Power^{Land}$	Derived Power: Inertial Measurement Unit Land
$Power^{TOff}$	Derived Power: Inertial Measurement Unit Take Off
RSI	Reactive Strength Index
$SAFT^{90}$	Soccer-Specific Aerobic Field Test (90 minutes)
SA-node	Sino-Atrial Node
SD	Standard Deviation
SJ	Squat Jump
SWC	Smallest Worthwhile Change
T2-3	Thoracic Vertebrae 2-3
URTI	Upper Respiratory Tract Infections

Chapter 1:

Introduction & Overview

1. Introduction & Overview

Soccer (association football) is the most commonly participated in sport across the globe (Giulianotti, 2012). Although, the physiological demands of soccer have been extensively researched (for review: Bangsbo, 1994 or Stolen *et al*, 2005), to determine fatigue processes associated with match play (Mohr *et al*, 2003; Mohr *et al*, 2005; Mohr *et al*, 2010), as well as recovery strategies to alleviate this fatigue (Nedelec *et al*, 2013), there is still no definitive gold-standard post-match recovery procedure or practical tool for monitoring subsequent readiness to train and perform. This would be important to ensure a return to non-significant variance from pre-match or pre-training levels.

Over recent decades, while the relative duration of each match has remained constant, for many athletes especially those performing well in competition, the frequency and intensity of match play has increased. In 2009-2010, the soccer season culminated with the Federation Internationale de Association (FIFA) World Cup in South Africa. At the end of this tournament several Spanish players had accumulated 70 competitive matches (Nedelec *et al*, 2012), with an average of 3 days separating the fixtures. This is in stark contrast to past experience in which elite players would have been expected to participate in approximately 40 matches per season.

Although the structure of many domestic leagues has not changed over the decades, from 1955 until the 1990's the European Cup (currently known as the Champions League) operated a 2-leg knockout format, for only the champions of each of the European leagues. In the 1990's however, three knockout qualifying rounds, a play-off round and then a 'round-robin' group stage were introduced before the knockout stages, and thus this has increased the numbers of matches that have to be played. Similarly, depending upon the UEFA coefficients of these countries, as many as 4 teams from a league could be entered into the competition, with this ‘limit’ to increase to 5 teams from the top ranked nations for the 2015-2016 competition. In addition, the UEFA Europa League, a competition, which operates alongside the Champions League introduced a ‘round-robin’ structure in 2004-2005, with a further expansion of this structure in 2009. As teams who do not qualify for the Champions League may be eligible to enter the UEFA Europa League at different stages, this again increases the number of fixtures that many teams, and not necessarily only those at the top of domestic leagues, must now fulfil.

Furthermore, technological advances are now facilitating a better understanding of the overall physiological and physical demands imposed upon elite soccer players. For example, GPS and in-stadium camera-based systems e.g. Prozone®, now provide performance staff with thousands of data points from each match. In a standard 90 minute match, players can be expected to run up to 10-13 kilometres (Bangsbo *et al*, 2006; Mascio *et al*, 2013), with many periods of play often close to anaerobic thresholds of 80-90% of VO_{2max} or perhaps even higher, detailing the short-intermittent high-intensity nature of the sport (Stolen *et al*, 2005; DiSalvo *et al*, 2007; Helgerud *et al*, 2011). To facilitate this intensity soccer players must therefore possess high aerobic capacities for recovery between bouts. VO_{2max} values of 62-64 ml/kg/min have been reported for elite soccer players in Norwegian leagues, with a small to moderate playing position effect (Tonnessen *et al*, 2012). Additionally, soccer also demands for a sufficient level of functional strength, power, tactical awareness, technical proficiency, anaerobic capacity, speed and repeated sprint ability (RSA), thus making the game much more demanding than it ever has been in the past (Helgerud *et al*, 2011). Although there have been minimal rule changes over the years, as mentioned the intensity of play has increased. Examining a 7-season period in the English Premier League with a multiple-camera computerised tracking system (Prozone®), Barnes and his colleagues (2014) were able to reveal that high intensity running increased by 30%, high intensity running actions by 50%, sprint distance by 35% and sprint actions by 54% over this time period. Players also performed 40% more passes and completed more successful passes in 2012-2013 vs. 2006-2007 (Barnes *et al*, 2014). This therefore demonstrates the evolution of the physical capacity required to play soccer in today's game. Many other factors could also be additionally responsible for this increase in playing intensity including improved ability, improved training techniques and understanding of science, as well as the introduction of 'ball boys' and 'spare balls' to the game.

The progressive increase in the volume of competitive soccer being observed at the elite level now places a significant physiological demand upon players. The increased physiological demand provides a stimulus to consider conditions such as NFOR and OTS when prescribing appropriate training stimulae. The normal training process aims to maintain or enhance performance capacity. By meticulously altering the physiological load that an athlete experiences via the intensity, duration and/or frequency of the sessions it is possible to improve their ability to perform athletic work.

The individual athletes will experience feelings of fatigue and performance decrements in the acute stages after an intensified training bout or after a period of competitive game play where exercise intensity is not prescribed (Magalhaes *et al*, 2010). When this physiological work overwhelms the player's capacity to adapt to the training stimulus then it may result in depressed performance that is termed functional overreaching (FOR). Subsequently if this decrement in performance does not subside within a few days to a week of rest or a lighter training load then the athlete may have a more serious condition referred to as NFOR. As the name suggests, the condition is non-functional and does not support the training process. If it persists and if a prolonged period of rest (days-weeks) does not allow it to subside then the athlete may be displaying signs of overtraining (Jeukendrup *et al*, 2004).

OTS has been the topic of much debate within the literature throughout recent years, where much of the confusion is due to the broad range of inconsistent definitions, which exist at present. Perhaps the definition, which explains the proposed condition most accurately, is an accumulation of training and/or non-training related stresses exhibiting physiological and/or psychological signs and symptoms. These symptoms often result in a long-term performance decrement which may take several months or years to recover to normal performance capacity (Jeukendreup *et al*, 2004).

In considering the premise of OTS it is important to start off with a basic understanding of the general adaptation syndrome first coined by Hans Selye (Selye, 1936) Exercise training can be thought of with an analogy to a dose response curve in pharmacology. Providing the body with an initial stimulus, often referred to as a shock (i.e. intensified training, which initiates a cascade of biochemical and physiological responses), will lead to a temporary decrement in performance. This temporary decrement in performance can take the form of acute fatigue or perhaps delayed onset muscle soreness (DOMS) but with adequate recovery following this shock the body can develop a new level of homeostasis (accompanied by an increased resistance to the initial stimuli through adaptation as a super-compensatory effect). To further increase performance or training status the individual must overload the body with a further 'shock' i.e. progressive overload. However, whenever the body is not afforded the required rest in order to adapt and reach a new level of homeostasis the body can be driven into a state of exhaustion in which further adaptation is unlikely and a longer period of recovery is required to return to the initial baseline

So as many medical practitioners prescribe a patient with a low initial dose of a medicinal agent to improve their health (and prevent side effects), so should a fitness coach or sports scientist prescribe a very controlled training dose when seeking to improve an athlete's performance. If the prescribed dose or shock in both cases is not strong enough then the initial status remains but is easy to increase. Whereas, if the prescribed dose or shock is too great then the side effects can be more problematic than the original condition (or lack thereof in relation to training). A skilled practitioner is able to administer just the appropriate stimuli and recovery to drive the athlete's performance forward, the process, which forms the scientific basis for periodization.

The sequelae of increased soccer match load means that in-season training programs are progressively shifting towards a greater maintenance and recovery based focus rather than athlete development to prevent any overtraining. Excess fatigue accumulation which is often observed during a congested schedule in soccer (Lago-Penas *et al*, 2011; for review: Nedelec *et al*, 2012), can lead to a) suppressed performance, b) increased incidence of injury and c) the potential for development of NFOR and perhaps OTS. Recent evidence suggests that soccer players subject to 2 fixtures per week display a higher injury rate than those playing once (25.6 vs. 4.1 injuries per 1000 hours of exposure respectively; Dupont *et al*, 2010).

To aid appropriate exercise prescription and preventing the detrimental consequences of overtraining performance analysts are constantly seeking to adopt a more evidence-based test to detect minute changes in an athlete's ability to perform work, generate force and power and maintain performance. Rather than trying to decipher basic science approaches to detecting the presence of such conditions it may be more practical to build a longitudinal database for training derived data that could highlight adverse patterns outwith an individual's normal response and out with that expected within an appropriate periodization model. A practitioner could, with appropriate procedures, carry out these measurements before each session and adapt training to the athlete's individual readiness to train. This would support a more pragmatic approach to monitoring an individual athlete's internal load and coping ability and aid in the prescription of an appropriate external load.

As soccer consists of a number of physically demanding tasks (e.g. sprinting, jumping, changing direction under pressure, tackling, dribbling, passing and shooting), it might be appropriate that the kinetics and kinematics of these parameters be monitored in order to determine athletic readiness to train and/or compete. In light of this, the aims of this thesis are to consider the current methods available to monitor athletic readiness, and subsequently to investigate the validation, reliability and sensitivity of utilizing a wearable GPS based IMU to determine vertical jump performance. This system could potentially provide an instantaneous marker of an athlete's ballistic performance capacity and therefore aid in the prescription of appropriate loading or recovery strategies.

Chapter 2:

Literature Review

Athletic Training Status and Training Readiness

2. Literature Review: Athletic Training Status and Training Readiness

In the new and modern days of elite sports, whenever a sports scientist, strength and conditioning coach or performance specialist implements an in-season training programme their primary objective is rarely to improve fitness levels but rather to maintain the health of the athlete and high levels of performance. Rather than applying interventions to cause a super compensatory effect in athletic fitness, in line with Hans Selye's general adaptation syndrome (Selye, 1936), the competitive season may be the most important phase of the year for those in charge of a team's fitness and peak performance to implement recovery strategies and techniques. These strategies should best provide the athlete with a smooth and speedy recovery to their pre-match abilities and physiological condition.

There are three primary components to recovery (sleep, nutrition and active/passive recovery modalities) and each contributes to an athlete returning to their maximal performance capacity. To ensure that an athlete has fully recovered before their next post-match training session or after a high intensity training session it is vital to have valid, reliable and sensitive markers of training status (i.e. 'availability' to train). The following sub sections will outline methods, which are currently implemented in today's elite team sports environment.

2.1 Heart Rate Measures

In recent times, heart related indices have acquired greater levels of interest from practitioners in the field seeking to quantify training status in their athletes. Although resting heart rate (HR) has normally been the only marker available, heart rate variability (HRV) measures are now more commonly recorded. HRV is a physiological measurement, which identifies the time intervals between each heartbeat (specifically the time interval between each 'R' peak in the PQRST electrocardiogram complex). It is a technique first described in the 1960's by a group of Soviet Russian scientists, through the success of space medicine research in the Soviet Union (Parin *et al*, 1965). In 1966 a symposium on the mathematical analysis of HR rhythm and HRV took place (Parin *et al*, 1968), a gathering, which resulted in a great increase in related research over the following decades. However, the techniques surrounding HRV monitoring have since exhibited heightened research in the elite sporting context since the turn of the millennium.

Since its first description back in the 20th century and its recent introduction into athletic analytics there have been a number of commercially developed systems which claim to be able to use HRV as a marker for potential overtraining e.g. ithlete, Bio Force and Omegawave. Prior to the development of these systems however, there has been much research carried out into the integrated regulation and control of the cardiovascular system by higher central command centres, as well as peripheral endocrinological mediators, metabolic by-products and feedback mechanisms including the baroreceptor reflex.

It is now readily apparent, that the autonomic nervous system (ANS) provides a chief source of regulation for the myocardial tissue and its ability to pump effectively both at rest and during intensive exercise (Aubert *et al*, 2003). The cardiac output (CO) of the heart can be determined by Fick's principle, which states that CO is the product of HR and stroke volume. Stroke volume is determined by preload (pressure of blood filling the ventricles), afterload (the resistance of ejection) and contractility (myocell shortening). HR is determined by the pacemaker activity of the sino-atrial node (SA-node), a small collection of cells located in the posterior wall of the right atrium. The SA-node causes the myocardium to exhibit an intrinsic automaticity of about 100-120 beats/min, which will decrease with age. Activation of the vagus nerve however innervates the SA-node at rest to decrease HR to below the intrinsic rate i.e. vagal tone (40-80 beats/min depending upon fitness level). The HR can however be quickly increased, for example by circulating catecholamines (fight-or-flight) acting via B_1-adrenoreceptors at the SA-node, temperature shifts (hyperthermia causes increase) and exercise.

The anticipatory effect of exercise causes a withdrawal of the vagal stimulation and subsequently promotes a higher level of sympathetic discharge from the medulla oblongata, increasing HR and altering the central haemodynamics of the heart. With continuous exercise there is a further withdrawal of parasympathetic discharge and an accentuated sympathetic release in a biphasic manner. Overtraining however has been associated with the disruption of several physiological systems (Kuipers *et al*, 1998; Gastmann *et al*, 1998) and due to the intricate link between the hormonal and autonomic control of the body, it is likely that any disruption will coincide with an imbalance of the ANS (Lehmann *et al*, 1998; Israel, 1976). Therefore it has been suggested that changes in HRV due to ANS disruption may present a monitoring tool to identify an overloaded or subsequently overtrained athlete in comparison to a healthy and well-rested athlete.

Although, the general belief in the commercial industry is that overtrained athletes exhibit an increase in sympathetic activation and a reduction in HRV compared to healthy athletes (Mourot *et al*, 2004), there are often very contradictory findings in the literature with regards to parasympathetic/sympathetic balance. These contradictions are likely due to methodological inconsistencies, misinterpretation of the data and perhaps partly due to the vast number of HR monitoring parameters at a practitioners disposal. These can be categorised into resting measures: resting HR, resting vagal-related HRV; exercise measures: exercise HR, exercise HRV; and post-exercise measures: post-exercise HR recovery (HRR), post-exercise vagal-related HRV (summarised in Table 1).

The basic principle of HRV monitoring and analysis is to determine any true variance in the status of the ANS over a period of time (Buchheit, 2014a), which may be indicative of any alterations in athletic wellness, fitness and readiness to perform, and thus allow practitioners to adequately alter training loads. With direct regard to HRV analysis there is a surfeit of techniques which may be utilised, all detailing a different feature of the ANS with some detailing sympathetic activity and others parasympathetic activity. These techniques include time domain, spectral and non-linear analyses. Time domain methods provide information relating to temporal features of variability. For example, rMSSD (square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals), a time domain method of analysis, reflects the vagal mediated autonomic control on the heart. From this measure it is possible to determine the balance of the sympathetic: parasympathetic tone.

Furthermore, spectral analysis (frequency domain analysis) relates to the cardiac signals with respect to frequency rather than time. It has often been said that the low frequency (LF; believed to reflect parasympathetic & sympathetic tone) to high frequency (HF; believe to reflect parasympathetic tone) metric is a measure of sympathetic: parasympathetic balance. However, spectral indices are very sensitive to the level of respiration, which could explain why they have been shown to have extremely high CV (as much as 82%; Al Haddad *et al*, 2011). Non-linear analyses of HRV using a Poincare plot can give a graphical representation of the variability between adjacent R-R beats. This analysis also provides a SD measure of instantaneous beat-to-beat R-R interval variability (SD1). An increase in SD1 is representative of an increase in HRV (increase in parasympathetic tone; a wide plot) whereas a decrease in SD1 is representative of a decrease in HRV (decrease in parasympathetic tone; a narrow plot). From this, sports scientists may be able to monitor the SD over time to determine the ability of athletes to switch from an active (sympathetic) state to a rested (parasympathetic) state.

Table 1. highlights the possible heart rate based measures of monitoring, their determining factors and the areas that most likely benefit from their utilisation (Buchheit, 2014a).

	Determinants	Monitoring Variables
Resting HR	Cardiac muscle morphology, plasma volume, autonomic activity, age, body position	Wellness, fitness & readiness to perform
Resting vagal-related HRV indices	Genetics, plasma volume, autonomic activity, body position	Wellness, fitness & readiness to perform
Exercise HR	Fitness, plasma volume	Aerobic fitness
Exercise HRV	Intensity-dependent: ANS < VT1, respiration > VT2	In theory, aerobic fitness
Post-exercise HRR	Theoretically ANS and genetics but essentially metaboreflex	In theory, wellness, fitness and readiness to perform. In practice, more fitness because of its link with relative exercise intensity
Post-exercise vagal-related HRV indices	ANS and baroreflex, but the metaboreflex has the greater effect	In theory, wellness, fitness and readiness to perform. In practice, more fitness because of its link with relative exercise intensity

In an athletic population, time domain indices e.g. rMSSD or SD1 seem most suited due to exhibition of parasympathetic information, simple calculation needs, their short recording times (Nussinovitch *et al*, 2011), low sensitivity to breathing patterns (Penttila *et al*, 2001), and smaller variations versus spectral indices as mentioned previously (Al Haddad *et al*, 2011).

However, with regards to the HR monitoring parameters there are often equivocal standpoints into their usefulness and how practically they can be employed in order to develop wellness against other parameters. It seems that exercise HRV and post-exercise measures i.e. post-exercise HRR and post-exercise vagal-related HRV indices, are very often difficult to utilise when aiming to monitor the activity of the cardiac ANS regulation over time due to a number of reasons:

1) If exercise intensity is too high i.e. > ventilatory threshold 1 (VT1; intensity at which point ventilation begins to increase in a non-linear fashion due to an increased production of carbon dioxide from buffering), exercise HRV becomes more non-dependent upon cardiac ANS activity and more relative to the intensity of exercise and fluctuations in respiration

2) Post-exercise HRR has been reported as an index likely to perhaps provide more information regarding adaptation to training although in team sports no correlation and lower correlations than that observed with exercise HR have been observed, while post-exercise HRR has also been questioned regarding its use as a marker for monitoring performance impairment (Buchheit, 2014a)

3) Post-exercise vagal-related HRV indices are likely to be more indicative of the degree of metaboreflex due to the aforementioned relation to intensity. As exercise intensity increases > VT1, a greater blood acidosis will slow the HRR and lower vagal HRV indices, thus any measured data is not truly indicative of fluctuations in the cardiac ANS regulation pattern but more so that of the nature of the peripheral environment.

It should also be noted that ANS activity has also been shown to be extremely sensitive to the environmental conditions at the time i.e. light exposure, noise, temperature (Achten *et al*, 2003), and thus the recordings need to be standardised to ensure that repeat-measures interpretation is dependent purely upon training load related factors. Night recordings seem optimal, providing a high standardization of the environment and thus optimal conditions for testing (Brandenberger *et al*, 2005). However, the practical constraints with elite athletes determine that these measures are difficult to implement temporally.

Methodological and scientific considerations must be made before any data analysis takes places in relation to HRV. Failing to account for a single ectopic or missed beat in R-R series' can skew HRV indices by as much as 50% (Buchheit, 2014a), therefore pre-analysis adjustments to account for this should be carried out. This extra daily analysis will then substantiate workloads of staff and thus the relevance of the data should be considered; excess time spent managing a large quantity of files takes the practitioner away from the athletes and the results obtained may not be worth the expenditure of time to obtain them.

Hydration and environmental conditions (e.g. temperature and barometric pressure) also have to be considered in analysis. In temperate conditions an increase in parasympathetic activity has been observed alongside an acute decrease in perceived wellness, observations which do not coincide with the expected drop in parasympathetic activity in parallel to exercise in hotter conditions (Buchheit *et al*, 2013; Brenner *et al*, 1998).

Training context should also be considered during analysis in relation to the phase of training for the periodization model applied, e.g. aerobic endurance moving into competition. Finally, considering the smallest worthwhile change (SWC) is also important to practitioners in order to determine if what they are observing may actually have a resultant impact on their athlete. This should be done whilst incorporating the error of measurement to aid in the prevention of false negatives (not intervening when you should) and false positives (intervening when you should not).

From the available literature, it appears that the best HRV-related measures for the athletic population would come about with a 5-10 minute resting test upon awakening in the morning (Plews *et al*, 2013), aimed at acquiring data pertaining to parasympathetic activity. Recordings in the supine condition are favoured over standing and seated although all are reported in the literature. A quiet morning environment would overcome the restrictions to night-time recordings referred to earlier while also providing an adequate level of standardization for monitoring. Additionally, it has been reported that a 30-60s HR recording during a submaximal exercise test could also be a useful marker (Buchheit *et al*, 2010).

It is important to note however that HR-measures cannot inform on all aspects of athletic wellness, several practical limitations are present in the use of these techniques nor are they gold standard. As mentioned previously the time required to analyse such data for a full team of athletes on a daily basis may prevent the use of such techniques in determining athletic status to train. Similarly small staff numbers, lack of expertise and lack of specialised equipment required to conduct such procedures may also limit the use of HRV techniques. Furthermore a debate still exists in the literature surrounding the usefulness and practicality of these measures. HRV measures mainly pertain to cardiac ANS and do not provide any insight into the regulation or wellness state of the neuromuscular or psychomotor environments. Therefore if HRV measures are to be employed they should be employed in combination with other non-invasive and non-expensive tests while staff members should display caution in interpretation of the results.

2.2 Subjective & Psychometric Questionnaires

Many sporting teams and athletes utilise subjective and psychometric measurements of training readiness to develop baseline data that can subsequently be used to identify fluctuations in an athlete's psychological state. OTS is generally accepted within the scientific world as having a major component of psychological as well as psychomotor inflicted stress (Jeukendrup *et al*, 2004), therefore psychological questionnaires may be useful to monitor athletes.

The ‘Profile of Mood State’ (POMS) questionnaire is often used to identify those athletes experiencing NFOR and OTS with an inverted ‘iceberg’ profile highlighting individuals at risk (Morgan *et al*, 1987). However, although a potential tool in preventing OTS it should be noted that increased training volumes have also resulted in abnormal profiles being exhibited even though they did not contribute to an overtraining state (Morgan *et al*, 1988). Additionally, there have been studies particularly in swimmers demonstrating that after short periods of increased training load an increased POMS score can be observed without any reductions in athletic performance (Morgan *et al*, 1988; O’Connor *et al*, 1991). In soccer specifically, POMS score changes have been shown to coincide with changes in performance level where reduced performance after a high-intensity training programme aligned with increases in depression and tension as well as decreases in vigor (Filaire *et al*, 2001). Therefore, while POMS may be indicative of athletes beginning to exhibit an overreached or overtrained state they remain subjective and can be influenced by mood disturbances that could subsequently influence the validity of the data resulting from their use.

In addition to psychometric measures, many elite sporting teams utilise general wellness questionnaires, which ask about muscle soreness and fatigue quantifying responses on Likert style scales (e.g. extreme pain, lot of pain, mild pain, little pain, no pain). These questionnaires allow practitioners some insight for subjective ratings of the individual athlete’s perception of their current status. While there doesn’t seem to be a standardised questionnaire, those developed ‘in-house’ can provide extremely valuable information provided the questions are formatted in the correct manner. For example, in rugby seven’s competition a simple 8-item questionnaire of fatigue alongside session rating of perceived exertion (sRPE) was useful in detailing changes in an individual's perception of training load and stress (Elloumi, 2012).

It should be considered however that in using psychometric measures of readiness to train and general wellness questionnaires there is a possibility for athletes to report what they think their coach should hear rather than what they truly feel. As athletes become accustomed to completing such questionnaires they may realise that in reporting certain responses they can elicit a desired outcome e.g. receive an extra recovery day with their teammates in the gym or hydrotherapy pool and therefore do not have to participate in training. Alternatively, athletes may also understate feelings of tiredness and readiness to train as they may be concerned that not training would compromise selection for competition, a situation which may lead to heightened risk of injury if fatigue is still present. Of course this is not the desired outcome of these questionnaires, however due to their subjective nature and their reliability relying on the full cooperation of the athlete and team they should be used in line with other measures of readiness to train, perhaps those discussed in this chapter, to ensure their resultant validity and reliability.

2.3 Hormonal & Biochemical Analysis

A range of   and biochemical markers have been suggested as potential descriptors of training status due to their association with the adaptive response to training and their dysregulation perhaps providing evidence of maladaptation. Participating in exercise places a physical stress on the body, which challenges our homeostasis. In response to such stressors several physiological systems will attempt to restore our dynamic equilibrium. For example, the sympathetic ANS and the hypothalamic-pituitary-adrenal-axis (HPAA) will react in order to try to re-establish a baseline level of normal resistance (i.e. adaptation). In doing so, many hormonal, immunological or biochemical factors will become elevated or depressed, including testosterone, cortisol and IgA. Accordingly, much of the literature supports the belief that an intolerable training load prescribed over time will firstly lead to a disturbance and an adaptation of the HPAA but eventually if it persists, a maladaptation (Meeusen *et al*, 2010). As a consequence, this maladaptation will lead to abnormal hormone responses as a result of continued training. Therefore theoretically, monitoring the normal and abnormal response of these markers to exercise may allow us to determine when certain athletes are not tolerating the prescribed training load and are beginning to display signs of maladaptation.

In a clinical setting or in athletes undergoing more extensive testing hormone levels would normally be monitored from blood plasma, however acquiring measures of hormone levels from athletes quickly and on the go can be difficult due to the invasiveness of the procedures. Therefore, saliva measures of hormone levels are often preferred in the field due to the strong relationships between salivary and serum hormone levels (Cook *et al*, 1987; Port, 1991; Vining *et al*, 1983). Through frequent saliva sample analysis, salivary hormone levels may be indicative of shifts in 'normal' concentrations under different conditional states, perhaps following periods of intensified training and thus aid in determining training status.

For example, inter-collegiate soccer match play has been shown to increase both salivary cortisol (catabolic: released in response to physical or mental stress) and salivary testosterone (anabolic: released to promote muscle tissue synthesis) in male and female players alike (Edwards *et al*, 2006), with a decrease in the testosterone/cortisol (T/C) ratio of ~30% being observed following a competitive half-season (Handziski *et al*, 2006). Although it may seem attractive to conclude that this decrease in the T/C ratio is indicative of a transgression from a greater anabolic state to a greater catabolic state, an observation which may be of interest to sports scientists, high individual variability (Hayes *et al*, 2012) may limit the efficacy of these conclusions. Similarly a depressed T/C ratio or an alteration in these hormones independently does not always necessarily lead to depressed performance ability (Hoogeveen *et al*, 1996) and any changes may perhaps be due to the normal variability of the nycthermal and seasonal rhythm of hormones. By monitoring the T/C ratio we are also looking for indicative measures that there is a problem and it is not a predictive measure of training status (i.e. when it is altered then the situation has occurred and cannot be prevented).

Salivary immunoglobulin-A (IgA) concentrations have recently been reported to exhibit immunosuppression following periods of high intensity training in elite soccer players, which consequently increases the likely incidence and risk of contracting upper respiratory tract infections (URTI's) (Owen *et al*, 2014). The author suggested that if monitored routinely over time for individual players, salivary IgA data may provide insight into the health status and training capabilities of an athlete and again aid sports science staff in their decision making process. However, there is limited supporting evidence available to suggest that other measures of immune function can provide reliable insight into athletic readiness to train and thus at present it seems that the cost of analysis may be far outweighing the benefit (Coutts *et al*, 2014).

Creatine Kinase (CK) has been regarded as an important marker of the physiological training and recovery process and is therefore routinely monitored to determine the level of damage and recovery in the muscular tissue. CK habitually resides within the myofibrils and participates in phosphorylation of adenosine diphosphate (ADP) to provide adenosine triphosphate (ATP) for mechanical work. Upon mechanical insult to the infrastructure of the tissue during exercise, there may be release of intracellular fluids and other metabolites into the extracellular space. These metabolites may be analysed to provide a degree of information regarding the level of mechanical muscle damage in the internal environment.

With particular reference to soccer performance CK tends to peak 12-20 hours post match and return to normal beginning-of-season baseline levels within 60-65 hours (Coelho *et al*, 2011). A rise in CK however is not necessarily due to maladaptation nor does it predict performance limitations. CK is more likely to provide information in assessing acute muscle damage, particularly during pre-season or following intensified periods of competition. Therefore if its presence persists following a reduction in load then there may be reason for concern due to a heightened risk of injury, however the high variability of CK and the time course to peak (peaking at 24-48hrs in some cases means that the damage and subsequent training are not linked) suggests that it should be interpreted with caution and used alongside other measures.

Accordingly, several limitations exist when using biochemical markers to determine status to train. The practicality of the analysis is a major limitation and must be considered in relation to the cost-reward benefit. For example, the need to frequently sample and quickly analyze samples is hindered by the complexity of assays, strict collection and storage procedures and normal variation within the nycthermal and seasonal rhythm of hormones as mentioned previously (Coutts *et al*, 2014). As a result, the nature of these measurements may limit the practicality of their use on a routine basis in a busy schedule often involving extensive inter-continental travel in team sports.

2.4 Neuromuscular Markers

Neuromuscular monitoring techniques for assessing training status are commonplace across sports and the world. Perhaps the most common involve lower body tests; for example vertical jump performance, maximum voluntary isometric contraction of the hamstrings/quadriceps or short sprint protocols (Nedelec *et al*, 2014). Although testing of maximum voluntary isometric contraction and short sprint protocols are reasonable in theory, they are, for the most part, impractical in daily monitoring of training status. Limitations include access to equipment, expertise needs, time required for muscle testing, time required conducting sprint protocols and the heightened risk of injury during sprinting in a potential state of fatigue. In order to measure maximum voluntary isometric contraction of the hamstrings and quadriceps muscles an isokinetic dynamometer is required. Although well-funded sporting organizations may have access to such equipment, financial constraints may limit this option to less well funded organizations alongside the expertise required in operating this equipment and the time required for testing of a large group of athletes.

Similarly, Small (2008) and his colleagues were able to conclude that gravity corrected eccentric hamstring peak torque decreased in a significant manner over each half period of the Soccer-Specific Aerobic Field Test ($SAFT^{90}$), a multidirectional intermittent 90-minute exercise protocol, alongside a reduction in the functional hamstring: quadriceps ratio (i.e. H_{ECC}/Q_{CON}) (Small *et al*, 2008a). Subsequently they also provided experimental evidence into the sprinting kinematics of hamstring injury risk through the employment of the $SAFT^{90}$ protocol and a high-speed motion capture system. They reported a significant time dependent decrease in sprint time alongside a significant reduction in stride length, combined maximal hip flexion and knee extension angle, as well as a reduction in hamstring length from pre-match to the ends of both halves of play respectively (Small *et al*, 2008b). Therefore as we observe a heightened risk of injury (hamstring tear, ACL tear) under the influence of fatigue, it would be unethical and poor practice to subject an athlete to a sprint protocol in the days following a match or high intensity training session to determine readiness to train when the risk-benefit ratio is so high.

Vertical jump analysis has become a commonly practiced tool by many high performance sporting practitioners in order to monitor neuromuscular fatigue (NMF) and its resultant recovery timeline in elite athletes (Taylor *et al*, 2012). Particularly in soccer, vertical jump analysis has become increasingly used to detect if athletes have fully recovered or are only partially recovered from an intensified bout of training or match play. Since the neuromuscular qualities of muscle are similar during running and vertical jumping (Wisloff *et al*, 2004**;** Maulder *et al*, 2006), monitoring vertical jump performance has been suggested to be relevant in sports in which running is involved quite considerably (Cormack *et al*, 2008a). In soccer this suggestion is supported by the strong correlations existing between maximal strength during half squats, sprint performance and vertical jumping height (Wisloff *et al*, 2004**;** Maulder *et al*, 2006). These correlations would be expected since vertical jump height and sprinting performance are both derivatives of maximal force production (F=ma) and rate of force development (P=W/t), and both are extremely important for soccer performance success (Wisloff *et al*, 2004).

In a recent review by Nedelec (2012) and his co-workers they present evidence that immediately after a soccer match the decrement in vertical jump performance can be up to 12% (Nedelec *et al*, 2012) and vertical jump performance can take 48 hours (Fatourous *et al*, 2010; Ispirlidis *et al*, 2008) to more than 72 hours (Magalhaes *et al*, 2010; Andersson *et al*, 2008) to recover. These observations are not unique to soccer and elite Australian footballers show depressed vertical jump capabilities up to 72 hours post match (Cormack *et al*, 2008b) and can exhibit long periods of NMF during the competitive season (games 11-15 of 22; Cormack *et al*, 2008b).

The suggested mechanism for these observations is that a high number of stretch shortening cycles (SSC) accumulated in these sports (due to high intensity running and changes in direction that play a determinant role in the outcome of the sports) cause muscle damage. Significant correlations have been found between the number of short sprints during a match and muscle soreness reported 48 to 72 hours post match, and the number of hard changes of direction (COD) during a match was shown to correlate well with countermovement jump (CMJ) performance (Nedelec *et al*, 2014).

Vertical jump performance (Maulder *et al*, 2006) does seem appropriate to use as a simple testing tool to predict training status in soccer (Arnason *et al*, 2004). The tests are *relatively* quick and easy to administer, have a strong ability to test ballistic or anaerobic components of performance and provide an indirect measure of lower body power output (Hoffman *et al*, 2000).

This has led to practitioners investigating indices such as ground contact time (GCT) and reactive strength index (RSI), in addition to the more traditional indices of FT, H and power in relation to performance (Flanagan *et al*, 2008). When an athlete makes contact with the ground during ballistic or plyometric movements (e.g. jumping, sprinting) they experience both an eccentric and then concentric contraction. The time between these contractions is known as the amortization (transition) phase and is measured as the GCT. This phase is perhaps the most crucial in generating power in ballistic movement, as it must be kept to a minimum to realise the full potential of the SSC and stored elastic energy. RSI is a measure used to quantify SSC and plyometric performance and is defined as the ratio of height jumped to the time spent developing the force on the ground to reach that height (i.e. GCT). Young (1995) recently described RSI as a measure of 'explosiveness' as it provides insight into an individual's ability to change quickly from an eccentric to a concentric contraction (Young, 1995). For example, by monitoring GCT during an Australian football season, fatigue is known to prolong the amortization phase between pre-match and post-match testing. This suppression is the result of prolonged contraction times and therefore reduced neuromuscular capacity and has correlated strongly with a decrement in performance (Cormack *et al*, 2008b). Additionally, drop jump RSI was monitored in 16 athletes in response to 4 soccer games in 4 days using a rotational squad. In comparison of pre-match to post-match testing there was a significant difference observed for games 2, 3 and 4 in those who completed a full match although mean squad baseline was not reported different between games, perhaps due to the rotational effect and the need to individually monitor athletes instead of means (Hamilton, 2009). CMJ performance monitoring over the season has therefore been identified as best practice for detecting motor development, functional ability, motor capacity and ultimately NMF in elite athletes (Taylor *et al*, 2012). Several gold-standard methods are available to monitor CMJ performance and these include force plates, stereophotogrammetry (a 3D model construction based on recognisable points in different photographs, outlining the dynamic characteristics of structures/objects) and contact/photocell mats.

However, although these measures seem theoretically appropriate to determine status to train and are useful in helping to determine if training load is specific and tolerable (Flanagan *et al*, 2008), using them to determine status to train may be limited in a large team sport setting. As either a force plate or contact/photocell mat is required, there exist both practical and logistical limitations. The availability of a single force plate will only allow for individual screening, unless there is a large amount of time available each day, a scenario which is not often the case. Therefore this limits their use for large group settings e.g. team sports. Additionally, for logistical reasons as they are often unportable, and financially constraining, transporting them to other training venues or to international training camps is not possible. Consequently most teams simply employ contact or photocell mats since they have been proven valid in the field e.g. validity and reliablity of the JJCM (Leard *et al*, 2007; Nuzzo *et al*, 2011) and can be more easily transported. However, while these devices are less expensive than a force plate, the practical time constraints still exist due to limited units and staff availability to monitor athlete compliance with the jump protocols.

The recent addition of GPS and IMU devices for monitoring athlete's performance in training and competition within elite team sports may provide an alternative to contact or photocell mats (Aughey, 2011; Owen *et al*, 2011; Hodgson *et al*, 2014; Johnston *et al*, 2014). Each unit is manufacturer equipped with an in-built IMU, which contains a triaxial accelerometer, gyroscope and magnetometer to provide an output of athlete movement in a 3-dimensional plane. Demonstrating the validity, reliability and sensitivity of a GPS coupled IMU as a tool to test for training readiness via jump performance may allow a practical method of detecting changes in performance in large groups screening required for team sports. Although it could be argued that a GPS coupled IMU would reduce the time of the data collection phase, but in contrast substantially increase the time of the data analysis phase with a loss of immediate feedback on readiness to train, recent advancements in such technology would be expected to overcome these limitations. GPS systems now come equipped with an ability for live tracking, in order that coaching staff can receive immediate pitch-side feedback and alter loads and training prescription as required. Furthermore, the ability for longitduinal data capturing and monitoring is attractive, alongside an on-screen integration with other relevant metrics that are being monitored. The complexity of the data may also allow for a much more in depth analysis of the performance e.g. force outputs, power ouputs and accelerations as opposed to simply a H or FT measurement as would be given by a contact/photocell mat. Finally, the value of player time is much higher than the value of staff time therefore data collection should be extremely quick, even if the data anlysis phase is a little longer.

Several research studies have investigated the validity and reliability of different microelectromechanical systems (MEMS), to obtain different kinematic variables whilst positioned at different parts of the body and much of the research has been centered around clinical biomechanical application (Hopper *et al*, 2002; Coventry *et al*, 2006). Only a few studies have investigated the use of these devices to specifically measure vertical jump performance in a sports setting but even then there appears to be several limitations in the investigative protocols. Two bi-axial accelerometers fixed at each subject's ankle were used in one study to obtain FT in comparison to force plate measurements (Quagliarella *et al*, 2010). Although there was a high correlation there is still a lack of information into the reliability and validity of these kinematic sensors and further research is therefore required before practical application can become the norm. For example, as the accelerometer used in this case was bi-axial it excludes information of movement in one of the planes of motion (i.e. tri-axial monitors roll, pitch & yaw). Similarly, they do not incorporate the use of other MEM's designed to monitor the kinetics and kinematics of human movement, which could be useful in providing additional biomechanical information.

Furthermore, another study employed mono-axial accelerometers attached to a Smith machine bar (Sleivert *et al*, 2004) but this data may not provide the most accurate representation of the bodies' centre of motion since the athlete may be subject to additional movement beyond the vertical plane (although an upper body bar harness was worn in the attempt to minimise this effect). The use of a triaxial accelerometer at the hip joint has also been investigated (Casartelli *et al*, 2010). Although these studies have been published in the literature, again none of them combined the use of other MEM's designed to monitor human movement. For example, gyroscopes can be integrated with the accelerometer data and make it more meaningful by demonstrating that it is recorded in the correct plane of motion.

Only two published studies exist at present to the author's knowledge investigating the use of commercially available 3D wearable IMU units containing triaxial accelerometers and gyroscopes. In the first, the researchers investigated the validity and reliability in contrast to stereophotogrammetric data (Picerno *et al*, 2011) whereas in the second the researchers investigated the validity and reliability of the Keimove system to data of a high-speed camera and a force-platform synchronised with a linear position transducer (Requena *et al*, 2012). The data collected by Requena (2012) and his co-workers revealed that the Keimove system provides a valid and reliable means of monitoring FT and take off-velocity and thus providing some hope for an ecological means of multiple screening of athletes. Similarly, the data from Picerno and his co-workers (2011) when corrected for trunk rotations provides an accurate estimation of vertical jump performance. Although there does exist a major shortcoming in that the protocol utilised derived an equation based on a fairly small sample size to be applied to all individuals who use this system, which may not be applicable to other groups of individuals.

In line with these investigations, there does not exist in the literature any investigative research into the validity, reliability and sensitivity of a GPS coupled IMU with respect to a gold-standard criterion method. The Catapult GPS tracking unit is a wearable athlete monitoring technology (Catapult Innovations, Canberra, ACT, Australia), which provides data relating to fitness, tactical & technical and rehabilitative movement. Each unit monitors 3-dimensional movement of athletes and can recognise specific movement patterns via integration of data from the in-built IMU. The IMU contains a 3D accelerometer with a sampling frequency of 100Hz for measuring impact, body loading, reaction times, and a 3D gyroscope with a sampling frequency of 100Hz and a resolution of up to 1200 degrees per second for biomechanics analysis (roll, pitch, yaw, turn rate).

Although the previously discussed mechanisms currently employed for athlete monitoring (i.e. heart rate measures, subjective & psychometric questionnaires, hormonal & biochemical analysis & neuromuscular markers), may provide insight at their own level to the bigger picture of training status, there are inadequacies and impracticalities that exist with these methods, as discussed. It is therefore essential that we continue to develop new and appropriate methods to monitor training status in football and other team sports. It is for this reason that we sought to investigate the validity, reliability & sensitivity of a GPS IMU to monitor training readiness in soccer.

The aims of this manuscript were to determine if the Catapult IMU system could show appropriate validity in a) deriving jump power through the use of simple calculations and b) determining FT derived measures of vertical jump performance. The investigations then aim to address issues of reliability, sensitivity and practicality in professional team sports. The JJCM was taken as a gold-standard reference instrument.

We hypothesise that IMU derived jump power measures would be an invalid method of monitoring vertical jump performance due to trunk rotation involvement and the positioning of the unit. In contrast, we hypothesise that IMU derived FT measures would provide a valid metric of performance in comparison to the JJCM.

Chapter 3:

Validity of Inertial Sensors

3.1 Participants

In this study, there were 23 youth professional soccer players recruited. All participants were in good physical and mental health and were not deemed as vulnerable. The participants all had a previous soccer-specific training history of more than 5 years and were currently nearing the end of the domestic season. The body mass, height and age (mean $\pm$ SD) for the participants were 72.83 $\pm$ 11.62 kg, 178.20 $\pm$ 6.55 cm, 18.78 $\pm$ 2.02 years, respectively. The body mass of the participants was measured on seca 867 heavy-duty digital mobile floor scales. The height of the participants was measured using a mounted scale. The College of Medical, Veterinary & Life Sciences ethics committee for non-clinical research involving human subjects at the University of Glasgow provided ethical approval for this study. Prior written consent was obtained from all participating individuals.

3.2 Methods

3.2.1 Just Jump Contact Mat

Gold-standard reference criteria were met through the use of a JJCM (Probotics Inc, Huntsville, Alabama, USA). The data was displayed on the incorporated handheld computer and recorded for analysis by the investigator.

3.2.2 Catapult GPS

A wireless, Catapult MinimaxX 10Hz S4 GPS tracking device (MinimaxX, Catapult Innovations, Canberra, ACT, Australia), which houses a 3D IMU was placed on the trunk at the level of T2-3 using a manufacturer issued harness in order that the Y axis of the IMU lay along the horizontal plane. The in house IMU contains a 3D accelerometer with a sampling frequency of 100Hz for measuring impact, body loading, reaction times, and a 3D gyroscope with a sampling frequency of 100Hz and a resolution of up to 1200 degrees per second for biomechanics analysis (roll, pitch, yaw, turn rate). Data was downloaded to the manufacturers software (Sprint 5.1.1 - MinimaxX, Catapult Innovations, Canberra, ACT, Australia) operated on an HP 620 laptop (Hewlett Packard, Palo Alto, California, USA).

3.2.3 Testing Procedure

The gold standard criterion reference was taken as a JJCM (Probotics Inc, Huntsville, Alabama, USA), as it is already widely accepted in the elite sporting environment as being a proven valid (Leard, 2007) and reliable (Nuzzo, 2011) tool for estimating vertical jump performance. IMU based determinations of FT and thus estimated H were taken for comparison as described below.

In this study, participants underwent a 5-10 minute standard warm-up involving jogging locomotion at an exercise intensity eliciting 40-60% of maximum HR. The participant was then required to perform in total 9 jumps on the JJCM whilst wearing a Catapult MinimaxX 10Hz S4 GPS device placed on the trunk at the level of T2-3 using a manufacturer issued harness. The Catapult GPS tracking device was located between the participant's scapulae at the level of T2-3 in order to ensure that measurements represent those best recorded in the field. The 9 jumps were divided into three bouts. All jumps were performed with the hands positioned on the pelvis and the trunk upright. The hands were placed upon the pelvis to maximally relate to the power output of the lower limbs alone. When the arms are utilised in a swinging motion, they can in part assist in elevating the centre of mass via the transfer of momentum, increasing jump height, increasing maximum force and altering the biomechanics of the jump (Akl, 2013).

Firstly, the participant performed 3 CMJ^{SSD}. The counter-movement jump was performed from a standing position with the knee extended at 180^0 and with the plantar surface of the foot contacting the ground. The participant was informed to flex the knees down to a self-selected depth and then perform a maximal vertical thrust. After the jump, the knees were kept extended at 180^0 and contact with the JJCM started with the toes.

Secondly, the participant performed 3 CMJ^{PDD}. Again, the counter-movement jump was performed from a standing position with the knee extended at 180^0 and with the plantar surface of the foot contacting the ground. The participant was informed to flex the knees down to an angle of 90^0 and then perform a maximal vertical thrust. For each jump the angle of 90^0 was determined by the investigator and the jump was repeated in the case that this angle was not met. After the jump, the knees were kept extended at 180^0 and contact with the JJCM started with the toes.

Thirdly, the participant finally performed 3 SJ. During the SJ the participant did not perform a counter-movement motion and so the knees were initially flexed to a depressed angle of 90^0 with the plantar surface of the foot contacting the ground. The participant again performed a maximal vertical thrust. After the jump, the knees were kept extended at 180^0 and contact with the JJCM started with the toes.

For CMJ^{SSD}, CMJ^{PDD} and SJ, three attempts were allowed with at least 90 seconds of recovery between each attempt, and three minutes between each bout of jumps. The best jump in terms of FT was used for analysis. All participants were familiar with the jump techniques and so no familiarization sessions were deemed necessary. All jumps were administered by the same investigator. To test validity, the data obtained from the JJCM and the Catapult MinimaxX 10Hz S4 GPS device were compared. All subjects were asked to refrain from strenuous physical activity and alcohol consumption for the 24-48 hours preceding each trial.

3.2.4 Calculations

Power Calculations

In accordance with Newton's second law of motion, 'net force = mass x acceleration' and Newton's third law of motion, 'for every action there is an equal and opposite reaction', we sought to firstly compare the derived JJCM power ($power^{JJCM}$) to the IMU derived power at landing (like-for-like; $power^{Land}$) and secondly, $power^{JJCM}$ to the IMU derived power at take off ($power^{TOff}$).

To calculate $power^{JJCM}$ the following equation was applied, whereby 'm' denotes body mass, g denotes the acceleration due to gravity ($g=9.81ms^{-2}$), 'H^{JJCM}' height jumped and 'FT^{JJCM}' flight time from the JJCM:

$$Power^{JJCM} = \frac{(mxg)xH^{JJCM}}{½\ FT^{JJCM}}$$

To calculate $power^{Land}$ the following equation was applied, whereby 'm' denotes body mass, 'Acc^{Land}' denotes the peak acceleration recorded at landing, 'FT^{P-T}' flight time from peak-trough and 'H' height jumped derived from 'FT^{P-T}' (see appendix 1 for FT^{P-T} measurements)

$$Power^{Land} = \frac{(mxAcc^{Land})xH}{½\ FT^{P-T}}$$

To calculate $power^{TOff}$ the following equation was applied, whereby 'm' denotes body mass, 'Acc^{PToff}' denotes the peak acceleration recorded at takeoff, 'FT^{P-T}' flight time from peak-trough and 'H' height jumped derived from 'FT^{P-T}' (see appendix 1 for FT^{P-T} measurements)

$$\text{Power}^{\text{TOff}} = \frac{(m \times Acc^{\text{PToff}}) \times H}{\frac{1}{2}\, FT^{\text{P-T}}}$$

The FT of the IMU was recorded manually from the data files displayed on the Catapult Sprint 5.1.1 software. FT^{P-P} denotes the calculation of flight time from peak-peak (see Appendix 1 for explanation). However, although this may be the case for ease of a potential software detection strategy of peak to peak, the toes touch the ground again at the 'trough' hence why the IMU would begin to register an acceleration in the vertical plane at this point (see Appendix 1 for explanation). To this end, our measurement FT^{P-T} is based upon these observations and thus calculates the flight time from peak-trough i.e. from the moment the body leaves the ground and begins to decelerate until the point that it retouches the ground and experiences an acceleration in the vertical plane. FT^{P-T} is utilised for power-based measurements for this sake.

Flight Time Derived Calculations

IMU derived heights based on FT^{P-P} and FT^{P-T} were calculated via the application of the following equation, whereby 'g' denotes the acceleration due to gravity ($g=9.81ms^{-2}$), 'FT' flight time, respectively and 'gFT/2', velocity at take-off:

$$\text{Height} = \frac{(gFT/2)^2}{2g}$$

JJCM displayed recordings of flight time (FT^{JJCM}) and height (H^{JJCM}) were taken for gold-standard reference, as previously stated. Gyroscope orientation was recorded manually from the data files and is presented as $\text{gyroscope}^{\text{Pitch}}$ (ds^{-2}).

3.2.5 Statistical Analyses

$Power^{JJCM}$ was investigated against IMU derived $power^{Land}$ and $power^{TOff}$, FT^{JJCM} with IMU derived $FT^{P\text{-}P}$ and $FT^{P\text{-}T}$ as well as $height^{JJCM}$ and IMU height, based on $FT^{P\text{-}P}$ and $FT^{P\text{-}T}$. Normality of data was tested via the Shapiro-Wilk test. Whenever both IMU and mat presented normal data distribution a paired-sample t-test was conduced and in the event that either the JJCM or IMU data presented a data set that was not normally distributed, a non-parametric paired-sample sign test was conducted. As physical status, age and weight were the same for both instruments and testing was conducted at the same time, these procedures were deemed appropriate to account for the relationship between the variables. Simple bivariate correlations are also reported where appropriate to determine whether changes in the two measurement methods occured in a synchronous manner.

Bland and Altman plots were also constructed to explore the agreement between methods and the mean bias and limits of agreement (upper and lower).

Data are presented as mean $\pm$ SD unless otherwise stated. Statistical significance was set at level $p<0.05$. All statistical procedures were conducted using Origin Pro. 9.1. 32-bit software (OriginLab Corporation, MA, USA).

The expected difference between means observed for jump performance, and their SD, was such that 10 players provided power at 0.95 to detect a difference at the 5% level. Reducing power to the standard 0.80 level would require only 6 participants and therefore the study is adequately powered to demonstrate differences in the testing procedures.

3.3 Results

Power Derived Results

$Power^{JJCM}$ (W) was shown to be significantly different from derived IMU $Power^{Land}$ (W), for CMJ^{SSD} (1123.15 $\pm$ 150.28 vs. 677.19 $\pm$ 218.57, $p<0.001$, R=0.415), CMJ^{PDD} (1101.06 $\pm$ 153.41 vs. 619.00 $\pm$ 238.39, $p<0.001$, R=0.484), and SJ (1082.49 $\pm$ 150.58 vs. 656.89 $\pm$ 203.26, $p<0.001$, R=0.291), respectively (Fig 1).

Similarly, the $Power^{JJCM}$ (W) was also significantly different from derived IMU $Power^{TOff}$ (W), for CMJ^{SSD} (1123.15 $\pm$ 150.28 vs. 63.11 $\pm$ 51.33, $p<0.001$, R=0.113), CMJ^{PDD} (1101.06 $\pm$ 153.41 vs. 54.79 $\pm$ 39.15, $p<0.001$, R=-0.112) and SJ (1082.49 $\pm$ 150.58 vs. 90.08 $\pm$ 62.95, $p<0.001$, R=0.222), respectively (Fig 2).

Acc^{PToff} (ms^{-2}) had a strong correlation with $gyroscope^{Pitch}$ (ds^{-2}) for CMJ^{SSD} (r=0.91), CMJ^{PDD} (r=0.94) and SJ (r=0.91), respectively, however $gyroscope^{Pitch}$ (ds^{-2}) had a poor correlation with $Power^{TOff}$ (W) for CMJ^{SSD} (r=-0.35), CMJ^{PDD} (r=-0.29) and SJ (r=0.10), respectively.

Acc^{Land} (ms^{-2}) also had a strong correlation with $gyroscope^{Pitch}$ (ds^{-2}) for CMJ^{SSD} (r=0.89), CMJ^{PDD} (r=0.92) and SJ (r=0.89), respectively, however $gyroscope^{Pitch}$ (ds^{-2}) had a poor correlation with $Power^{Land}$ (W) for CMJ^{SSD} (r=0.36), CMJ^{PDD} (r=-0.10) and SJ (r=-0.23), respectively.

Figure 1. Bland-Altman plots (n=23) of Power^{JJCM} versus IMU Power^{Land} for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM power (W). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

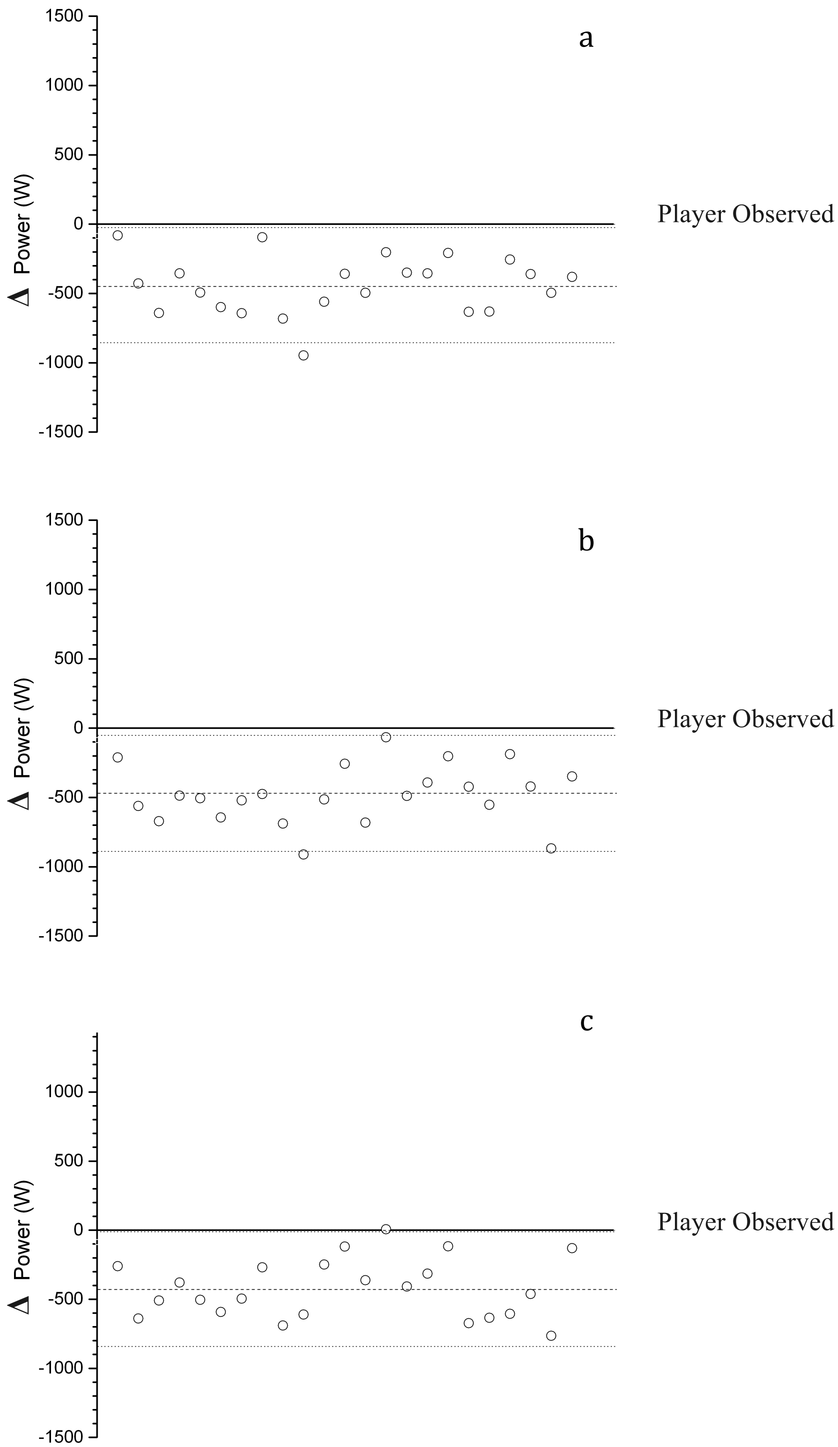
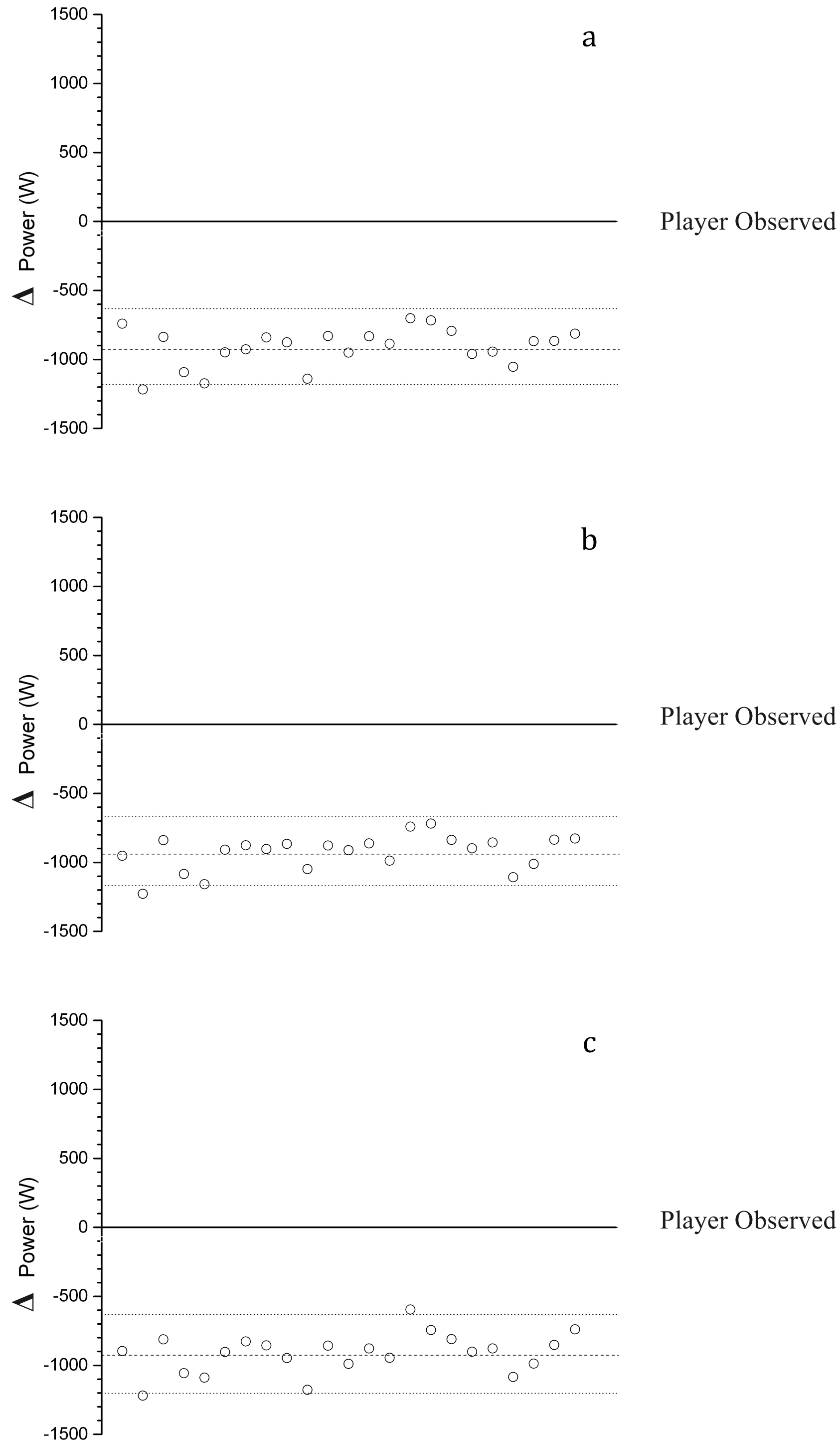


Figure 2. Bland-Altman plots (n=23) of Power^{JJCM} versus IMU Power^{TOff} for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM power (W). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.



Flight Time Derived Results

FT^{JJCM} (s) was significantly different from derived IMU FT^{P-P} (s), for CMJ^{SSD} (0.633 ± 0.044 vs. 0.683 ± 0.041, p<0.001, R=0.902), CMJ^{PDD} (0.621 ± 0.048 vs. 0.666 ± 0.044, p<0.001, R=0.869), and SJ (0.610 ± 0.052 vs. 0.661 ± 0.043, p<0.001, R=0.890), respectively (Fig 3).

FT^{JJCM} (s) was not significantly different from derived IMU FT^{P-T} (s), for CMJ^{SSD} (0.634 ± 0.046 vs. 0.636 ± 0.042, *p*>0.05, R=0.918), CMJ^{PDD} (0.625 ± 0.045 vs. 0.624 ± 0.043, *p*>0.05, R=0.947) and SJ (0.616 ± 0.049 vs. 0.612 ± 0.004, *p*>0.05, R=0.931), respectively (Fig 4).

$Height^{JJCM}$ (cm) was significantly different from derived IMU height based on FT^{P-P} (cm), for CMJ^{SSD} (50.12 ± 7.13 vs. 57.38 ± 6.96, p<0.001, R=0.907), CMJ^{PDD} (48.15 ± 7.46 vs. 54.56 ± 7.18, p<0.001, R=0.869) and SJ (46.37 ± 7.82 vs. 53.73 ± 7.01, p<0.001, R=0.883), respectively (Fig 5).

$Height^{JJCM}$ (cm) was not significantly different from derived IMU height based on FT^{P-T} (cm), for CMJ^{SSD} (50.40 ± 7.39 vs. 49.86 ± 6.71, *p*>0.05, R=0.920), CMJ^{PDD} (48.60 ± 7.18 vs. 47.93 ± 6.73, *p*>0.05, R=0.953) and SJ (47.16 ± 7.63 vs. 46.14 ± 7.31, *p*>0.05, R=0.931), respectively (Fig 6).

Figure 3. Bland-Altman plots (n=23) of FT^{JJCM} versus IMU $FT^{P\text{-}P}$ for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM flight time (s). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

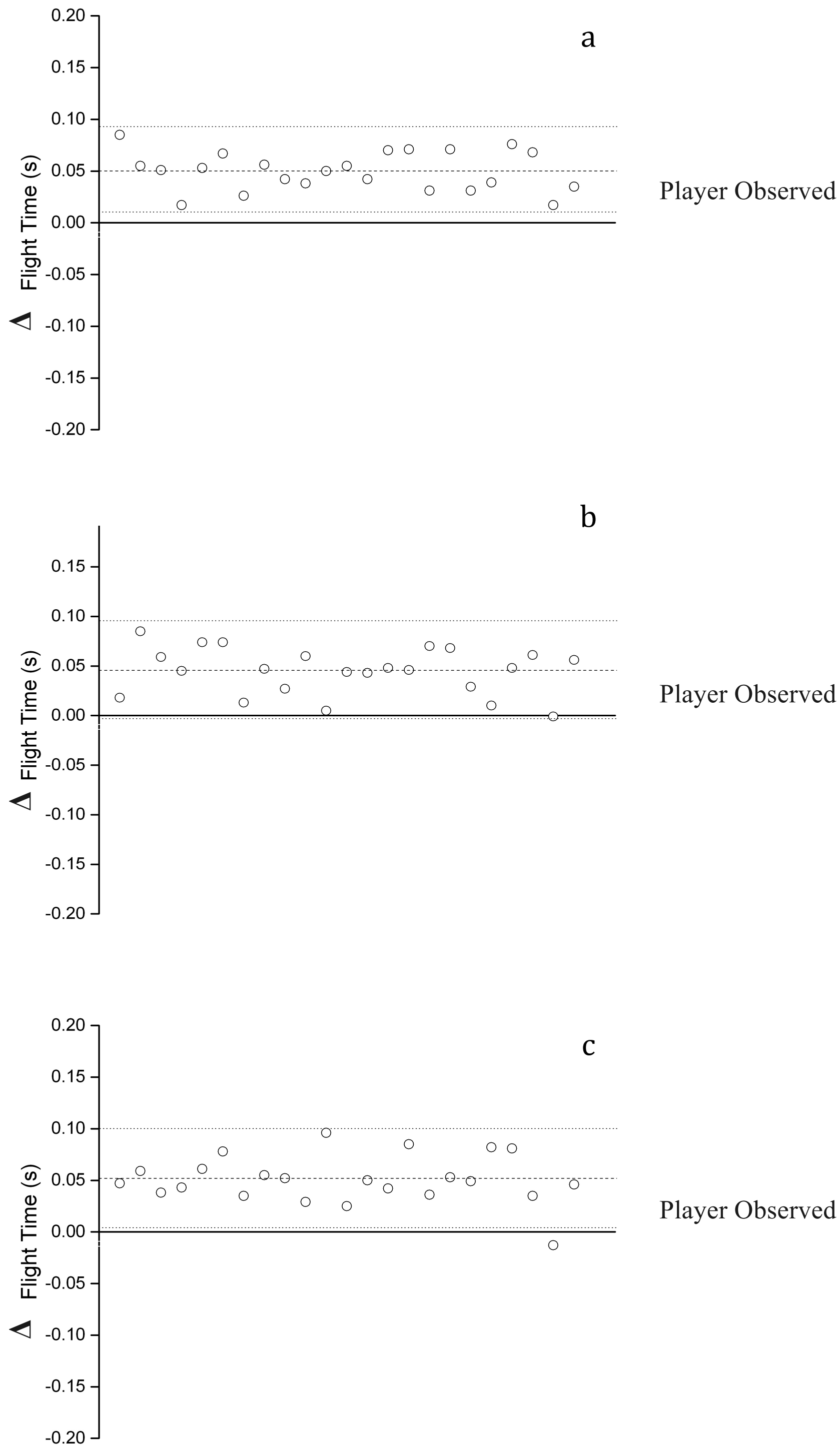


Figure 4. Bland-Altman plots (n=23) of FT^{JJCM} versus IMU FT^{P-T} for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM flight time (s). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

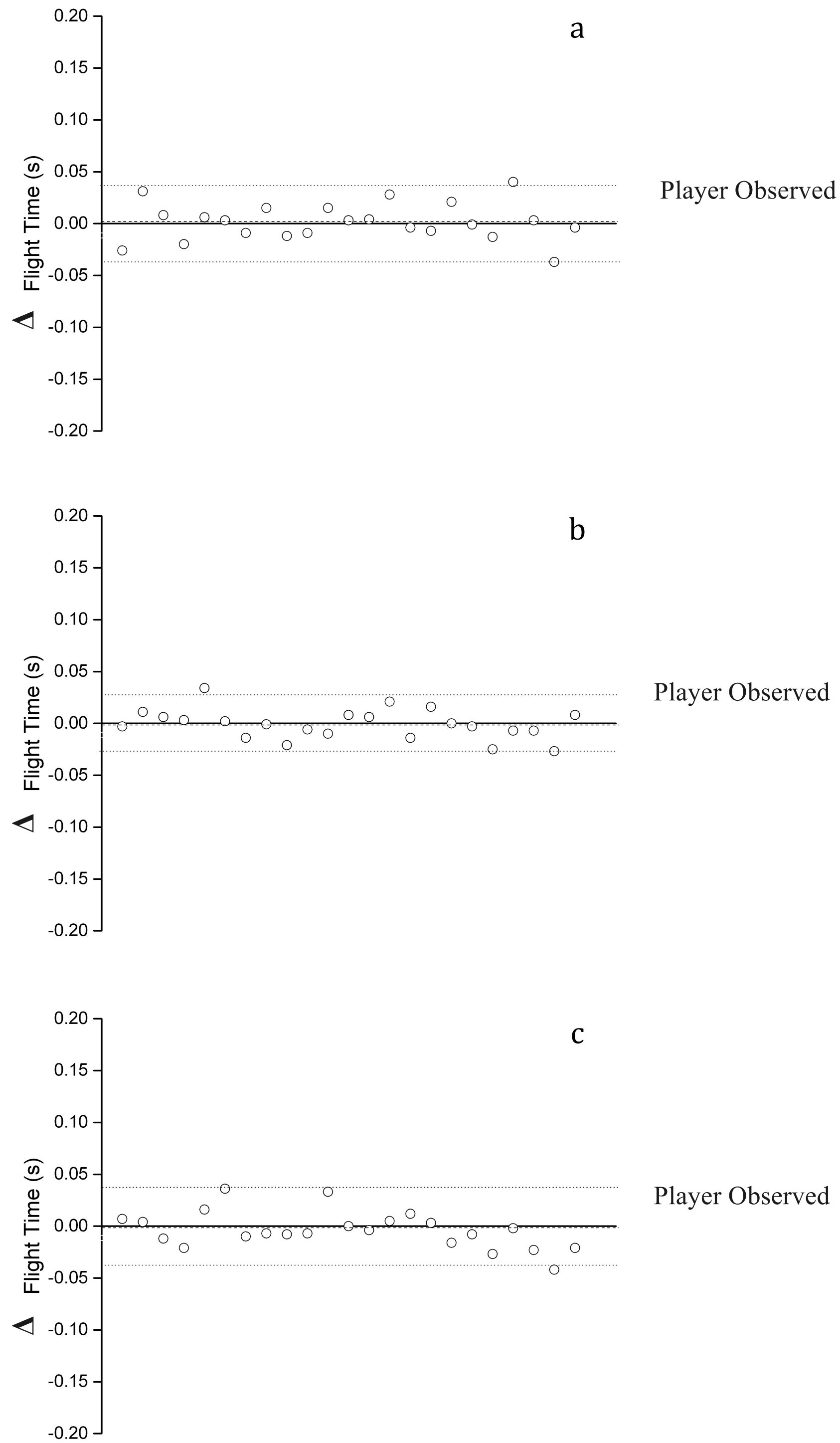


Figure 5. Bland-Altman plots (n=23) of H^{JJCM} versus IMU derived height (based on FT^{P-P}) for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM height (cm). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.

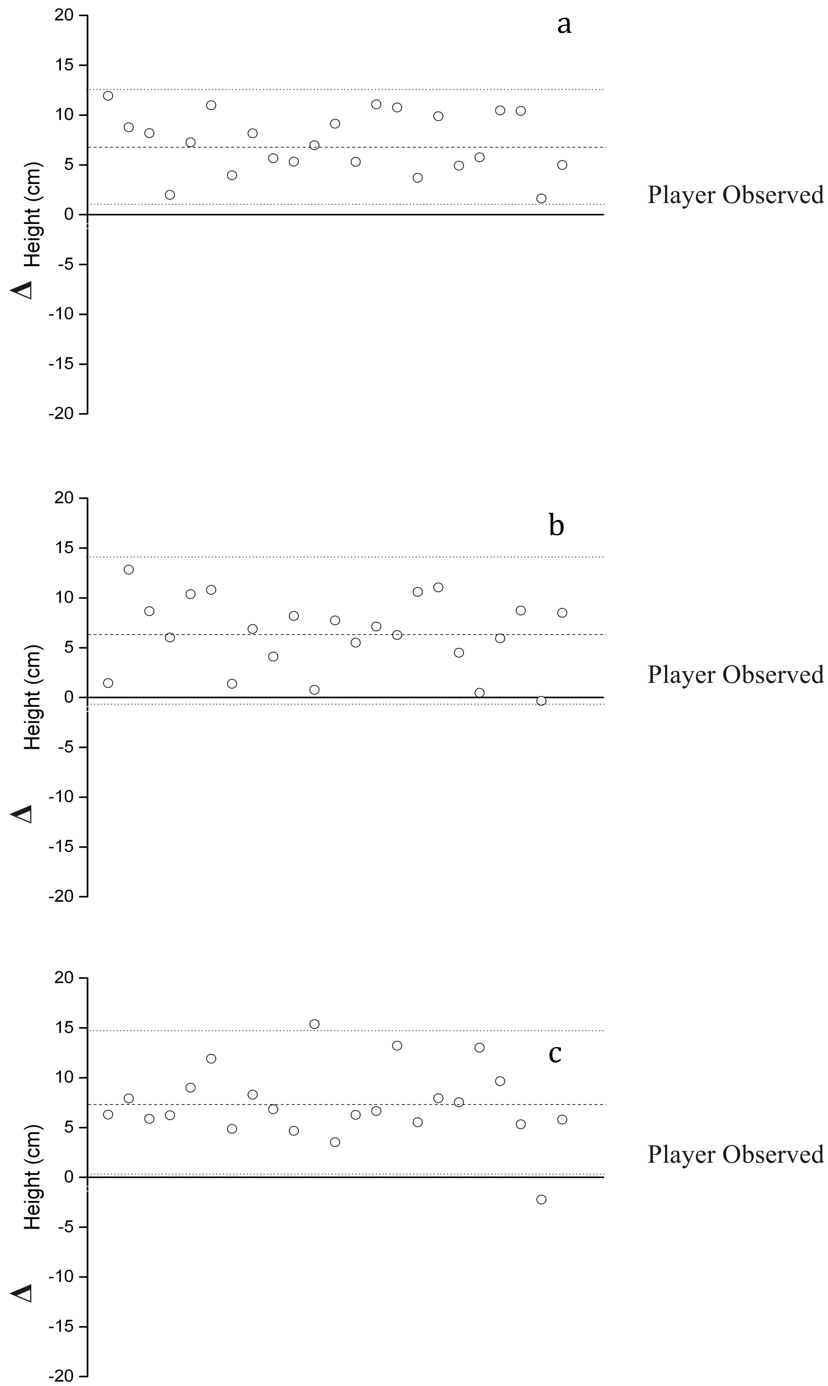
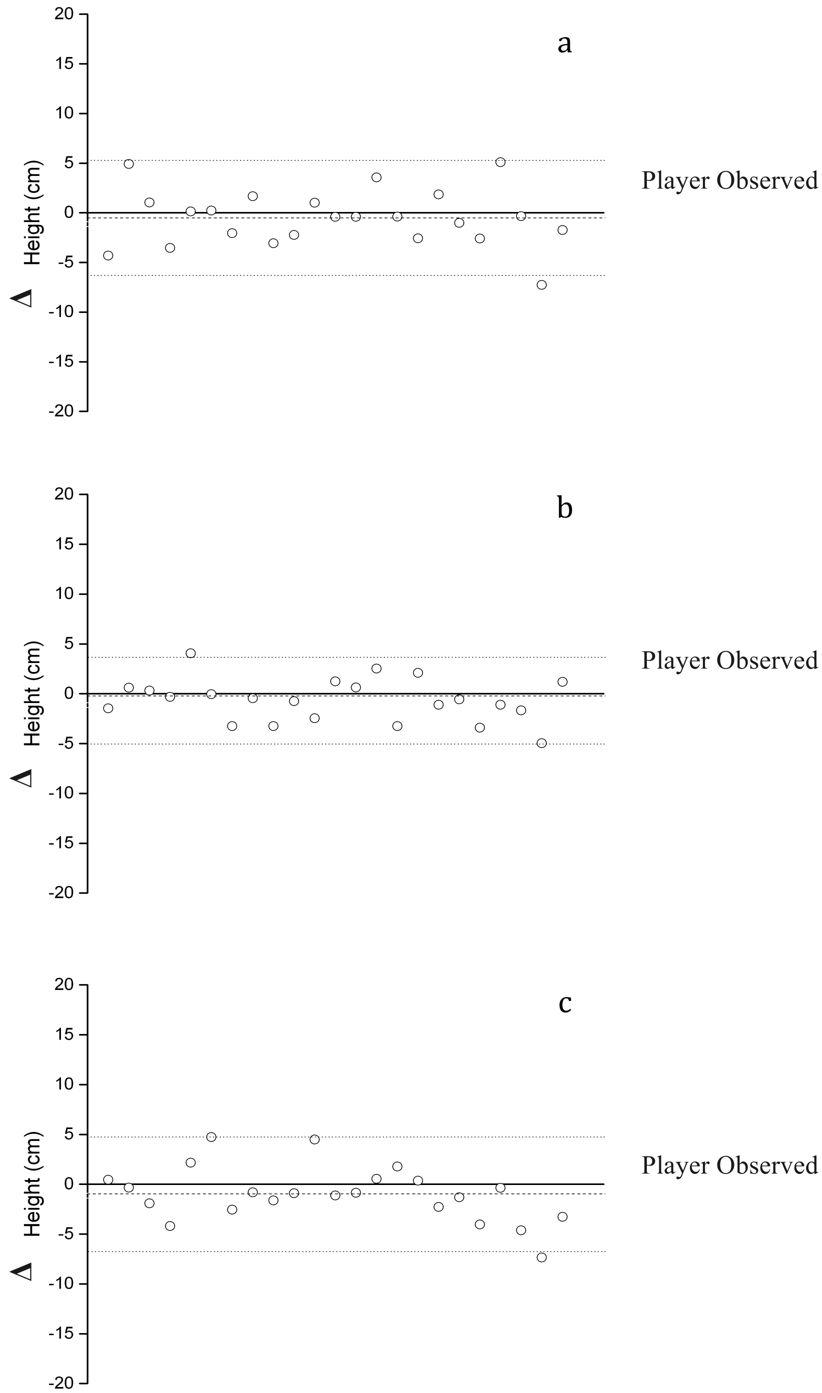


Figure 6. Bland-Altman plots (n=23) of H^{JJCM} versus IMU derived height (based on FT^{P-T}) for a) CMJ^{SSD} b) CMJ^{PDD} and c) SJ. X-axis represents players observed. Y-axis represents bias observed between IMU & JJCM height (cm). Mean bias (dashed line) and upper & lower limits of agreement (dotted lines) are also displayed. Positive difference signifies IMU measure is greater.



3.4 Discussion

From these data it is evident that power measures from the IMU both at take-off and landing exhibit poor validity. In both cases the IMU showed an underestimation of the power measures in comparison to the JJCM (Fig. 1 & 2), as well as poor correlation with the gyroscope data. Our hypothesis that the degree of trunk rotation would impact upon the acceleration recorded in the vertical plane was supported by strong associations between $gyroscope^{Pitch}$ and Acc^{PToff} and Acc^{Land}, respectively and thus provided good theoretical basis to investigate the association further. As one other group studying a similar IMU setup successfully removed trunk rotation with regards to movement about the lateral axis i.e. pitch (Picerno *et al*, 2011), we thought that this may be a likely possibility for further investigation. However, our data did not support such data manipulations and it would unlikely be a time efficient and ecological process in the field in the event that it was possible. This would be in relation to a short turnaround time and quick feedback unless an automated process could be employed for analysis. Although the Acc^{PToff} and Acc^{Land} both had strong correlations with $gyroscope^{Pitch}$, this would be expected as the more upright the body in motion at take off, the greater the degree of acceleration registered in the vertical plane and thus the vertical recordings of the triaxial accelerometer. As mentioned however, the gyroscope data did not correlate well with the power outputs of the respective jumps, as poor correlations were observed between these variables, and thus it would be inaccurate to attempt to remove the trunk rotation to account for lower peak accelerations in the vertical plane and thus lower power outputs. The gyroscope data did not appear to be reproducible and thus a conversion factor would be unreliable.

As our investigations into power derived measures as well as the utilisation of the acceleration and gyroscope data had not provided us with a valid means to monitor vertical jump performance, we resorted to investigating whether the IMU could be utilised in a similar fashion to the JJCM, by determining flight time and height.

Contact and photocell mats implement a simple process of detecting flight time i.e. the time period between the subject leaving the mat and then subsequently making contact with the mat again. Although flight time may perhaps not be the best method for determining jump height as the centre of mass (COM) can change with the biomechanical profile of the jump technique e.g. bending the knees mid-flight will extend the flight time and thus provide an erroneous measure of vertical jump performance, whenever the jump technique is executed correctly there is evidence that contact mat systems can provide accurate details about jump performance (Leard *et al*, 2007, Nuzzo *et al*, 2011). Contact and photocell mats are inexpensive, mobile and anecdotally, have widespread employment in individual and team sports alike. The mass screening ability of these devices is however clearly low, as only one athlete can jump per unit time unless there are multiple units available. As mentioned previously, most athletes in team sports now wear a GPS unit, so that sporting practitioners can quantify the micromechanical movements of their athletes during training. If these devices could be utilised in a similar way to a contact mat to also quantify vertical jump performance it may provide great insight into the athlete's ability to perform ballistic activity during a particular training session. As a result of this the manufacturer has developed an algorithm, which seeks to determine the flight time and jump height of the athlete during any jump pattern. However, our observations of attempting to implement this algorithm as part of our validity investigations, especially as a potential advantage in relation to the temporal factors of data handling, revealed to us that it is unreliable. In attempting to gather enough data to analyse its reliability we realised that the algorithm did not always detect a jump sequence. Anecdotal evidence from other groups (unpublished data), have suggested that this algorithm overestimates the flight time and jump height in comparison to a force plate, although we cannot provide support for this as there was insufficient data for analysis based off of the algorithm. In our investigations, independent of the jump style utilised e.g. CMJ^{SSD} vs. CMJ^{PDD} vs. SJ, when using FT^{P-P} to determine jump performance there is an approximate 0.05s (Fig. 3) or 7cm (Fig. 5) mean bias towards overestimation. This overestimation however, would be expected due to the nature of this measurement i.e. this measure overestimates the flight time as a result of not quantifying the landing period correctly. From appendix 1, we would suggest that the conclusion of the jump comes about at the point of the 'true landing' i.e. the trough, as opposed to the 'proposed landing' i.e. the peak, concluding the end of the flight phase and thus signalling re-contact with the surface of which the athlete jumped from. Our data provide support for this argument as the mean difference is not as extreme, lies very close to the 0s (Fig. 4) and 0cm (Fig. 6) lines and statistical procedures did not show any significant difference between both IMU and JJCM data sets based on FT^{P-T}, independent of jump style. As a result we did not attempt to correct for the systematic bias of FT^{P-P} and H^{P-P} as FT^{P-T} and H^{P-T} exhibited sufficient validity, measures, which are more biomechanically sound.

In support of this, whenever a given jump profile is analysed on a force plate the typical procedure is to take the flight time as being the moment that there is no longer any force being exerted on the platform to the moment that the force on the platform is reinitiated. In a similar sense with regards to the IMU data it is theoretical to record the point of contact with the ground as the moment in which the acceleration initiates in the vertical direction as opposed to at the point of peak plyometric acceleration as measured by the IMU. The reason for this is that the peak acceleration measured by the IMU is not the point at which the body reinitiates contact with the ground, mainly due the unit location, as contact will occur shortly beforehand (at the trough of the peak). As the unit is often worn at the scapulae, as per our investigations, there would exist a short time latency before the onset of the peak plyometric signal at landing, primarily due to transference of the force through the kinetic chain to the device, thus extending the FT^{P-P} of the subject in motion. Anecdotal unpublished data from the group mentioned previously suggest that less overestimation is observed at a lower body position i.e. one imitating the COM, which would coincide with our argument as the deamplified signal has less distance to travel (unpublished data). By placing the device at the scapulae we are basically trying to measure flight time from a position that has not yet been observed nor supported in the literature previously. However, by determining the true point of reengagement with the ground as per FT^{P-T} we would have better biomechanical rationale and better support with regards to validity. Although, our measurement of FT^{P-P} was mainly concerned with trying to determine a time efficient means of monitoring vertical jump performance via a potential automated analytical algorithm, manually measuring FT^{P-T} for ~10-20 athletes per day is time labouring and may perhaps not be any quicker than measuring athletes on a JJCM or force plate. Although the actual measurement time is less with regards to mass screening ability, the data handling time becomes much greater and must be considered both in the development of any potential automated process and also by the practitioner themselves.

There is a possible limitation that must be recognised in this investigation. As all participants were active athletes and familiar with the jump techniques as part of their routine training programs we deemed that no familiarization sessions were necessary before the study period commenced. Although lack of familiarization to the specific study protocol at the time was not believed to have been a possible drawback as a result of this, it is acknowledged that an argument could be made against this statement and thus this limitation should be addressed in future research.

3.5 Conclusion

To this end, our data suggest that the use of Catapult accelerometer power-derived measures are not a valid indicator for vertical jump performance. On the contrary, jump height as well as flight time appears to provide a more accurate and valid measure of vertical jump performance, when employing the techniques put forth in this chapter. It should be noted however, that when utilizing FT^{P-P} to determine flight time, although it may overestimate the height jumped, for measuring change in performance, provided the data is reliable, reproducible and sensitive to change then we would also provide support for its in-field utilisation particularly with regards to the temporal factors of data handling, should a valid and reliable automated process be developed. Taking these observations into consideration there is potential for the IMU to be utilised to provide a time efficient means of determining status to train in team sports.

In lieu of this, the next chapter will discuss the reliability of such measures. This will allow us to satisfy the arguments put forth in the literature that any measure should be quantified based upon the usefulness of the information to the athlete, the marker's reliable power i.e. reproducibility with regards to systematic variance in the measure as well as the practical and logistical constraints required for the measurement (Buchheit, 2014a).

Chapter 4:

Reliability of Inertial Sensors

4.1 Participants

In this study there were 12 youth soccer players recruited, of which 11 met the requirements for analytical procedures. All participants were in good physical and mental health and were not deemed as vulnerable. The participants all had a previous soccer-specific training history of more than 5 years and were currently beginning the 2014-2015 domestic season. The body mass, height and age (mean $\pm$ SD) for the participants were 73.18 $\pm$ 8.64 kg, 177.51 $\pm$ 6.56 cm, 19.73 $\pm$ 0.90 years, respectively. Subject characteristics were recorded and ethical approval granted as described in Chapter 3.

4.2 Methods

4.2.1 Catapult GPS

GPS unit was utilised as described in Chapter 3.

4.2.2 Testing Procedure

For reliability purposes each participant conducted $\geq$2 of 3 jump testing days using the protocol outlined below within 7 days. In the event that they did not meet this requirement they were subsequently excluded from analysis. During this period each of the participants were assigned their own GPS unit to remove the issue of inter-unit variability (Buchheit, 2014b). Each jump test was conducted at 7.30pm for standardization and was conducted on the following chronological days: Tuesday, Thursday and Tuesday. All subjects were asked to refrain from strenuous physical activity and alcohol consumption for the 24-48 hours preceding each trial.

During each monitoring session, participants underwent a 15-minute standard warm-up at a HR eliciting 40-60% of maximum HR, which included a dynamic stretching protocol. The participants were then required to perform in total 3 jumps whilst wearing a Catapult MinimaxX 10Hz S4 GPS device placed on the trunk at the level of T2-3 using a manufacturer issued harness. The Catapult GPS tracking device was located between the participant's scapulae at the level of T2-3 in order to ensure that measurements represented those best recorded in the field. Each participant performed a single CMJ^{SSD}, a single CMJ^{PDD} and a single SJ. All participants performed their jump protocol at the same time in order to mimic the proposed use for these investigations in the field and were asked to perform a maximal effort for each jump. All participants were familiar with the jump techniques and so no familiarization sessions were deemed necessary. All jumps were administered by the same investigator.

4.2.3 Calculations

As per our observations in chapter 3 we mainly sought to monitor FT^{P-P}, FT^{P-T} and the derived estimation of height jumped based upon these flight time measures, H^{P-P} and H^{P-T}, to ensure their reproducibility for longitudinal analysis in a team sport setting. FT^{P-P} and FT^{P-T} were measured manually (for explanation see appendix one). The estimation of height, H^{P-P} and H^{P-T}, was based upon the application of the following equation (as done so previously), whereby 'g' denotes the acceleration due to gravity ($g=9.81ms^{-2}$), 'FT' flight time, respectively and 'gFT/2' velocity at take-off:

$$\text{Height} = \frac{(gFT/2)^2}{2g}$$

4.2.4 Statistical Analyses

For each participant the CV was calculated for CMJ^{SSD}, CMJ^{PDD} and SJ across ≥ 2 testing days for both FT and H measures. The CV was taken as a measure of inter-day variation in vertical jump performance. All statistical procedures were conducted using Origin Pro. 9.1. 32-bit software (OriginLab Corporation, MA, USA).

4.3 Results

Flight Time Measures

To investigate the reproducibility for $FT^{P\text{-}P}$ and $FT^{P\text{-}T}$, the CV for each subject alongside the mean CV for all subjects are displayed in Table 2. The median flight time, mean flight time and SD are also displayed for each subject.

For $FT^{P\text{-}P}$, these investigations report a mean CV of 5.80%, 3.24% & 3.90% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively. The largest CV for $FT^{P\text{-}P}$ across all subjects was <8.55%, <6.33% and <14.86% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively (Table 2).

For $FT^{P\text{-}T}$, these investigations report a mean CV of 5.96%, 4.63% & 5.14% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively. The largest CV for $FT^{P\text{-}T}$ across all subjects was <13.72%, 8.10% and <20.25% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively (Table 2).

Height Measures

To investigate the reproducibility for $H^{P\text{-}P}$ and $H^{P\text{-}T}$, the CV for each subject alongside the mean CV for all subjects are displayed in Table 3. The median height, mean height and SD are also displayed for each subject.

For H^{P-P}, these investigations report a mean CV of 7.58%, 6.46% & 7.85% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively. The largest CV for H^{P-P} across all subjects was <16.62%, <12.61% and <30.52% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively (Table 3).

For H^{P-T}, these investigations report a mean CV of 11.81%, 9.18% & 10.27% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively. The largest CV for FT^{P-T} across all subjects was <27.19%, <15.85% and <40.60% for CMJ^{SSD}, CMJ^{PDD} and SJ, respectively (Table 3).

Table 2. Inter-day reliability for all subjects (n=11) for flight time (s) (≥ 2-3 days of testing).

SD: standard deviation.

CV%: coefficient of variation.

CMJ^{SSD}

	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	0.67	0.65	0.04	5.38%	0.60	0.58	0.03	6.01%
2	0.64	0.64	0.01	2.17%	0.59	0.59	0.02	2.84%
3	0.62	0.63	0.01	0.97%	0.59	0.57	0.04	6.27%
4	0.67	0.64	0.05	8.55%	0.61	0.59	0.06	10.05%
5	0.63	0.63	0.00	0.67%	0.56	0.56	0.01	1.50%
6	0.64	0.65	0.01	1.66%	0.58	0.59	0.02	2.90%
7	0.65	0.66	0.03	4.14%	0.60	0.59	0.03	5.64%
8	0.65	0.65	0.03	4.97%	0.60	0.60	0.04	5.86%
9	0.61	0.61	0.03	5.58%	0.52	0.52	0.07	13.72%
10	0.60	0.60	0.01	2.09%	0.52	0.54	0.03	6.23%
11	0.62	0.62	0.04	5.80%	0.54	0.54	0.02	4.55%
				5.80%				5.96%

CMJ^{PDD}

	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	0.67	0.65	0.04	5.58%	0.60	0.58	0.04	7.33%
2	0.65	0.65	0.01	1.00%	0.60	0.59	0.03	4.95%
3	0.61	0.60	0.03	4.17%	0.57	0.56	0.05	8.10%
4	0.66	0.66	0.04	6.33%	0.61	0.61	0.03	4.20%
5	0.63	0.63	0.01	1.36%	0.56	0.56	0.00	0.63%
6	0.66	0.67	0.03	4.18%	0.61	0.62	0.04	5.74%
7	0.64	0.65	0.02	2.94%	0.58	0.58	0.02	3.61%
8	0.65	0.65	0.01	1.52%	0.60	0.60	0.02	3.90%
9	0.64	0.64	0.01	1.43%	0.59	0.59	0.01	1.44%
10	0.61	0.60	0.02	4.05%	0.56	0.55	0.03	5.63%
11	0.65	0.65	0.02	3.14%	0.59	0.59	0.03	5.42%
				3.24%				4.63%

SJ

	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	0.53	0.58	0.09	14.86%	0.47	0.49	0.10	20.25%
2	0.63	0.64	0.02	2.71%	0.58	0.59	0.01	2.51%
3	0.62	0.61	0.01	1.61%	0.54	0.53	0.02	3.41%
4	0.66	0.63	0.04	6.81%	0.59	0.58	0.04	6.25%
5	0.62	0.62	0.01	2.28%	0.59	0.59	0.01	2.52%
6	0.63	0.63	0.01	0.98%	0.59	0.58	0.01	2.02%
7	0.54	0.54	0.01	2.57%	0.47	0.47	0.00	0.68%
8	0.61	0.61	0.02	2.55%	0.56	0.56	0.01	2.16%
9	0.61	0.61	0.03	4.49%	0.54	0.54	0.04	7.16%
10	0.62	0.62	0.01	1.29%	0.54	0.55	0.04	7.18%
11	0.64	0.64	0.02	2.74%	0.57	0.57	0.01	2.36%
				3.90%				5.14%

Table 3. Inter-day reliability for all subjects (n=11) for height (cm) (≥ 2-3 days of testing).
SD: standard deviation.
CV%: coefficient of variation.

	CMJ^{SSD}							
	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	54.9	52.3	5.5	10.58%	44.1	41.5	4.90	11.79%
2	49.4	50.0	2.2	4.36%	42.3	43.4	2.48	5.71%
3	47.4	47.9	0.9	1.95%	42.1	39.5	4.85	12.28%
4	54.6	50.5	8.4	16.62%	45.6	43.3	8.47	19.55%
5	48.2	48.7	0.7	1.35%	39.0	39.0	1.17	3.01%
6	50.2	51.1	1.7	3.33%	41.1	42.5	2.48	5.84%
7	52.3	53.0	4.4	8.31%	44.0	42.9	4.78	11.14%
8	52.5	52.5	5.2	9.93%	44.7	44.7	5.23	11.71%
9	41.8	45.4	5.1	11.15%	33.5	33.5	9.12	27.19%
10	44.1	44.8	1.9	4.21%	33.7	35.5	4.47	12.62%
11	47.4	47.4	5.5	11.59%	36.3	36.3	3.30	9.10%
				7.58%				11.81%

	CMJ^{PDD}							
	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	54.2	52.0	5.7	10.98%	43.7	42.1	6.06	14.40%
2	51.5	51.1	1.0	1.99%	44.4	42.7	4.16	9.75%
3	45.5	44.6	3.7	8.26%	40.3	38.4	6.09	15.85%
4	52.9	52.9	6.7	12.61%	45.5	45.4	3.80	8.37%
5	47.9	47.9	1.3	2.72%	38.9	38.9	0.49	1.25%
6	53.6	55.1	4.6	8.43%	46.2	47.5	5.49	11.55%
7	50.5	52.0	3.1	5.93%	41.5	41.5	2.99	7.22%
8	52.3	52.3	1.6	3.03%	44.0	44.0	3.43	7.79%
9	50.6	50.6	1.4	2.86%	42.5	42.5	1.23	2.88%
10	46.2	44.6	3.6	8.01%	38.2	37.1	4.12	11.11%
11	52.4	52.4	3.3	6.27%	42.4	42.4	4.58	10.82%
				6.46%				9.18%

	SJ							
	P-P				P-T			
Subject	**Median**	**Mean**	**SD**	**CV%**	**Median**	**Mean**	**SD**	**CV%**
1	34.8	41.3	12.6	30.52%	27.6	30.7	12.47	40.60%
2	49.0	50.4	2.7	5.45%	41.5	42.6	2.15	5.06%
3	46.5	46.1	1.5	3.20%	35.6	34.7	2.35	6.76%
4	52.6	49.5	6.6	13.33%	42.3	40.7	5.00	12.30%
5	47.3	47.3	2.2	4.55%	42.5	42.5	2.14	5.04%
6	48.2	48.0	0.9	1.95%	42.1	41.5	1.66	4.01%
7	35.5	36.3	1.9	5.18%	26.9	27.0	0.37	1.37%
8	45.8	45.8	2.3	5.09%	38.0	38.0	1.64	4.32%
9	46.4	46.4	4.2	8.97%	36.3	36.3	5.18	14.27%
10	47.3	47.3	1.2	2.58%	36.2	37.9	5.49	14.51%
11	51.0	51.0	2.8	5.48%	39.8	39.8	1.88	4.72%
				7.85%				10.27%

4.4 Discussion

As previously stated, in order to mimic the proposed use for these investigations in the field all participants performed their jump protocol at the same time. Unfortunately, this design did not allow for the investigation of a reference degree of normal biological variability, measured via the JJCM. Therefore, in order to determine if our reliability measures were of a sufficient degree of statistical strength, the literature was referenced to determine the reliability of the JJCM. Nuzzo (2011) and his colleagues, in a holistic study analysed the vertical jump reliability of three different systems to determine and highlight the degrees of variance in each of the three different monitoring systems (Nuzzo *et al*, 2011); Vertec, JJCM and Myotest. Their study reported that for males, vertical jump height mean CV was as follows: Vertec: 5.9%, JJCM: 6.3% and Myotest: 5.3%. In lieu of this, if we were to utilise these data as a peer-reviewed guide then the mean data produced by our investigations would be supportive of good reliability for one jump condition with regards to height estimation; the lowest mean CV that we found was for H^{P-P} for the CMJ^{PDD} condition (CV = 6.46%), with the other conditions up to two times higher and thus not supported by the literature reference (Table 2). Although no CV data on flight time could be found in the literature with regards to the JJCM, sufficient reliability of H was shown and thus as H is based on FT, we would suggest that the FT^{P-P} is also exhibiting sufficient measure of reliability.

Despite the fact that FT^{P-T} and H^{P-T} showed sufficient validity in chapter 3, these measures do not exhibit sufficient reliability in comparison to the peer-reviewed guide that we have chosen to utilise. The reason for this poorer degree of reliability can likely be explained by the analytical procedure, at least in part. With reference to appendix 1, we can see that the 'true landing (T)' point is sharp and allows for a clear distinguishing marker of when the body made contact with the ground again. However, this was not always the case with this point on the trace and many did not display such a sharp rise, but more a gradual rise with no clear distinction as in appendix 1. Perhaps this was due to a slight knee bend in the landing sequence of participants although we tried to limit this by asking the participants to maintain a 180^0 knee angle at landing. Understandably, upon landing it is only natural to slightly bend the knees to eccentrically absorb force, especially when concurrently taught to do so in strength and conditioning programs which incorporate power related exercises such as plyometrics. The actions of the kinetic chain as elucidated to in the previous chapter may be playing a role here in dissipating the landing forces and thus contributing to the display of a gradual rise in the post-analysis trace as opposed to a sharp rise as seen in appendix 1. This is perhaps due to the natural position of the unit thus making it difficult to truly determine the exact FT when the impact acceleration is not so distinct.

Concurrently, the poorer degree of reliability in the CMJ^{SSD} condition may also be due to the participant descending to a different depth across testing days dependent upon how comfortable they feel in that position on that day, and therefore the jumps not being standardised. Although we had no direct measure of the eccentric depth that the participants descended to on each day, this may be something for future research to consider, perhaps with the employment of gold standard references such as stereophotogrammetry. The poorer degree of reliability in the SJ may also be explained by the observation of more trunk rotation in the so-called 'hold position' at the bottom, as compared to the other jump types. Whenever the subject then suddenly begins to ascend artefactual movement in the unit could add additional noise to the trace. Therefore, our observations of the data would suggest that the CMJ^{PDD} has the best marker of reliability with reference to $H^{P\text{-}P}$ and $FT^{P\text{-}P}$ because both the jump and analysis are standardised best i.e. the participant has to descend to a pre-set depth during each jump (90^0) and the distinct peaks on the post-analysis trace allow for consistent analysis. Although this measure, as outlined in chapter 3 overpredicts both FT and H, its sufficient degree of reliability would permit for its use as a measure of change in monitoring athletic readiness, provided it is shown sensitive to change.

Despite the several steps taken to limit the number of confounding factors in this short study, there are several which the author would like to highlight, as they were likely to introduce some degree of variance across testing days and may explain why several of the jump styles displayed poor reliability measures as can be observed in Table 2 & Table 3. As the UK distributor of the technology states, 'the standard Catapult 'crop top' [is] manufactured from performance anti-bacterial fabric with an elasticated seam [in which] the Catapult unit is housed in a padded pocket at the top of the back' (Perform Better, 2014). Although the participant wears the vest and the unit is therefore held within close proximity to the participant's body, artefactual movement of the unit, which does not represent the movement of the athlete per se, cannot be conclusively ruled out. Although, it had been considered to tape the GPS unit to the participant's skin to limit this potential artefactual variance across testing days, this is extremely impractical in a team sports setting and would only add time to the monitoring procedure when employed. Similarly, the distributor supplies the vests in several different sizes i.e. small, medium, large, x-large, and although every effort was made to ensure that the participants were wearing the same sized vest across testing days, each vest is manufactured independently and thus will likely have slight differences. As a consequence, variance may also be introduced at this level across testing days as the unit may move excessively when the participants do depending on the vest size.

Also, although all subjects were asked to refrain from strenuous physical activity for the 24-48 hours preceding each trial, each jump test was conducted at 7.30pm due to participant availability as well as for standardization purposes. Performing the tests at 7.30pm did not allow for the control of normal daily activity, which may have introduced a fatigue variance into the results. In certain cases the individual variability for FT and H was much higher than in other cases (Table 2 & Table 3), and therefore the IMU may in fact be showing a strong degree of sensitivity to fatigue. However, without robust reliability measures this sensitivity cannot be determined nor concluded for certain. Additionally, in the case of subject 1 for the SJ condition it is noted that they exhibited an extremely high CV. Although this variability is much higher than all of the other subjects there was no reason identified from analyses that would merit exclusion of the data from the investigation. This may simply be due to the reliability of the particular unit or due to some unidentified underlying factor.

4.5 Conclusion

In conclusion, these investigations would be supportive of good reliability for one jump condition with regards to FT and H estimation; the lowest mean CV that we found was for H^{P-P} for the CMJ^{PDD} condition (CV = 6.46%), with the other conditions up to two times higher and thus not supported. As the H^{P-P} estimation is shown to be reliable and the H estimation is based on FT, we would also provide support for the utilisation of FT as a reliable measure when utilizing FT^{P-P}. Although this particular condition was not shown valid in chapter 3 as it overestimated both the FT and H its reliability would supports its use across time. That is it overestimates what it is supposed to measure but does so consistently.

Although, FT^{P-P}, H^{P-P}, FT^{P-T} and H^{P-T} for CMJ^{SSD} and SJ as well as FT^{P-T} and H^{P-T} for CMJ^{PDD} exhibited poor reliability, future research, which takes into consideration the confounding factors put forth in this chapter, may perhaps support their use in determining readiness to train. Our next steps will seek to determine if FT^{P-P} for the CMJ^{PDD} condition is sensitive to change over several weeks of training and match play. This will then provide us with a measure of function regarding an athlete's readiness to train, although will not provide us with a system diagnostic with regards to fatigue. Once we have a 'flag' with regards to diminished readiness we can then set out to determine where the reduction in performance is manifest i.e. acute fatigue, DOMS, depression, anxiety, longer lasting fatigue etc. and treat it accordingly.

Chapter 5:

Sensitivity of Inertial Sensors

5.1 Participants

In this study, there were 10 youth professional soccer players recruited. All participants were in good physical and mental health and were not deemed as vulnerable. The participants all had a previous soccer-specific training history of more than 5 years and were currently making preparations for the 2014-2015 domestic season. The body mass, height and age (mean $\pm$ SD) for the participants were 74.0 $\pm$ 7.3 kg, 181.7 $\pm$ 7.7 cm, 18.1 $\pm$ 1.4 years, respectively. Subject characteristics were recorded and ethical approval granted as described in Chapter 3.

5.2 Methods

5.2.1 Catapult GPS

GPS unit was utilised as described in Chapter 3.

5.2.2 Testing Procedure

In order to test the sensitivity of the Catapult IMU to minute changes in performance, each participant was required to perform a test battery on two occasions in a repeated-measures protocol, both before and after a short 6-week preparatory period leading into the 2014-2015 youth professional domestic soccer season. The test battery consisted of body mass measurement, 5m-sprint, 10m-sprint, 20m-sprint, FJ and CMJ^{PDD} (chapter 3 & 4) performance measures. The sprint times were measured on an indoor artificial surface via a Brower TC System (Brower Timing Systems, Draper, Utah, USA), accurate to 1/1000th of a second. FJ performance was monitored via a JJCM (Probotics Inc, Huntsville, Alabama, USA). CMJ^{PDD} performance was monitored via a wireless, Catapult Optimeye 10Hz X4 GPS tracking device (Optimeye, Catapult Innovations, Canberra, ACT, Australia). For both sprint and FJ performance the results were recorded from the devices as displayed, respectively. For

CMJ^{PDD} performance, FT^{P-P} for the CMJ^{PDD} was manually recorded as explained in the previous chapters and appendix 1 (see Chapter 3 & 4, see appendix 1).

For FJ the participants performed a countermovement with arm swing permitted and then vertically ascended as high as possible. CMJ^{PDD} was conducted as outlined in previous chapters with the subject descending to a 90^0 angle as part of the countermovement with no arm swing permitted. For sprint procedures participants were asked to perform a maximal 20m sprint with split-times for 5m, 10m and 20m recorded. After lining up at a pre-designated start marker they were then permitted to proceed with their effort through the timing gates whenever ready. 3 efforts were allowed for sprint performance with at least 90 seconds between each effort.

5.2.3 Statistical Analyses

Firstly, in order to determine if there was any change in performance over this time period, for each performance test i.e. 5m-sprint, 10m-sprint, 20m-sprint, FJ and CMJ^{PDD} a paired samples t-test was conducted. Normality of data was tested via the Shapiro-Wilk test. Statistical significance was set at level $p<0.05$. All statistical procedures were conducted using IBM SPSS Statistics Version 21.0 (IBM Corp. Armonk, NY, USA).

3x3 contingency tables for direction and frequency of change were constructed for FJ and CMJ^{PDD} versus 5m-sprint, 10m-sprint and 20m-sprint, respectively. These contingency tables were analyzed primarily for trends rather than statistical power i.e. chi-squared test or fisher exact test. This was mainly related to the smaller sample size in this study as a sample of convenience and the number of subjects available, cell frequencies with expected values <5 (potentially making chi-squared statistical analyses unreliable) and lack of observed trends within the tables.

5.3 Results

In testing for a change in performance, statistical procedures revealed that there was no significant difference between before and after measures for 5m-sprint time (1.08 ± 0.05 s vs. 1.08 ± 0.05 s, p>0.05), 10m-sprint time (1.83 ± 0.07 s vs. 1.81 ± 0.06 s, p>0.05), 20m-sprint time (3.08 ± 0.07 s vs. 3.06 ± 0.08 s, p>0.05) and FJ performance (24.74 ± 3.27 inches vs. 24.55 ± 2.68 inches, p>0.05), respectively, following the short 6-week preparatory period leading into the 2014-2015 youth professional domestic soccer season. There was however a significant difference shown between before and after measures for FT^{P-P} for CMJ^{PDD} (0.67 ± 0.03 s vs. 0.64 ± 0.03, p=0.003, CI: 0.0128, 0.0449).

Figure 7. Contingency tables for direction and frequency of change for A) FJ vs. 5m-sprint time, 10m-sprint time and 20-m sprint time B) CMJ^{PDD} vs. 5m-sprint time, 10m-sprint time and 20-m sprint time. The green shading highlights the normal trends that would normally be expected.

A	5m Sprint Improved	5m Sprint No change	5m Sprint Worse	10m Sprint Improved	10m Sprint No change	10m Sprint Worse	20m Sprint Improved	20m Sprint No change	20m Sprint Worse
Free Jump Improved	3	0	2	4	1	0	3	2	0
Free Jump No change	1	0	0	1	0	0	1	0	0
Free Jump Worse	1	1	2	2	0	2	2	0	2

B	5m Sprint Improved	5m Sprint No change	5m Sprint Worse	10m Sprint Improved	10m Sprint No change	10m Sprint Worse	20m Sprint Improved	20m Sprint No change	20m Sprint Worse
CMJ IMU Improved	0	0	1	0	0	1	0	0	1
CMJ IMU No change	0	0	0	0	0	0	0	0	0
CMJ IMU Worse	5	1	3	7	1	1	6	2	1

5.4 Discussion

Statistical tests for repeated-measures revealed that our test battery did not show any change in performance (5m-sprint time, 10-m sprint time, 20-m sprint time and FJ) over the 6-week preparatory period leading into the 2014-2015 youth professional domestic soccer season, except in the case of the CMJ^{PDD} with the mean lower in the after observation.

Although there was no decrease in performance, there also was not any improvement in performance and thus several implicative factors could have played a part in the net result of no change in performance markers over this period. The participants from this study were part of a professional youth development squad. Although their gym-based training was focussed upon upper body strength and hypertrophy mesocycles as well as lower body strength, the large volume of field based conditioning sessions incorporating alactic-aerobic high intensity running as well as the need for incorporating technical-tactical sessions in the preparatory period to allow the players to 'regain their touch' following the off-season, provide a need to manage the resistance based gym-load depending on the managers ambitions for the football-based training schedule. This is not to say however, that the participants were not participating in resistance training, but as a result of the large field-based volume in the preparatory stages, perhaps were not engaging as extremely high intensity loads relative to body weight in the gym for peak power or maximal strength development. Similarly, several of the participants were required to report for international training camps, first team training camps and intercontinental first team pre-season fixtures as part of the development process at the club. As a result of these requirements, their focus thus moves away from developmental gym-based work at the training centre to preparing for matches with the first team interspersed with periods of travel between different countries. These factors are uncontrollable and part of the applied nature of elite team sports.

A lack of performance change however does not allow for the sensitivity of a system to be investigated. If a gold-standard measure of CMJ^{PDD} was included in the testing battery e.g. JJCM there may have been an observation of a change in performance over this period e.g. a reduction in height jumped when utilizing a CMJ^{PDD} with hands on hips. This is recognised as a limitation of this investigation, but unfortunately could not be overcome due to the nature of gaining access to and testing elite athletes. Naturally, this squad perform a FJ as part of their testing battery, however as we have employed a CMJ^{PDD} utilizing the IMU it is not possible to determine what may have been the case if a CMJ^{PDD} on a JJCM was included in testing. The primary reason for utilizing a CMJ^{PDD} with hands on hips with regards to the IMU is the nature of the jump biomechanics. With the hands positioned on the pelvis and the trunk upright, the jump maximally targets the power output of the lower limbs alone. When the arms are utilised in a swinging motion, for example in the FJ, they can in part assist in elevating the centre of mass via the transfer of momentum, as well as incorporate upper body muscles such as the spinal erectors thus increasing the hang time in the jump. As the SSC taxation of the lower limbs is greater than any upper body mechanical damage during soccer match play, it may seem rational to try to highlight lower limb performance i.e. CMJ^{PDD}.

Additionally, a major problem arises when utilizing a triaxial accelerometer and gyroscope as a means to quickly test vertical jump performance with arm motion. Utilizing a swinging motion as part of the jump would likely result in a slightly different jump profile to that observed in appendix 1, principally due to extra movement in the unit in the triaxial planes and extra movement of the torso as well as other factors mentioned previously (Akl, 2013). For quickly analysing data in the team sports setting this would require extraneous work, which may not be possible in this environment. For these reasons, we sought to test CMJ with no arm involvement.

Accordingly, as the sensitivity of the system could not be investigated directly, we sought to determine if the data revealed specificity i.e. does it still follow a particular trend? In order to do this we constructed 3x3 contingency tables as part of our analytical approach. Contingency tables quickly facilitate the observation, or perhaps absence, of a general relationship between two or more categorical data. From Figure 7 however we can clearly distinguish that with the limited data available there is no consistent trend.

As strong correlations have been reported between maximal strength during half squats, 10m and 30m sprint performance as well as vertical jump height (Wisloff *et al*, 2004**;** Maulder *et al*, 2006), it would be expected that for a change in 10m sprint time a correlating change in vertical jump height would be seen. However, Figure 7A highlights for FJ that although in some cases these data do follow a trend, one that may in fact be expected i.e. an improvement in FJ equates to an improvement in sprint time and vice versa this was not always the case e.g. FJ got worse as 10m sprint time improved in 2 of the cases. Similarly Figure 7B also does not support a trend observation when employing the Catapult IMU CMJ^{PDD} procedure. In some cases, as CMJ^{PDD} performance gets worse, sprint performance improves, whereas in other cases, as CMJ^{PDD} performance improves, sprint performance gets worse. This therefore shows that a trend in CMJ^{PDD} change cannot be conclusively predictive of a change in performance with these data, as the current evidence suggests that it is non-predictive in nature. However, lending back to the observation that there was no statistical difference in the performance markers employed i.e. 5m-sprint time, 10-m sprint time, 20-m sprint time and FJ, although we can determine the direction of change and the frequency of the direction of change in our analytical approach, these changes again are not significant. They are negligible and therefore could very well be a result of normal biological variability. For example, one day could be negligibly above the before measure and the next day could be negligibly below the before measure, resulting in the observations displayed in Figure 7 and therefore not really a change.

Despite the fact that these data do not provide robust support for the employment of the IMU system in this instance, perhaps due to the limitations in the study, we would suggest that monitoring a change in CMJ^{PDD} performance of more than 2 SD from the individuals mean performance over time could provide reason to question training readiness. SD is a valid measure of variability, in which approximately 95% of all data points in a distribution should fall within 2 SD of the mean. It is used as a measure of confidence and spread in statistical conclusions, in that a change in vertical jump performance of 2 SD from the mean would lead to a result that is statistically different, provided the noise of the measure is less than this. Therefore any observations, which lie outwith these limits, would provide reason for questioning (Altman *et al*, 2005). This may be warranted at least until more robust experimental procedures can be carried out investigating the true sensitivity of the Catapult IMU and its predictive value. A positive change is not alarming for training readiness, however a negative change would definitely warrant further investigation of an athletes physiological state.

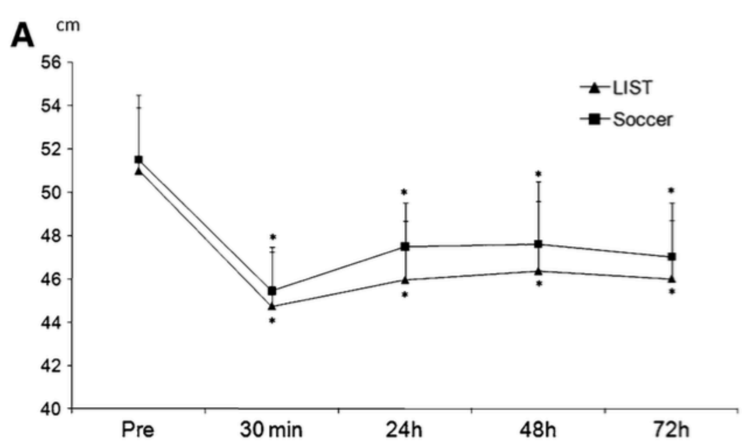
For example, over time if an individual athlete's mean vertical jump performance lends a mean flight time of 0.65 ± 0.02s, and two days after a match they performed a jump test and recorded a flight time of 0.59s, it may be worthwhile to re-test for clarity and if it persists investigate other markers of readiness alongside. Or perhaps even simply have a conversation with the athlete in question to determine how they feel and establish if they are physically and emotionally ready to commence the training week.

In doing this however, it is extremely important to consider the normal biological variability of a measure. Biological variability is a natural variability in the body's performance from day-to-day and can be attributed to inter-individual factors e.g. native diet or genetics, to intra-individual factors e.g. diurnal cycle, age, and biological repair, or to a combination of the two.

For example maximum aerobic power has been shown to have a normal biological variability of approximately 5.6% (Katch *et al*, 1982). Therefore, when attempting to implement a program to improve aerobic power it is important to consider whether any observed improvement is in fact due to the program itself or simply due to the natural (biological) variability of the measure. The same can also be said for monitoring vertical jump performance. When attempting to determine if there has been a change in training readiness it is important to consider the normal fluctuation in the measure and that a true change is only present if the data is greater than the natural variation.

In terms of future research however, much more robust investigations should be carried out. Following both a soccer match and the Loughborough Intermittent Shuttle Test (LIST) protocol, mean vertical jump height was reported to be depressed by at least 2 SD of the group average from pre, at 30 minutes, 24 hours, 48 hours and 72 hours following both conditions (shown in Figure 8; Magalhaes *et al*, 2010).

Figure 8. Jump performance (A) during the 72-hour recovery following LIST (triangles) and soccer (squares). Values are mean and SD. Asterisk signifies significance at $p<0.05$ versus pre-exercise for both exercises (LIST and soccer). Reproduced from (Magalhaes *et al*, 2010).



Although we expected to see a decline in vertical jump performance following a short 6-week preparatory period before a brief taper to restore performance in a super-compensatory manner leading into the competitive season, this was not the case. It is recognised that this may have been due to a number of factors outlined previously and a similar experimental approach to that employed by Magalhaes (2010) e.g. using an acute fatiguing protocol would have been more appropriate to investigate the sensitivity of the IMU. An approach, which employs a fatiguing protocol, is therefore recommended for future investigations.

5.5 Conclusion

Therefore, as it is difficult to draw conclusions at present based on the sensitivity of the Catapult IMU system with these limited data, we would suggest that monitoring a change in performance of more than 2 SD from the individuals mean performance over time lends reason to question training readiness as a means of statistical power until much more robust and conclusive research can be conducted.

Chapter 6:

Practical Implications

6.1 Practical Implications

In terms of the practicality of these investigations, the limited data and the limitations surrounding it make it difficult to draw conclusions regarding the predictive capacity of the Catapult IMU for monitoring readiness to train. At present we would suggest that in applying the IMU system to monitor vertical jump performance, practitioners should exercise caution and if doing so that a change in performance of more than 2 SD from the individuals mean over time lends reason to question training readiness.

The theoretical capacity for reducing testing time in a multiple screening scenario through a GPS coupled IMU system does seem attractive, especially in regards to many of the limitations of the other methods outlined in the literature review, however it does require much more extensive research.

Although we were able to show sufficient validity for FT^{P-T} and H^{P-T}, these metrics exhibited poor reliability in our investigations and thus it would be non-practical to employ them for monitoring purposes. Similarly, FT^{P-P} and H^{P-P} exhibited sufficient reliability however in validity investigations observed a systematic bias. We did not attempt to correct for this bias however as FT^{P-T} and H^{P-T} were shown valid and had a more sound biomechanical rationale as a measure, although future investigations should seek to reinvestigate these observations. In relation to the sensitivity of the system, the potential analyses that could be conducted was restricted, as our test battery did not show any change in performance for 5m-sprint time, 10-m sprint time, 20-m sprint time and FJ over the 6-week preparatory period. Although CMJ^{PDD} mean was lower in observations at the end of the preparatory period we could not conclusively predict the reason for this.

It is therefore appreciated that the research outlined in this thesis is not comprehensive, nor does it answer all of the questions raised. Future investigations should seek to determine the true sensitivity and predictive capacity of the Catapult IMU in a more robust manner. By building upon this work, reinvestigating the validity and reliability of the system would help to clarify if the system really does have a place for monitoring vertical jump performance and consequently athletic readiness to train. When determining the reliability of the system, attempts to establish both intra-day and inter-day reliability should be made as a measure of normal variance of the system, so that any change monitored can be attributed to a change in readiness and as opposed to the normal biological variability of the metrics analysed.

In determining the true sensitivity of the system in the future we would suggest three more robust experimental approaches to achieving this. As conducted by Magalhaes (2010), an acute fatiguing protocol could be effective in investigating the sensitivity of the IMU. Perhaps testing vertical jump performance before and after a soccer match we would gather a greater insight into the capacity of the IMU for detecting change. As outlined previously, vertical jump performance would be expected to be depressed for up to 72 hours following a match (shown in Figure 8; Magalhaes *et al*, 2010). Secondly, a period of higher resolution training monitoring in which a daily test is conducted may be warranted in accordance with training load e.g. RPE, total distance etc. Monitoring in this manner with such density would allow us to detect immediate shifts and trends in performance and may be more appropriate for the intended use of the system i.e. on a daily basis. Finally, applying a strength-power hybrid gym-based intervention to improve rate of force development and maximal strength may allow us to better test the sensitivity of the system with regards to an expected improvement in vertical jump performance. It is commonly documented that Olympic weightlifting performance and vertical jump performance are very closely correlated (Carlock *et al*, 2004), and that engaging in an appropriate Olympic weightlifting style program will likely increase vertical jump performance (Channell *et al*, 2008). Therefore a similar program to Table 4 could be implemented as part of further investigations to more directly test the sensitivity of the IMU.

Table 4. highlights an example of a simple strength-power hybrid gym-based intervention program to improve rate of force development and maximal strength, which may allow for more robust sensitivity testing of the IMU system.

Monday	Wednesday	Friday
Power Clean 5x3 @85%	Bench Press 5x5 @85%	Back Squat 5x5 @85%
DB Chest Press 3x10 @65%	Walking Lunge 3x25m @25%BW	Power Snatch 5x3 @75%
Jump Squat 3x5 @30%BW	RFE Split Squat 3x10 @65% BW	Clap Push Up 3x6-8 @BW
Box Jump 3x3 @0.75m	Depth Jump 3x3 @24"	Hurdle Hop 3x5 @ 32"

It should be noted however, that in recent research Gathercole and his colleagues (2014) presented data that suggests that even although jump height may have recovered from an acute fatiguing bout after 72 hours, alongside other standard variables e.g. peak power, the jump movement itself remained sub-optimal e.g. decreased eccentric utilization and time was longer to perform the jump (Gathercole *et al*, 2014). It is unclear at this stage how the GPS IMU could be used to monitor for such alterations in jump movement patterns because if jump height has recovered yet movement quality remains sub-optimal and the GPS IMU is unable to detect this e.g. decreased eccentric depth, then this could lead to potential risk of injury. Perhaps it is worth considering using the GPS IMU in a comprehensive manner with previous methods discussed in the literature review, if of course further research is positive.

Additionally, throughout our investigations we were not able to implement the automated jump detection algorithm, which the manufacturer has developed. The algorithm did not always detect a jump sequence and therefore we could not investigate its reliability. At present, it is therefore suggested that practitioners manually interpret the data until further investigations can be carried out into the robustness of this automated algorithm. This of course will increase the time required to conduct such monitoring for a full team of players, especially on a daily basis and thus practitioners may find it more suitable to simply continue testing using a jump mat for now e.g. JJCM. This of course depends upon the practitioners experience with Catapult's GPS products. The continued use of a jump mat may also be appropriate when small staff numbers are available as it is vital for standardization purposes that it can be ensured that each athlete conducts the same jump style from day-to-day i.e. knee angle of 90^o. Staff must be present to ensure that athletes do not complete 'false' jumps i.e. knee angle $>90^o$ or $<90^o$ as this will likely alter the result of the test. If staff are not available to ensure this effect then the monitoring system becomes invalid.

In conclusion, as strong correlations have been reported between maximal strength during half squats, 10m and 30m sprint performance as well as vertical jump height (Wisloff *et al*, 2004**;** Maulder *et al*, 2006), it is rationally clear why a reduction in vertical jump performance may breed insight into training readiness, ability to generate explosive force and therefore perform sprints whilst on the soccer field. It would also seem to lend support to the reason why vertical jump analysis has become a commonly practiced tool by many high performance-sporting practitioners in order to monitor NMF and its resultant recovery timeline in elite athletes as reported by a recent survey (Taylor *et al*, 2012). Although there does exist limitations in this manuscript and perhaps it has generated more questions than answers, these investigations should act only as the first essential step in the process of understanding if there is a true use for GPS coupled IMUs in estimating vertical jump performance and ultimately readiness to train in team sports.

References

1. Achten, J. Jeukendrup, A.E. 2003. Heart rate monitoring: applications and limitations. Sports Med. 33: 517-538.
2. Akl, A.R. 2013. A Comparison of Biomechanical Parameters between Two Methods of Countermovement Jump. International Journal of Sports Science and Engineering. 7(2): 123-128.
3. Al Haddad, H. Laursen, P. B. Chollet, D. Ahmaidi, S. Buchheit, M. 2011. Reliability of resting and post exercise heart rate measures. Int J Sports Med. 32: 598-605.
4. Altman, D.G. Bland, J.M. 2005. Standard deviations and standard errors. 331(7521): 903.
5. Andersson, H. Raastad, T. Nilsson, J. 2008. Neuromuscular fatigue and recovery in elite female soccer: effects of active recovery. Med Sci Sports Exerc. 40(2): 372-380.
6. Apor, P. 1988. Successful formulae for fitness training. In: Science and Football. Edited by: Reilly, T. London: E&FN Spon. 95-107.
7. Arnason, A. Sigurdsson, S.B. Gudmundsson, A. 2004. Physical fitness, injuries, and team performance in soccer. Med Sci Sports Exerc. 36(2): 278-285.
8. Aubert, A.E. Seps, B. Beckers, F. 2003. Heart Rate Variability in Athletes. Sports Med. 33(12): 889-919.
9. Aughey, R.J. 2011. Increased High-Intensity Activity in Elite Australian Football Finals Matches. International Journal of Sports Physiology and Performance. 6: 367-379.
10. Barnes, C. Archer, D.T. Hogg, B. Bush, M. Bradley, P.S. 2014. The Evolution of Physical and Technical Performance Parameters in the English Premier League. International Journal of Sports Medicine. 35: 1-6.
11. Bangsbo, J. 1994 Acta Physiol Scand Suppl. 619: 1-155. The physiology of soccer with special reference to intense intermittent exercise. 619: 1-155.
12. Bangsbo, J. Mohr, M. Krustrup, P. 2006. Physical and metabolic demands of training and match-play in the elite football player. J Sports Sci. 24(7): 665-674.

13. Brandenberger, G. Buchheit, M. Ehrhart, J. Simon, C. Piquard, F. 2005. Is slow wave sleep an appropriate recording condition for heart rate variability analysis? Auton Neurosci. 121: 81-86.
14. Brenner, I.K. Thomas, S. Shephard, R.J. 1998. Autonomic regulation f the circulation during exercise and heat exposure. Inference from heart rate variability. Sports Med. 26: 85-89.
15. Buchheit, M. Chivot, A. Parouty, J. Mercier, D. Al Haddad, H. Laursen, P. B. 2010. Monitoring endurance running performance using cardiac parasympathetic function. Eur J Appl Physiol. 108: 1153-1167.
16. Buchheit, M. Racinais, S. Bilsborough, J.C. Bourdon, P.C. Voss, S.C. Hocking, J. 2013. Monitoring fitness, fatigue and running performance during a pre-season training camp in elite football players. J Sci Med Sport. 16: 550-555.
17. Buchheit, M. 2014a. Monitoring training status with HR measures: do all roads lead to Rome? Frontiers in Physiology. 5(73):1-19.
18. Buchheit, M. Al Haddad, H. Simpson, B.M. Palazzi, D. Bourdon, P.C. Di Salvo, V. Mendez-Villanueva, A. 2014b. Monitoring accelerations with GPS in football: time to slow down? Int J Sports Physiol Perform. 9(3): 442-445.
19. Carlock, J.M. Smith, S.L. Hartman, M.J. Morris, R.T. Ciroslan, D.A. Pierce, K.C. Newton, R.U. Harman, E.A. Sands, W.A. Stone, M.H. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. J Strength Cond Res. 18(3): 534-539.
20. Casartelli, N. Muller, R. Maffiuletii, A.M. 2010. Validity and reliability of the myotest accelerometric system for the assessment of vertical jump height. J Strength Cond Res. 24(11): 3186-3193.

21. Channell, B.T. Barfield, J.P. 2008. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. J Strength Cond Res. 22(5): 1522-1527.
22. Coelho, D.B. Morandi, R.F. De Melo, M.A.A. Silami-Garcia, E. 2011. Creatine Kinase Kinetics in Professional Soccer Players During a Competitive Season. Rev Bras Cineantropom Desempenho Hum. 13(3): 189-194.
23. Cook, N.J. Ng, A. Read, G.F. Harris, B. Riad-Fahmy, D. 1987. Salivary cortisol for monitoring adrenal activity during marathon runs. Hormone Research. 25(1): 18-23.
24. Cormack, S.J. Newton, R.U. McGuigan, M.R. Cormie. P. 2008b. Neuromuscular and Endocrine Responses in Elite Players During an Australian Rules Football Season. Int J Sports Physiol Perform. 3(4): 439-53.
25. Cormack, S.J. Newton, R.U. McGuigan, M.R. Doyle, T.L.A. 2008a. Reliability of Measures Obtained During Single and Repeated Countermovement Jumps. International Journal of Sports Physiology and Performance. 3: 131-144.
26. Coventry, E. O Connor, K.M. Hart, B.A. Earl, J.E. and Ebersole, K.T. 2006. The effect of lower extremity fatigue on shock attenuation during single-leg landing. Clinical Biomechanics 21: 1090-1097.
27. Di Salvo, V. Baron, H. Tschan, F. J. Montero, N. Bachl. Pigozzi. F. 2007. Performance characteristics according to playing position in elite soccer. International Journal of Sports Medicine 28(3): 222-227.
28. Dupont, G. Nedelec, M. McCall, A. 2010. Effect of 2 soccer matches in a week on physical performance and injury rate. American Journal of Sports Medicine. 38(9): 1752-1758.
29. Edwards, D.A. Wetzel, K. Wyner D.R. 2006. Intercollegiate soccer: Saliva cortisol and testosterone are elevated during competition, and testosterone is related to status and social connectedness with teammates. Physiology & Behaviour. 87(1): 135-143.

30. Elloumi, M. Makni, E. Moalla, W. Bouaziz, T. Tabka, Z. Lac, G. Chamari, K. 2012. Monitoring Training Load and Fatigue in Rugby Sevens Players. Asian J sports Med. 3(3): 175-184.

31. Fatouros, I.G. Chatzinikolaou, A. Douroudos, I.I. 2010. Timecourse of changes in oxidative stress and antioxidant status responses following a soccer game. J Strength Cond Res. 24(12): 3278-3286.

32. Filaire, E. Bernain, Z. Sagnol, M. Lac, G. 2001. Preliminary Results on Mood State, Salivary Testosterone:Cortisol Ratio and Team Performance in a Professional Soccer Team. Eur J Apply Physiol. 86: 179-184.

33. Flanagan, E.P. Comyns, T.M. 2008. The Use of Contact Time and the Reactive Strength Index to Optimize Fast Stretch-Shortening Cycle Training. J Strength Cond Res. 30(5): 32-38.

34. Gastmann, U.A. Lehmann, M.J. 1998. Overtraining and the BCAA hypothesis. Med Sci Sports exerc. 30(7): 1173-1178.

35. Gathercole, R. Sporer, B. Stellingwerff, T. Sleivert, G. 2015. Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue. International Journal of Sports Physiology & Performance. 10(1): 84-92.

36. Giulianotti, R. 2012. Football. The Wiley-Blackwell Encyclopedia of Globalization.

37. Hamilton, D. 2009. Drop jumps as an indicator of neuromuscular fatigue and recovery in elite youth soccer athletes following tournament match play. JASC. 17(4): 3.

38. Handziski, Z. Maleska, V. Petrovska, S. Nikolik, S. Mickoska, E. Dalip, M. Kostova, E. 2006. The changes of ACTH, cortisol, testosterone and testosterone/cortisol ratio in professional soccer players during a competitive half-season. Bratisl Lek Listy. 107(6-7): 615-621.

39. Hayes, L.D. Grace, F.M. Kilgore, J.L. Young, J.D. Baker, J.S. 2012. Diurnal Variation Of Cortisol, Testosterone, And Their Ratio In Apparently Healthy Males. Sport SPA. 9(1): 5-13.

40. Helgerud, J. Engen, L.C. Wisløff, U. et al. 2001. Aerobic Endurance Training Improves Soccer Performance. Med Sci Sports Exerc. 33: 1925-1931.

41. Helgerud, J. Rodas, G. Kemi, O.J. Hoff, J. 2011. Strength and Endurance in Elite Football Players. Int J Sports Med. Online.

42. Hodgson, 2014. Akenhead, R. Thomas, K. Time-motion analysis of acceleration demands of 4v4 small-sided soccer games played on different pitch sizes. Human Movement Science. 33: 25-32.

43. Hoffman, J.R. Epstein, S. Einbinder, M. Weinstein, Y. 2000. A Comparison Between the Wingate Anaerobic Power Test to Both Vertical Jump and Line Drill Tests in Basketball Players. J Strength Cond Res. 14(3), 261–264.

44. Hoogeveen, A.R. Zonderland, M.L. 1996. Relationships between testosterone, cortisol and performance in professional cyclists. International Journal of Sports Medicine. 17(6): 423-428.

45. Hopper, D.M. Goh, S.C. Wentworth, L.A. Chan, D.Y.K. Chau, J.H.W. Wootton, G.J. Strauss, G.R. and Boyle, J.J.W. 2002. Test-retest reliability of knee rating scales and functional hop tests one year following anterior cruciate ligament reconstruction. Physical Therapy in Sport. 3: 10-18.

46. Ispirlidis, I. Fatouros, I.G. Jamurtas, A.Z. 2008. Time-course of changes in inflammatory and performance responses following a soccer game. Clin J Sport Med. 18(5): 423-431.

47. Israel, S. 1976. Problems of overtraining from an internal medical and performance physiological standpoint. Med Sport (Berl). 16: 1-12.

48. Jeukendrup, A.E. Halson, S.L. 2004. Does Overtraining Exist? An Analysis of Overreaching and Overtraining Research. Sports Med. 34(14): 967-981.

49. Johnston, R.D. Gabbet, T.J. Jenkins, D.G. 2014. Applied Sport Science of Rugby League. Sports Med. Published online: 19 April 2014.

50. Joyce, D. Lewindon, D. 2014. High Performance Training For Sports. USA: Human Kinetics. 79.

51. Kuipers, H. Training and overtraining: an introduction. 1998. Med Sci Sports Exerc. 30(7): 1137-1139.

52. Lago-Penas, C. Rey, E. Lago-Ballesteros, J. Casais, L. Dominguez, E. 2011. The influence of a congested calendar on physical performance in elite soccer. J Strength Cond Res. 25(8): 2111-2117.

53. Leard, J.S. Cirillo, M.A. Karsnelson, E. Kimiatek, D.A. Miller, T.W. Trebincevic, K. Garbalosa, J.C. 2007. Validity of two alternative systems for measuring vertical jump height. J Strength Cond Res. 21(4): 1296-1299.

54. Lehmann, M. Forster, C. Dickhuth, H.H. 1998. Autonomic imbalance hypothesis and overtraining syndrome. Med Sci Sports Exerc. 30(7): 1140-1145.

55. Magalhaes, J. Rebelo, A. Oliveira, E. 2010. Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. Eur J Appl Physiol. 108(1): 39-48.

56. Mascio, M. Bradley, P.S. 2013. Evaluation of the most intense high-intensity running period in English FA premier league soccer matches. J Strength Cond Res. 27(4): 909-915.

57. Maulder, P.S. Bradshaw, E.J. Keogh, J. 2006. Jump Kinetic Determinants of Sprint Acceleration Performance from Starting Blocks in Male Sprinters. Journal of Sports Science and Medicine. 5: 359-366.

58. Meeusen, R. Nederhof, E. Buyse, L. Roelands, B. De Schutter, G. Placentini, M.F. 2010. Diagnosing overtraining in athletes using the two-bout exercise protocol. Br J Sports Med. 44: 642-648.

59. Mohr, M. Krustrup, P. Bangsbo, J. 2003. Match performance of high-standard soccer players with special reference to development of fatigue. Journal of Sports Sciences. 21: 519-528.

60. Mohr, M. Krustrup, P. Bangsbo, J. 2005. Fatigue in soccer: a brief review. J Sports Sci. 23(6): 593-599.

61. Mohr, M. Mujika, I. Santisteban, J. Randers, M.B. Bischoff, R. Solano, R. Hewitt, A. Zubillaga, A. Peltol, E. Krustrup, P. 2010. Examination of fatigue development in elite soccer in a hot environment: a multi-experimental approach. Scand J Med Sci Sports. 20(3): 125-132.

62. Moir, G. Button, C. Glaister, M. 2004. Influence of familiarization on the reliability of vertical jump and acceleration sprinting performance in physically active men. J Strength Cond Res. 18(2): 276-280.

63. Morgan. W.P. Brown. D.R. Raglin, J.S. O'Connor, P.J. Ellickson, K.A. 1987. Physiological Monitoring of Overtraining and Staleness. Brit J sports Med. 21(3): 107-114.

64. Morgan, W.P. Costill, D.L. Flynn, M.G. 1988. Mood disturbance following increased training in swimmers. Med Sci Sports Exerc. 20(4): 408-414.

65. Mourot, L. Bouhaddi, M. Perrey, S. Cappelle, S. Henriet, M.T. Wolf, H.P. Rouillon, J.D. Regnard, J. 2004. Decrease in heart rate variability with overtraining: assessment by the Poincare plot analysis. Clin Physiol Funct Imaging. 24(1): 10-18.

66. Nedelec, M. McCall, A. Carling, C. Legall, F. Berthoin, S. Dupont, G. 2012 Recovery in Soccer Part 1 – Post-Match Fatigue and Time Course of Recovery. Sports Med. 42(12): 997-1015.

67. Nedelec, M. McCall, A. Carling, C. Legall, F. Berthoin, S. Dupont, G. 2013. Recovery in Soccer Part II – Recovery Strategies. Sports Med. 43:9-22.

68. Nedelec, M. McCall, A. Carling, C. Legall, F. Berthoin, S. Dupont, G. 2014. The influence of soccer playing actions on the recovery kinetics after a soccer match. J Strength Cond Res 28(6): 1517-1523.

69. Nussinovitch, U. Elishkevitz, K. P. Kaminer, K. Nussinovitch, M. Segev, S. Volovitz, B. 2011. The efficiency of 10-second resting heart rate for the evaluation of short-term heart rate variability indices. Pacing Clin Electrophysiol. 34: 1498-1502.

70. Nuzzo, J.L. Annin, J.H. Scharfenberg, J.M. 2011. The Relaibility of Three Devices Used For Measuring Vertical Jump Height. Journal of Strength and Conditioning. 25(9): 2580-2590.

71. O'Connor, P.J. Morgan, W.P. Raglin, J.S. 1991. Psychobiologic effects of 3 d of increased training in female and male swimmers. Med Sci Sports Exerc. 23(9): 1055-1061.

72. Owen, A.L. Wong, D.P. Dunlop G. Groussard, C. Kebsi, W. Dellal, A. Morgans, R. Zouhal, H. 2014. High Intensity Training and Salivary Immunoglobulin-A Responses in professional Top-Level Soccer Players: Effect of Training Intensity. J Strength Cond Res. In Press.

73. Owen, A.L. 2011. Heart Rate Responses And Technical Comparison Between Small vs. Large-Sided Games In Elite Professional Soccer. J Strength Cond Res. 25(8): 2104-2110.

74. Parin, V.V. Baevsky, R.M. Gazenko, O.G. 1965. Heart and Circulation under Space Conditions. Cor Vasa. 7(3): 165.

75. Parin, V.V. Baevsky, R.M. 1968. Methods of heart rate's mathematical analysis. Science Publ. Moscow.

76. Penttila, J. Helminen, A. Jartti, T. Kuusela, T. Huikuri, H. V. Tulppo, M. P. 2001. Time domain, geometrical and frequency domain analysis of cardiac vagal outflow: effects of various respiratory patterns. Clin Physiol. 21: 365-376.

77. Picerno, P. Camomilla, V. Capranica, L. 2011. Countermovement jump performance assessment using a wearable 3D inertial measurement unit. Journal of Sports Sciences. 29(2): 139-146.

78. Plews, D.J. Laursen, P.B. Kilding, A.E. Buchheit, M. 2013. Training adaptation and heart rate variability in elite endurance athletes – opening the door to effective monitoring. Sports Med. 43: 773-781.

79. Port, K. 1991. Serum and saliva cortisol responses and blood lactate accumulation during incremental exercise testing. International Journal of Sports Medicine. 12(5): 490-494.

80. Quagliarella, L. Sasanelli, N. Belgiovine, G. Moretti, L. Moretti, B. 2010. Evaluation of standing vertical jump by ankles acceleration measurement. J Strength Cond Res. 24: 1229-1236.

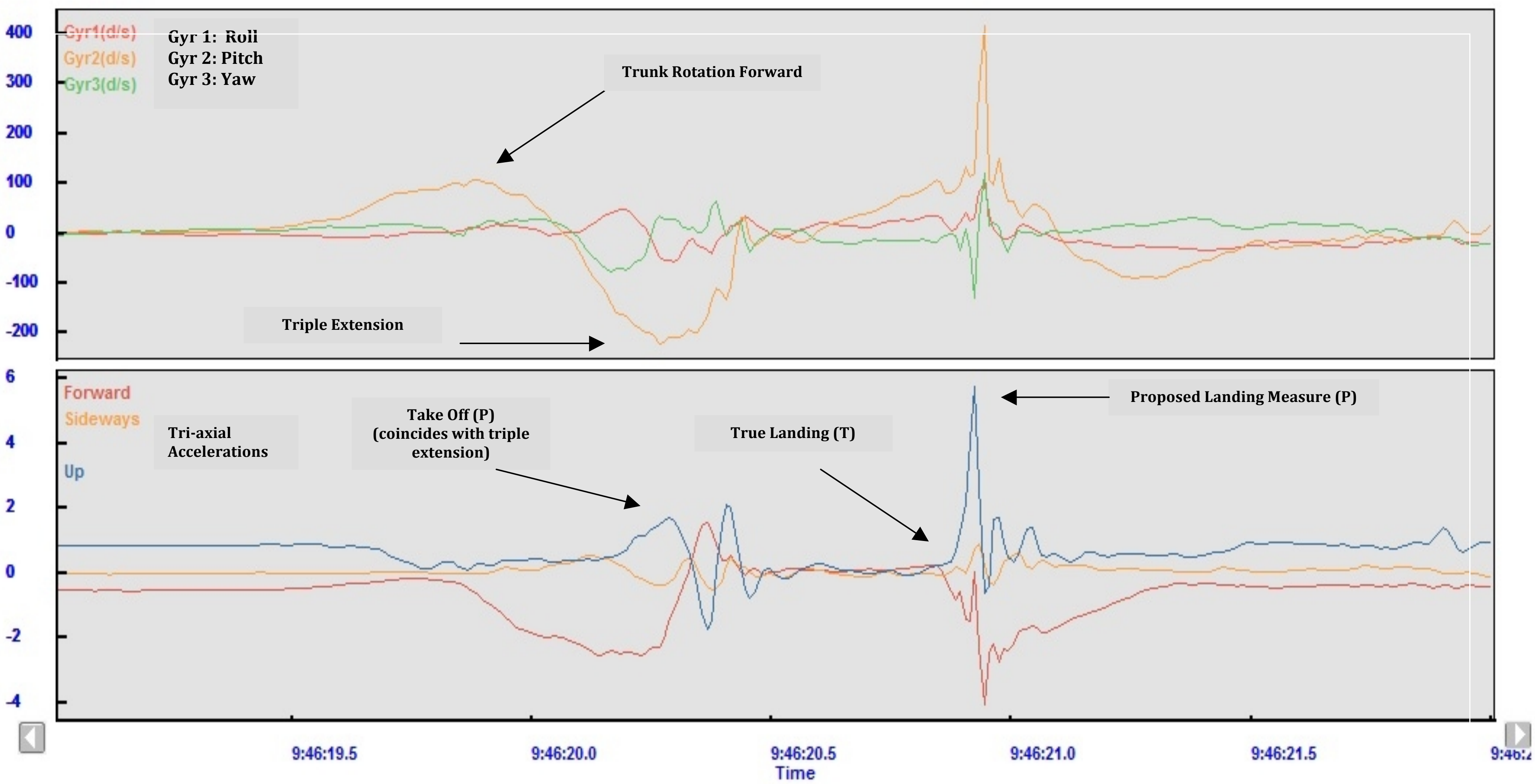
81. Requena. B. Requena, F. Garcia, I. Saez-Saez de Villareal. E. Paasuke, M. 2012. Reliability and validity of a wireless microelectromechanicals based system (Keimove™) for measuring vertical jumping performance. Journal of Sports Science and Medicine. 11: 115-122.

82. Selye, H. 1936. A syndrome produced by diverse nocuous agents. Nature. 138: 32.

83. Sleivert, G. Taingahue, M. 2004. The relationship between maximal jump squat power and sprint acceleration in athletes. European Journal of Applied Physiology. 91: 46-52.

84. Small, K. McNaughton, l. Greig & Lovell, R. 2008a. The Effects of Multidirectional Soccer-Specific Fatigue on Markers of Hamstring Injury Risk. Journal of Science and Medicine in Sport. In Press.
85. Small, K. McNaughton, L. Greig & Lovell, R. 2008b. Soccer Fatigue, Sprinting & Hamstring Injury Risk. International Journal of Sports Medicine. In Press.
86. Stolen, T. Chamari, K. Castagna, C. Wisløff, U. 2005. Physiology of Soccer: An Update. Sports Med. 35(6): 501-536.
87. Taylor K.L. Chapman, D.W. Cronin, J.B. Newton, M.J. Gill, N.D. 2012. Fatigue monitoring in high performance sport: A survey of current trends. Journal of Australian Strength and Conditioning. 20(1): 12-23.
88. Tonnessen, E. Hem, E. Leirstein, S. Haugen, T. Seiler, S. 2013. VO2 max Characteristics of Male Professional Soccer Players 1989-2012. International Journal of Sports Physiology & Performance. 8(3): 323-329.
89. Valquer. W. Barros. T.L. Santanna, M. 1998. High Intensity Motion Pattern Analyses of Brazilian Elite Soccer Players. In: IV World Congress of Notational Analysis of Sport. Porto: HM Tavares Fernanado. Page 80.
90. Vining, R.F. McGinley, R.A. Symons, R.G. 1983. Hormones in saliva: Mode of entry and consequent implications for clinical interpretation. Clinical Chemistry. 29(10): 1752-1756.
91. Wisløff, U. Castagna, C. Helgerud, J. Jones, R. Hoff, J. 2004. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. Br J Sports Med. 38(3): 285-288.
92. Young, W. 1995. Laboratory strength assessment of athletes. New Stud. Athletics. 10: 88–96.

Appendix 1:
IMU Jump Profile



The above display details an example of a CMJ profile as measured by the Catapult IMU technology.

The following gives a summarised overview of the above display:

- ‘Trunk Rotation Forward’: Bottom point of the countermovement when hip angle is decreased
- ‘Triple Extension’: Point at which there is maximal hip, knee and ankle extension – coincides with the point of ‘Take Off’
- ‘Take Off’ (P): The point at which the feet leave the ground & deceleration commences
- ‘True Landing’ (T): This is the point at which the athlete hits the ground
- ‘Proposed Landing’ (P): This is the point of peak plyometric force after the impact force has been dissipated through the kinetic chain – theorised as a possible point of automatic detection for automatic analysis

All points were analysed manually using the manufacturers software.

P-T: Take-off to True Landing
P-P: Take-off to Proposed Landing (attempts for automated purposes)