A Study of Warm-Up and Injury in Hamstring Muscles

A Thesis Submitted for the Degree of Doctor of Philosophy in the Institute of Biomedical and Life Sciences

by

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Dedication

This thesis is dedicated to my wife and children for all sacrifices they have made during my study. I would like to express my extraordinary love to them for their never ending support and encouraged to achieve success.

Acknowledgement

The dream has finally become true. It is a completion of my PhD thesis. I thank Allah for giving me the courage, strength, patience and wisdom to complete this study. The help and support from other people is also appreciated and without the help from them this study may has not been present in this appearance. It may be difficult to mention every individual person by his name and effort while my expression may be different than writing. Thus, my warmest and deepest thanks for every person helped me in this PhD thesis.

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Abstract

Muscle strains are common in sports involving explosive power development and maximum speed such as those in the sprint events. Researchers in this field have failed to identify the reasons why some athletes are more at risk of injuries than others and why some muscles are more susceptible to strains than others. Several factors have been proposed as causes of hamstrings injuries: age, muscle weakness and previous injury. Warming-up and stretching before exercise have been recommended to prevent injury. Many athletes perform warm-up but some are still injured. Despite thorough reviews in the literature, the prevalence of hamstring injuries is still high. Researchers have tried to find a direct relationship between warm-up and injury prevention. The nature of the relationship is still unclear.

This project is the first to investigate blood perfusion in the human hamstrings during isometric exercise with a near infrared spectroscopy (NIRS). A Kin Com dynamometer has been used to fix the knee positions and to measure torques during contractions. Both the NIRS optodes and the electromyography (EMG) electrodes were attached to the skin over the hamstrings. Previous studies used a NIRS to measure muscle blood flow in the forearm, quadriceps and calf muscles. The changes in haemoglobin concentrations were calculated using Spike 2 software.

A total of 46 male volunteers participated in the four series of experiments described in this thesis. In chapter 3, perfusion of the hamstrings was investigated in 14 volunteers during contractions at a series of different limb

positions. The aim was to investigate the perfusion at different force intensities at three different knee flexion angles in the left and right limbs. The results show that no significant difference was found in the mean changes in total haemoglobin concentration [tHb] in the hamstrings at the three positions at either 25% or 50% MVC. The changes in [tHb] were greater at 50% compared to 25% MVC.

Chapter 4 describes an investigation of the effects of warm-up in 14 volunteers. The aim was to measure the size and duration of the increased blood perfusion after 4 minutes of specific warm-up contractions of the hamstrings muscles. The results show a clear hyperaemia in the hamstrings after warm-up exercise and lasted approximately 8 minutes. No significant difference in the size of the hyperaemia was found at 30% and 40% MVC. The increase in blood perfusion did not affect overall change in arterial blood pressure or heart rate. A mild specific warm-up exercise at 30% maximal voluntary contraction (MVC) increased the overall blood perfusion and oxygen (O_2) supply to the hamstrings.

In chapter 5, blood perfusion was measured in the hamstrings during periods of induced muscle damage in 12 volunteers. The aim was to investigate blood perfusion during periods of induced muscle damage. High forces during eccentric exercises cause microscopic damage in the muscle fibres causing pain and tenderness in the followed day. These symptoms were gone about one week later. This mechanism may increase the risk of further injury if athletes attempt an early return to sport. The results after two days of the exercise reported significant increase in muscle soreness and the concentration of creatine kinase

[CK], whereas mean torque fell. These observations confirmed that the exercise protocol succeeded in provoking delayed onset muscle soreness DOMS. The changes of total haemoglobin concentration [tHb] at 10 to 40% of MVC over the 3 visits were small and statistically non-significant. This suggests that no change occurred in blood perfusion during the period of DOMS.

In the fourth series of experiments, 6 cases of hamstring strains were evaluated. The aim was to investigate hamstrings blood perfusion in a series of case studies of athletes recovering from injury. One of the most important aims of these case studies was to investigate changes in [tHb] in the injured and non-injured limbs, as well as to investigate the electromyography (EMG) activity in the injured hamstrings and then compare it with the EMG activity in the non-injured hamstrings. The results of [tHb] had shown that there is no significant difference in blood perfusion between injured and non-injured hamstrings. The results of EMG activity had shown that some volunteers were not able to relax fully the injured hamstrings and others had some problems with relaxation of their hamstrings.

The following overall conclusions can be drawn: perfusion decreases in the hamstrings during contractions and then returns to normal levels after a period of time, changing the limb position at which the contractions are made does not affect the perfusion, warm-up exercises increase in blood perfusion for 8 minutes at 30 and 40% of MVC. The perfusion did not significantly change during an episode of DOMS or in the injured and non-injured limbs. These conclusions show the importance of warm-up before sports activities but not

necessarily avoid injury. It can be concluded that there is no association between such conditions with hamstring injuries. The maintained perfusion at different conditions is a positive finding as the perfusion is not restricted indicating good delivery of oxygen despite muscle injury.

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Abbreviations

NIRS	Near infrared spectroscopy
EMG	Electromyogram
[tHb]	Concentration of total haemoglobin
O_2	Oxygen
[CK]	Concentration of creatine kinase
DOMS	Delayed onset muscle soreness
MVC	Maximum voluntary contraction
BF	Biceps femoris muscle
CT	Computed tomography
ml/100g/min	Millilitre per hundred gram per minute
VO_2	Oxygen consumption
VO_{2max}	Maximum oxygen consumption
[HbO_2]	Concentration of oxy-haemoglobin
[HHb]	Concentration of deoxy-haemoglobin
nm	Nano-metre
Hb	Haemoglobin
Mg	Myoglobin
PhD	Doctor of Philosophy
CED	Cambridge electronic design
Hz	Hertz
Nm	Newton metre
ANOVA	Analysis of variance
StDev	Standard deviation
PC	Personal computer
~	Approximately
°	Degree
cm	Centimetre
Kg	Kilograms
BP	Blood pressure
HR	Heart rate
bpm	Beat per minute

U/L	Unit per litre
mm Hg	Millimetres of mercury
ROM	Range of movement
RICE	Rest, ice, compression and elevation
R	Right
L	Left
WU	Warm-up

Chapter One

Introduction & Literature Review

1.1 Introduction

The human body contains bones and skeletal muscles that enable us to perform a variety of actions such as walking, running, throwing and jumping. During these and other movements the body may be at risk of injury. These injuries could occur during the activities daily life but are seen most clearly as sports injuries. The frequency and severity of injuries may be different in activities of daily living and in sport. For instance, in daily life people of all ages are at risk of some type of injuries such as unexpected falls or trips, awkward twisting or sudden movements. Many of these injuries are left treated, though a few are reported to hospital Accident and Emergency Department or to General Practitioners. Sports injuries probably affect a younger population. These injuries commonly occur due to many causes. These include slips, accidental collisions, training errors and faulty technique. They all lead to acute muscle strains, joint sprains or fractures. The similarities between the causes of injury in the general and the sporting populations include high speed and high force movements.

Athletes attempt to reduce the likelihood of muscle damage by including a period of warm up in their preparation for activity. However, even with this precaution some injuries occur. The diagnosis and management sporting injuries require particular expertise. They can be treated in either a sports injury clinic or

hospital. The main aim of the processes of treatment and rehabilitation following sports injury is to return the athlete to his previous level of competition as soon as possible.

Muscle strains are common in all sports with the muscles of the thigh being affected most frequently (Fried & Lloyd, 1992). Hamstring strains are 2.5 times more frequent than quadriceps strains among professional football players in England (Hawkins, Hulse, Wilkinson, Hodson and Gibson, 2001). It is important to know the major factors causing injury in order to prevent injury. Neely, (1998); Taimela, Kujala and Osterman, (1990); Croisier, (2004) reviewed risk factors for sports injuries. They reported that risk factors for exercise and training-related injuries can be divided into two categories. The first category is related to the athlete and can be described as intrinsic risk factors e.g. age, muscle strength and previous injury. The second category is related to the environment and can be described as extrinsic risk factors e.g. type of activity, warm-up and stretching. They also mentioned that muscular strains are mostly associated with compound risk factors.

Yamamoto, (1993) studied the relationship between hamstring strains and leg muscle strength. He concluded that several factors are involved in predisposing the hamstrings to injury such as the weakness of muscle strength and imbalance of antagonists. Lack of flexibility was found to be a risk factor by Witvrouw, Danneels, Asselman, D'Have and Cambier, (2003). These studies found that strains of the hamstring muscles were more common than strains of the quadriceps muscles. Other factors have been reported by Kujala, Orave and

Jarvinen, (1997). They studied the current trends in treatment and prevention of hamstring injuries. Although hamstring muscle strains are frequently reviewed in the literature, it is rare for authors to identify which of the three muscles is injured.

In a study of hamstring injuries in English professional football Woods, Hawkins, Maltby, Hulse, Thomas and Hodson, (2004) found that hamstring strains accounted for 12% of the total injuries with 53% involving the biceps femoris (BF) muscle. This study covered 91 professional football clubs over two seasons. In 57% of cases, the injury occurred during running. Garrett, Rich, Nikolaou and Vogler, (1989) evaluated 10 college athletes within 48 hours of the occurrence of hamstring strains. The mechanism and location of injury were clinically examined with computed tomography (CT) scans. He found that all injuries occurred while sprinting or kicking a ball. The injuries were primarily found in the BF muscle typically in proximal and lateral locations. The long head of the BF was the most frequently injured muscle in his sample (9 of 10 athletes). The number of cases in this study is small, but it shows that BF muscle is likely to be the most frequently injured muscle in the hamstring muscle group.

Many sports involve repeated forceful muscle actions. These may begin to make a partial tear in the muscle and this can become aggravated to severe muscle strains. During sudden changes in direction or in explosive sports, fast movements cause shortening and lengthening of hamstring muscles. The muscle length affects the torque produced. For instance, Lunnen, Yack and LeVeau, (1981) found that during maximal efforts, torque decreases when the hamstrings

shorten. The BF muscle developed a greater amount of torque in the lengthened position than in the shortened position.

In the case of the hamstrings, changes in muscle length may influence blood perfusion. It is not known which knee angles or muscle lengths might restrict the hamstrings blood perfusion most. Similarly, it is not known if there is a relationship between the length of the muscle and the risk of muscle injuries. Previous studies of muscle blood flow looked at the differences between the upper and lower limb. The peak oxygen uptake is significantly lower in the upper limb compared to lower limb (Bhambhani, Maikala and Buckley, 1998; Bonde-Petersen, Mørk and Nielsen, 1975). However, information regarding the difference in either muscle force and muscle blood perfusion between left and right lower limbs is lacking.

Muscle blood flow during dynamic exercise is higher than intermittent isometric exercise at the same exercise intensity (Laaksonen, Kalliokski, Kyröläinen, Kemppainen, Teräs, Sipla, Nuutila and Knuuti, 2003). Hicks, McGill and Hughson, (1999) studied muscle blood flow in the forearm during isometric contractions. They stated that the physiological literature contains conflicting data concerning the intensity of contraction at which blood flow is impaired by sustain contractions. Other studies suggested that blood flow appeared to be interrupted by contractions between 25 and 45% maximal voluntary contraction (Kahn, Jouanin, Bussière, Tinet, Avrillier, Ollivier and Monod, 1998; Daley, Khan and Hogemen, 2003). During intermittent static exercise, each contraction is followed by a recovery period. Muscle oxygenation reduces during

contractions and increases during recovery intervals. The extent of this change depends on the force and duration on the contraction and the length of recovery periods.

Athletes at all levels of performance, from recreational to elite, typically perform a warm-up before commencing their activity. Warm-up could be explained as a period of time that the body moves from resting position to some type of physical exercise. This may result in an increase in muscle temperature. Psychological and physiological benefits are expected after a period of warm-up. The psychological and mechanical benefits of warm-up are expected to be noticed as rehearsal but may not increase the athlete's body temperature. However, physiological benefits by some type of muscle exercise may be more effective in increasing body temperature. The important issue is to determine the intensity and duration.

Warm-up is believed by many to enhance performance, prepare athletes physiologically as well as psychologically and to prevent injuries (Shellock & Prentice, 1985; Sallay et al. 1996). This belief is held by coaches who are generally convinced of the positive effects of warm-up procedures. Although amateur and professional athletes perform warm-up, some are still injured. Other athletes, who for some reason did not warm-up effectively or did not warm-up at all, often avoid injuries. Thus, the question, which arises here is, does warm-up prepare athletes physiologically and/or reduce the risk of injury? It is difficult to state that warm-up definitely enhance performance and/or reduce risk of injury. It is still not clear how intense warm-up should be and for how

long the effect lasts. All the information in the literature is considered to be recommendations and suggestions rather than statements. In this study, trials were made to investigate the effects of the intensity of warm-up contractions on the magnitude and duration of increase in muscle blood perfusion.

Muscle strain injuries occur to "speed athletes" such as sprinters and football players. One common soft-tissue injury in sports involving sprinting and kicking a ball is the hamstring strain (Garrett, 1996). In a study which aimed to identify athletes at risk of hamstring strains, Proske, Morgan, Brockett and Percival, (2004), found that strain injuries often occur while the contracting muscle is lengthened in an eccentric contraction. Microscopic damage to muscle fibres occurs after a period of unaccustomed eccentric exercise that can lead to a more severe strain injury. When an individual undertakes intense exercise or unfamiliar eccentric exercise, muscle damage can result, leading to pain the next day or soon after. However, the muscle recovers and soreness disappears about one week later. This is called delayed-onset muscle soreness (DOMS).

DOMS is common at the beginning of the season when athletes are returning to training after a period of reduced or no activity. Previous experiments have shown that eccentric exercise can provoke of muscle damage and soreness. For instance, McHugh, Connolly, Eston, Kremenic, Nicholas and Gleim, (1999) studied the symptoms of exercise-induced muscle damage. In days after eccentric exercise, participants reported sensations of stiffness, tenderness and pain. There were reductions in force and higher creatine kinase concentration [CK]. DOMS can affect sport performance by causing a reduction in muscle

strength. This mechanism may increase the risk of further injury if athletes attempt an early return to sport. It is interesting to study the perfusion of the hamstrings during DOMS since there is no previous study in the literature. In addition, the high frequency of hamstring strains and recurrence encouraged the researcher to focus on this muscle group in the hope that a better understanding of the problem will help to prevent further sports injuries.

1.2 Literature Review

1.2.1 Sports Injuries

Physical exercise exerts large stress on the functions of the human body. Participation in sports is expected to deliver health positive benefits. However, it is also accompanied by injuries, which may be sports-specific. An increased participation in sports will result in an increase in exercise related injuries. Benazzo, Mosconi and Zanon, (2000) studied the epidemiology of traumatic injuries in track and field athletes. They stated that sporting injuries to skeletal muscles may occur either through direct trauma or through overuse strains causing kind of muscle damage. Direct muscle injuries more often occur in contact sports by a collision with an opponent. Indirect muscle strains are common in sports involving maximum speed, explosive sports such as sprinting and long jump events. In track and field specifically, traumatic and overuse injuries are common.

Studies show that most of injuries were seen in the lower limb. For example, the study of sports and exercise related injuries in the United Kingdom by Nicholl, Cileman and Williams, (1995) revealed that the most frequent injuries were sprains of the lower limbs. Fried & Lloyd, (1992) reported that musculoskeletal injuries are common in different sports and mainly affect the lower limb e.g. thigh and calf muscles. Petersen & Hölmich, (2005) reported that muscle injuries represent a continuum from mild muscle cramp to complete muscle rupture and in between is delayed onset muscle soreness and partial strain

injury. Garrett, (1990) described a strain injury as an acute and usually painful event which is recognised by the patient as an injury. Strains not only result in significant loss of time from sports activities, but are also a frequent source of pain and impaired performance following return to competition (Safran, Seaber and Garrett, 1989)

1.2.2 Risk Factors Associated with Sports Injuries

Sports injuries may occur as a result of various factors intrinsic and extrinsic (Bahr & Holme, 2003) and the interaction between them prepares the athlete for an injury to occur in particular situation. It is important to focus on the major associated risk factors to understand sports injuries. There is an agreement amongst studies that a musculoskeletal injury results from compound risk factors. Lysens, Weerdt and Nieuwboer, (1991) studied factors associated with injury proneness, reported that injury occurs as a result of a summation of various factors at a given time. Van Mechelen, Hlobil and Kemper, (1992) studied the incidence, severity, aetiology and prevention of sports injuries. They considered the injuries to be associated with internal and external risk factors. The external risk factors include sport-related factors e.g. type of sport, level of competition, nature of event, environmental aspects e.g. type and condition of playing surface, weather conditions, training programme e.g. fast progression in intensity, distance, faulty technique, incorrect equipment, surfaces and poor conditions. The internal risk factors include physical characteristics e.g. age, height, weight, physical fitness e.g. poor flexibility, muscle weakness, muscle imbalance, history of previous injury (Taimela et al. 1990 and Van Mechelen et

al. 1992). Furthermore, Bahr & Holme, (2003) added to the previous studies the following risk factors; modifiable factors e.g. strength and flexibility and non-modifiable factors e.g. gender and age. It appears that all the reported factors predispose the athlete to injury and lead to pain as well as reducing sports participation. Thus, it is important to study and understand the associated risk factors influencing the incidence of sports injuries in attempt to introduce preventative strategies. The aim is to look at some of the associated risk factors influencing the hamstring injury. Although there has been a rapid growth in understanding the associated risk factors of the hamstring strains, the incidence of injuries during sports participation is still high. Orchard & Best, (2002) had a different opinion. They stated that despite apparently thorough management plans, objective testing and clinical evaluation before return to play, these injuries often recur. Their impression was that the clinician has failed by allowing the athlete to return to sport too early.

1.2.3 The Prevalence of Hamstring Muscle Strains

The hamstring muscles seem to be the most commonly injured among athletes in many sports, especially those which require speed or rapid accelerations. For example, Dadebo, White and George, (2004) found that 11% of all injuries and 33% of muscle strains in English football clubs are hamstring strains and that 14% of these hamstring strains are re-injuries. Orchard & Seward, (2002) in epidemiological study of Australian Football League injuries found the injury prevalence was 16% with high incidences of lower limb muscle strains. The hamstring strain was the most common injury, resulting in 21 missed matches

per club per season. Verrall, Slavotinek, Barnes, Fon and Spiggins, (2001) found that hamstring injuries are common among elite footballers in Australian football clubs and previous posterior thigh injury is a significant risk factor. In water skiing Sallay et al. (1996) found that hamstring muscle strains account for the largest percentage of muscle injuries of any of the muscle groups and were associated with severe injuries near the origin of hamstring muscles. Also, in a follow up study of athletics injuries in Scotland, lasting five years, Walker, (1989) found that the hamstring was the most frequently injured muscle in all age groups and 25% of the injuries were a strain or tear of the hamstring muscles. Adeniran & Toriola, (1985) found that the hamstrings muscle was one of the most frequently injured by young Nigerian athletes.

1.2.4 Mechanisms of Hamstring Injuries

Researchers have attempted to decrease the number of sports injuries (Safran, Garrett, Seaber, Glisson and Ribbeck, 1988; Nicholl et al. 1995; Orchard & Seward, 2002; Proske et al. 2004). Reducing the frequency of injuries requires further investigation and clearer understanding of the causes and mechanisms of sports injuries. The mechanism of injury may be divided into (a) traumatic injuries caused by large forces (macrotrauma) and (b) overuse syndromes caused by repetitive microtrauma. Traumatic injuries are common in contact sports such as football, rugby etc. The cause and severity are usually obvious and may occur suddenly with immediate pain and swelling which may develop to reach a maximum after several hours. Overuse syndromes are common in sports requiring skilled technique and repetitive movements such as long-

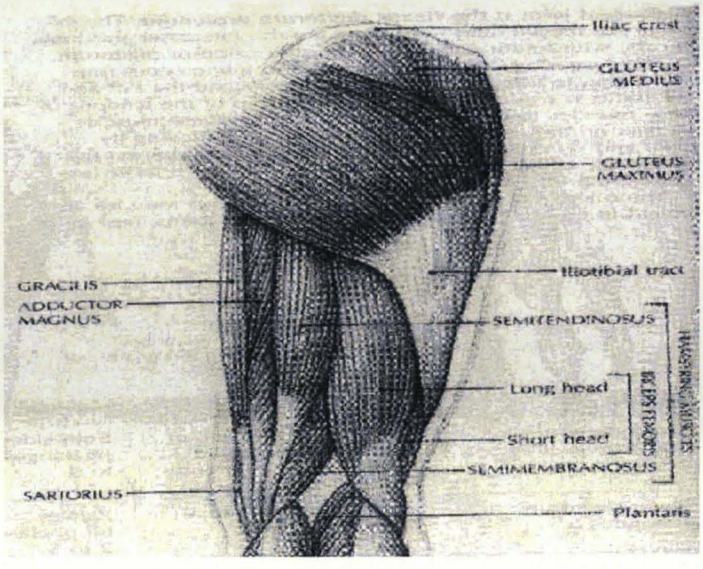
distance running, tennis, weightlifting etc. Overuse injuries are generally caused by repetitive overloading, resulting in microscopic injuries to the musculoskeletal system and difficult to diagnose and treat (Peterson & Renstrom, 2001).

The mechanism of muscle injuries has been discussed by several authors (Orchard, Marsden, Lord and Garlick, 1997; Yamamoto, 1993). Most of them relate hamstring weakness to the possibility of future re-injury. In a study of the incidence of injuries, Yamamoto, (1993) found that the imbalance of hamstring strength and significant lower hamstring to quadriceps ratio were the parameters related to the occurrence of hamstring strains. Also, Orchard et al. (1997) measured the hamstring muscle torque at intervals throughout the season and found a significant association between preseason hamstring muscle weakness and subsequent development of hamstring muscle strain injury. This study suggested that strength deficits are more relevant to the development of hamstring muscle injury than abnormal flexibility. These authors believe that hamstring strains occur when strong concentric quadriceps contractions generate forces greater than the eccentric strength of the hamstrings that cannot withstand. They concluded that hamstring strains were significantly associated with low hamstring to quadriceps ratio of peak torque on the injured side and a low hamstrings side to side ratio of peak torque. Woods et al. (2004) related the high incidence of hamstring injuries to its action over two joints. It is still not clear why some muscles are more susceptible to strains than others.

1.2.5 Anatomy of Hamstrings Muscle

The hamstrings muscle lies in the posterior thigh. It has three parts: biceps femoris, semitendinosus and semimembranosus. With the exception of the short head of the biceps, they all cross the hip and knee joints. The biceps femoris (BF) muscle has two heads. The long and short heads of the biceps have different origins and innervations. They are almost separate muscles. The primary action of the long head of the BF muscle is extension of the thigh. The primary actions of the short head are flexion and lateral rotation about the knee (Agre, 1985; Arrington & Miller, 1995; Terry & LaPrade, 1996). Both heads can act at the hip and knee joints simultaneously to maintain and coordinate movements such as extending the hip and flexing the knee.

Figure 1.1: The hamstring muscles



The hamstrings are muscles at the back of the thigh consisting of the biceps femoris (long and short heads), semitendinosus and semimembranosus muscles.

The BF muscle is the most commonly injured muscle of the hamstring group (Kujala et al. 1997).

At the level of the thigh, the external iliac arteries become the femoral arteries, providing the major blood supply to the lower extremity. The femoral artery gives off several branches in the thigh region, including the deep femoral artery, which serves the posterior and lateral thigh muscles such as the hamstrings. In addition, the lateral and medial femoral circumflex arteries supply the region of the femoral head (Anderson, Hall and Martin, 2000).

1.2.6 Types of Muscle Contractions

Skeletal muscles are specialised for the process of contraction. Faulkner, Brooks and Opitek, (1993) stated that when skeletal muscle fibres are activated three different types of contractions can result. If the force developed by the muscle is greater than the load on the muscle, a shortening or concentric contraction occurs. When the force developed by the muscle and the load are equivalent, or the load is immovable, a fixed length or isometric contraction results. The third type of contraction occurs when the load on the muscle is greater than the force developed by the muscle and the muscle is stretched whilst active. This produces a lengthening or eccentric contraction.

Muscle force can be measured under isometric, isotonic or isokinetic conditions. Isometric measurement is a popular and simple technique compared to those mentioned above. Isotonic testing is more closely related to functional

movements; isokinetic testing controls angular velocity and provides measurement of dynamic strength (Lord, Aitkens, McCrory and Bernauer, 1992). Most sports activities are mixture of these three types of activities. For example, rock climbing involves intense periods of sustained and intermittent isometric forearm muscle contractions mixed with dynamic eccentric and concentric contractions during movement (Grant, Shields, Fitzpatrick, Mingloh, Whitaker, Watt and Kay, 2003).

Torque is the product of a force and its moment arm. Torques rotate a body segment about a joint. Peak torque is the highest output of the joint produced by muscular contraction as a limb moves through the range of motion (Kannus & Kasuda, 1992). Isometric contraction develops muscle tension with no joint movement. When a muscle crossing a joint develops tension, it produces a force pulling on the bone to which it attaches; thereby creating torque at the joint the muscle crosses (Hall, 1991). The amount of torque produced by a muscle depends on the number of motor units activated, the muscle length and the moment arm of the muscle (Lunnen et al. 1981).

It is important to determine how the hamstring muscles behave during different movements. When the hamstring muscles shorten, they cause flexion at the knee. The hamstring muscle group has an important role in sports activities especially during the gait cycle of walking and running. Worrell & Perrin, (1992) reported that with increasing speed of running and sprinting, the period of time in which the muscles of the lower extremity are active is shortened.

Therefore, these muscles must contract faster and absorb more force during a shorter period of time.

There is no previous study investigated the relationship between torque and blood perfusion of the hamstring muscles. In addition, it is not known if some limb positions, and muscle lengths, impose particular problems for maintaining blood perfusion.

1.2.7 Delayed-Onset Muscle Soreness (DOMS)

When athletes carry out eccentric exercises the active muscles are lengthened during muscle contraction. This results in post exercise muscle soreness or delayed-onset muscle soreness (DOMS) (Clarkson & Tremblay, 1988; Nosaka & Newton, 2002). For example, lifting weights up and down causes muscle soreness and stiffness 24 to 48 hours after exercise and this usually goes after 5 to 7 days. The result of eccentric exercise is fibre damage. This leads to pain and tenderness the following day or soon after and these symptoms recover about one week later. Pain is defined as an unpleasant sensory experience associated with actual or potential tissue damage (Visser & van Dieën, 2005). It has been reported that there are two main types of pain associated with exercise, one arising during the activity and the other occurring some time afterwards. This 'muscular stiffness' is often described in the literature as DOMS (Jones, Round and de Haan, 2004). DOMS is classified as type I muscle strain injury and presents with tenderness or stiffness to palpation and/or movement (Cheung, Hume and Maxwell, 2003). Other changes include increase in plasma levels of

muscle proteins, swelling and inflammation observed 24 to 48 hours post exercise. These changes are commonly accepted as indicators of muscle damage.

During a week following eccentric exercise mechanical and chemical changes are expected. The mechanism and mechanical signs of muscle damage have been discussed by Proske & Morgan (2001). They considered a number of factors involved in muscle damage such as fatigue due to metabolic exhaustion, structural damage to the contractile filaments and failure of the excitation-contraction coupling process. Most blood chemistry changes peak within 24 hours following exercise. The presence of enzymes normally confined to muscle, such as CK, is a reliable indicator of muscle damage (Cheung et al. 2003). In normal resting conditions, plasma CK is approximately 60-190 IU/L (Newham, Jones and Clarkson, 1987). However, following eccentric exercise, circulating levels of CK have been known to rise to 40,000 IU/L. This significant increase indicates disruption in muscle fibres (Cheung et al. 2003).

Eccentric contraction-induced muscle injury has become important in the investigation of muscle injury. The main aim is to find a way of preventing muscle injury. However, there is no general methodological agreement. A number of theories have been proposed to explain the pain associated with DOMS. These include lactic acid accumulation, muscle spasm, connective tissue damage, muscle damage, muscle inflammation and enzyme leakage or cell damage. The general consensus amongst researchers is that a single theory cannot explain the onset of DOMS (Cheung et al. 2003). Blood concentrations

of creatine kinase (CK) have been used as a marker of eccentric contraction-induced injury in many studies (Newham et al. 1987; Nosaka & Newton, 2002). The peak concentrations of [CK] in blood occur after 24 hours. It is not clear what will happen to the blood perfusion of the hamstrings after strenuous exercise.

The study of changes in passive tension of muscle after eccentric exercise by Whitehead, Weerakkody, Gregory, Morgan and Proske, (2001) revealed that after a series of eccentric contractions passive muscle stiffness increases. As a result, it requires more force to produce a given stretch of the whole muscle even when it is fully relaxed. This is present immediately after a series of eccentric contractions and it is independent of fatigue. Passive tension rises as a result of damage to fibres. This may be explained by damaged sarcomeres shortening as a result of active cross-bridge cycling. The level of passive tension generated by the injured fibres decreases over time. The increase in series compliance represented by the presence of the disrupted sarcomeres will tend to lower passive tension and will delay onset of the rise in passive tension during a stretch. So there are two opposing influences acting on the muscle, an increase in passive tension and an increase in series compliance.

1.2.8 Do Eccentric and/or Concentric Exercises Produce Muscle Damage?

Previous experiments have shown that eccentric exercise causes muscle damage with varying degrees of swelling and levels of muscle soreness. For example,

Nosaka & Newton, (2002) showed that eccentric training is more effective than concentric training in damaging the elbow flexor muscles. The other finding was that repeated bouts of the same eccentric exercise induced less muscle damage than the initial bout. However, others have different opinions. Whitehead, Allen, Morgan and Proske, (1998) compared trained and untrained calf muscles during eccentric and concentric exercises. They concluded that concentric training regimes produce changes in muscle which will make it more prone to damage from eccentric exercise. Delayed-onset muscle pain develops in stretched muscles and is more specifically associated with eccentric contractions. It can also be induced by high-force isometric contractions if the muscle is exercised at a long length (Jones et al. 2004). The intensity of the exercise is critical factor in producing muscle damage.

Studies have shown that certain types of exercise produce temporary, repairable muscle damage (Newham et al. 1987; Clarkson & Tremblay, 1988; Nosaka & Newton, 2002). The most effective type is the eccentric exercise that causes damage and destruction to muscle fibres. After the initial damage muscle fibres may fail to repair and subsequently undergo degeneration, recovering and releasing soluble enzymes. Few days after exercise, a rapid adaptation in the muscle fibres appears that become more resistance to the fatiguing and damaging effects of eccentric exercise (Clarkson & Tremblay, 1988). A different mode of eccentric actions for the same muscle group could produce the protective effect. It seems that training prevents against eccentric exercise damage or reduces muscle damage (Nosaka & Newton, 2002).

1.2.9 Warm-Up

Warm-up could be explained as a period of time when the body moves from rest to some type of physical exercise. Specifically, in sport the term warm-up refers to a type of exercise performed by the athlete before starting sporting activity. The results are higher core temperature, higher heart rate and more blood flow throughout the body especially to the exercising muscles (Bergh & Ekblom, 1979; Gerbino, Ward & Whipp, 1996).

Three types of warm-up were reported by Shellock, (1983); passive, general (non-specific) and specific. Passive warm-up raises the muscle temperature by some external means such as a hot shower, heating pads or spending time in a heat chamber. General or non-specific warm-up increases the muscle temperature through active movement of the various major muscle groups. This is typically performed by low intensity of any type of aerobic activity such as jogging, cycling or jumping. This type of warm-up has an effect on cardio-respiratory functions and body temperature. Also, it has physiological benefits that are directly related to increased muscle temperature. Specific warm-up increases the limb temperature of the body parts involved in the activity, provides a slight rehearsal of the required sport event and concentrates on the neuromuscular portions of the body that will be used in the anticipated exercise (Kato, Ikata, Takai, Takata, Sairyo and Iwanaga, 2000). Specific warm-up usually focuses on muscles that will be used during the activity. This type of warm-up is particularly useful for strenuous activities that involve repeated movements and complex skills that require fast reactions such as sprinters

during acceleration exercise or hurdlers during stretching. Another example is the weight lifter as he increases the weight gradually close to maximum. For these reasons, specific warm-up appears to be the most desirable method.

It is accepted by the majority of people that warm-up exercise enhances performance (Inbar & Bar-Or, 1975; Bishop, Bonetti and Dawson, 2001) and reduces the chance of muscle injury to occur (Thacker, Gilchrist, Stroup and Kimsey, 2004). Despite the general belief of the benefits of warm-up, there are limited scientific data on this issue. The advantages can be described as physiological, psychological and injury prevention. A period of warm-up is intended to help the athlete physically and psychologically. By controlling the intensity and duration of warm-up, different physiological changes can be achieved. This includes increasing blood flow to the muscles (Daley et al. 2003). If blood flow in the muscle increased after a period of warm-up, it is expected to increase muscle temperature and so improve the speed of muscle contraction. In addition it helps to maintain the supply of oxygen and nutrients to the exercised muscle and removes waste products (Harms, Babcock, McClaran, Pegelow, Nickele, Nelson and Dempsey, 1997; Clark, Rattigan, Clark, Vincent, Clark, Youd and Newman, 2000).

The above paragraph shows that the majority of the effects of warm-up are related to physiological changes. The psychological benefits are also associated with improvements in performance. The psychological benefits of warm-up are may not increase the athlete's body temperature. Psychologically, performance can be considered to be a function by extension the interaction of intrapersonal

factors, that is between the athlete and himself e.g. making decisions and interpersonal factors, that is between the athlete and others e.g. stress or pressure from other people. Both intra-personal and inter-personal factors are important in the successful performance of individual sports (Hamilton, 2000). Shellock & Prentice, (1985) suggested that warm-up may improve performance by providing time to concentrate. Psychological benefits can be achieved when an athlete believes that warm-up has an advantage for whatever reason e.g. rehearsal and belief in oneself. This leads to an inspiring feeling and can give the athlete the confidence about his body. This has the potential to affect his performance positively; especially when this belief is supported by the coach or physiotherapist.

Physiotherapists recommend the performance of warm-up routines for muscle injury prevention (Thacker et al. 2004). Researchers have tried to find a direct relationship between warm-up and injury prevention. Little scientific evidence exists to support this idea. High & Howley, (1989) studied the effects of static stretching and warm-up on prevention of DOMS. They concluded that stretching and warm-up does not prevent DOMS resulting from exhaustive exercise. Safran et al. (1988) reported that pre-exercise stretching and adequate warm-up are important in the prevention of hamstring injuries by increased perfusion increasing the supply of nutrients and reducing fatigue. Therefore, a recommended preventative procedure of warm-up would help athletes to be prepared both physically and mentally for a competitive sport.

In some sports e.g. athletics and football, athletes start their warm-up with light exercise followed by stretching. In other sports e.g. weight lifting and cycling, they may start with some type of light sport-specific exercise or without any type of warm-up. Then, depending on the sport involved, athletes concentrate on technique and movements to prepare them to their sport. A specific warm-up is a type of exercise involves movements of body parts that will be used during the sporting event (Shellock & Prentice, 1985). Most runners consider that a proper warm-up consists of jogging or light cardiovascular activities (5-10 minutes) followed by light stretching exercises of different muscle groups. The aim of this procedure is to increase the body temperature.

Depending on the nature of the sport; athletes usually use different places for training. Environmental conditions such as climate may sometimes play an important role in the outcome of an injury. The performance of warm-up may depend on environmental factors e.g. cold and hot weather. Cold winter and hot summer temperatures may have had a harmful impact on the athlete's performance and risk of injury. Cold climates may have indirect effects on athletes in some sports. Lind, (1963) found that the body core temperature during exercise is influenced by environmental temperature over a wide range of temperatures. They concluded that above the upper critical temperature, core temperature increases to a higher level than during exercise, while below the lower critical temperature the core temperature falls. Severe cold has an effect on the central nervous system and cardiovascular system.

Sallis & Chassay, (1999) reported that at low temperatures, skin exposed to cold air may affect deep body regions such as muscles. Cold conditions can interfere with athletic ability by weakening and slowing muscle contractions and delaying nerve conduction time. This reduction in the temperature may put the muscles at risk of strains. Athletes who did not maintain warm temperatures could affect his performance or may be at risk of injury. Therefore, an appropriate warm-up may be necessary in these situations to maintain body temperature. Sallis & Chassay, (1999) also reported that most injuries that occur during cold weather are due to inability to protect oneself from the environment. Starting the exercise without or with insufficient or poor warm-up may put the athlete at risk. Warm-up and stretching may help decrease injury rates in cold environmental conditions. Warm-up is important in cold environmental conditions in order to maintain body and muscle temperature.

The situation is different during hot environmental conditions as the temperature of the athlete's body is already warm and is no need to spend long periods warming-up. It has been reported that athlete's heart rate and core temperature increases more in hot weather conditions and that may affect their performance (Fink, Costill and Van Handel, 1975).

Many athletes believe that stretching exercise as part of warm-up reduces the chance of injury. The role of stretching in enhancing flexibility or preventing injury is still unclear. Some studies find stretching reduces the risk of injury while others do not find this. Witvrouw et al. (2003) evaluated muscle flexibility as a risk factor. They considered stretching as one of the risk factors associated

with hamstring strains. Williford, East, Smith and Burry, (1986) evaluated the effects of warming up by jogging and then stretching on joint flexibility. They demonstrated that increases in flexibility can occur as a result of sustained stretching training programme.

From the above studies, benefits of warm-up can be summarised as preparing the body, heart, mind, rehearsal of specific skills and injury prevention before commencing the sports activity.

1.2.10 Does Warm-Up Improve Performance?

In humans, the normal value of the temperature is 37 °C. Various parts of the body are at different temperatures and the magnitude of the temperature difference between the parts varies with the environmental temperature (Bergh & Ekblom, 1979). The extremities are cooler than the rest of the body. The rectal temperature is representative of the temperature at the core of the body and varies least with changes in environmental temperature. The normal human core temperature undergoes a regular circadian fluctuation of 0.5 – 0.7 °C. It is lowest during rest and rises with activity. During exercise, the heat produced by muscular contraction accumulates in the body and the rectal temperature may rise at high as 40 °C (Saltin, Gagge and Stolwijk, 1968). The rise is due in part to the inability of the heat-dissipating mechanisms to handle the greatly increased amount of heat produced, but there is evidence that in addition there is an elevation of the body temperature at which the heat-dissipating mechanisms are activated during exercise. Body temperature also rises slightly during

emotional excitement, probably owing to unconscious testing of the muscles. It is chronically elevated by as much as 0.5 °C when the metabolic rate is high as in hyperthyroidism and lowered when the metabolic rate is low as in hypothyroidism (Levick, 2003).

Barcroft & Swan, 1953 established the theoretical basis for the quantification of heat transfer in perfused tissue. The major source of heat production is the activity of skeletal muscle. The amount of heat reaching the skin from the deep tissues can be varied by changing the blood flow to the skin. During muscular exertion in a hot environment, sweat secretion reaches values as high as 1600 ml/h and in a dry day atmosphere most of this sweat is vaporized.

Temperature is widely recognised as an important determinant of skeletal muscle function (Bennett, 1984). One effect of heating muscle is to alter the force/velocity relationship both in humans (De Ruiter & De Haan, 2000). This is despite the fact that the in vivo temperature of human skeletal muscles can vary over a wide range depending on environmental conditions and the metabolic heat liberated in the muscle itself (Ferguson et al. 2002). It is common practice for athletes to perform warm-up exercises prior to training or competition. However, the effect of muscle temperature on the mechanical efficiency of exercise in humans may be velocity-specific since it would imply a shift in the efficiency/velocity relationship (Sargeant, 1999). Increasing muscle temperature increases the speed of muscle contraction, thereby decreasing both time to peak tension and half relaxation time (Bennett, 1984). The alterations in metabolic response during exercise e.g. after an active or passive warm-up is associated

with elevations in muscle temperature (Gray & Nimmo, 2001). Heat production by contracting human skeletal muscle doubled over 3 minutes of intense dynamic exercise at essentially constant power output. Half of this increase in rate of heat production occurred during the first 38 s of exercise (González-Alonso et al. 2000).

Three important conditions affect the oxygen-haemoglobin dissociation curve: the pH, the temperature and the concentration of 2,3-disphosphoglycerate (DPG; 2,3-DPG). A rise in temperature or a fall in pH shifts the curve to the right. When the curve is shifted in this direction, a higher PO_2 is required for haemoglobin to bind a given amount of O_2 and vice versa. Exercise has been reported to produce an increase in 2,3-DPG within 60 minutes although the rise may not occur in trained athletes. The PO_2 increases during exercise, because the temperature rises in active tissue and CO2 and metabolites accumulate lowering the pH. In addition more O_2 is removed from each nit of blood flowing through active tissue because tissue pH2 declines. Finally, at low PO_2 values the HbO_2 dissociation curve is steep and large amount of O_2 are liberated per unit drop in PO_2.

Any muscle vasodilation associated with increased temperature may facilitate muscle perfusion allowing an increase in muscle blood flow (Koga, Tomoyuki, Narihiko and Thomas, 1997). Blood flow increases in the exercising muscles as the arterioles dilate. Oxygen delivery to muscles may be affected by a number of metabolic changes that occur in response to warm-up. The enhancement in O_2 delivery may be due to vasodilatation of muscle blood vessels at elevated

temperatures, increasing muscle blood flow. Physical work increases the potential energy output and the temperature of the muscles (Peterson & Renström, 2001). Shellock & Prentice, (1985) suggest that increasing body temperature causes more oxygen to dissociate from haemoglobin and myoglobin, lowers activation energy rates of metabolic chemical reactions, increases muscle blood flow, decreases muscle viscosity, increases sensitivity of nerve receptors and increases speed of nerve impulses.

Blood flow in resting skeletal muscle is known to be low at about 4 ml/100g/min (Barcroft & Swan, 1953; Laaksonen et al. 2003). During exercise, muscle blood flow increases by about 65 ml/100g/min (Harms et al. 1997). During maximal exercise, blood flow increases in the range of 50-150 ml/100g/min (Laughin, 1987). This increase in blood supply is to deliver the additional O_2 and nutrients that are needed as well as to remove any excess heat and products of metabolism (Bird, Black and Newton, 1997). Koga et al. (1997) carried out a study of the effect of increased muscle temperature on O_2 uptake kinetics during exercise. Their hypothesis was that increased muscle temperature may speed VO_2 kinetics in at least two ways: 1) it may speed limiting reaction associated with oxidative phosphorylation and 2) a rightward shift of the oxy-haemoglobin dissociation curve. Their results showed that as work intensity or muscle temperature increased, O_2 supply was not the limit to the initial muscle O_2 consumption. Thus VO_2 kinetics were not enhanced by increased temperature.

It has been reported that warm-up improves exercise performance in different ways. Buchthal, Kaiser and Knappeis, (1944) carried out a study of the elasticity, viscosity and plasticity in the skeletal muscle fibre. They found that at all degrees of stretch, tension in the resting muscle fibre decreases with increasing temperature. An increase in muscle temperature has effects on decreasing the stiffness of muscle during contraction. Inbar & Bar-Or, (1975) reported that anaerobic performance is significantly increased when preceded by an intermittent treadmill warm-up at 60% VO_{2max}. An increase in muscle temperature has been reported to change the force-velocity relationship by (Binkhorst, Hoofd and Vissers, 1977; Davies & Young 1983). Warm-up was also found to significantly improve peak power on a cycle ergometer by Sargent & Dolan (1987). Also, Gerbino et al. (1996) found that warm-up affected pulmonary gas-exchange kinetics during high-intensity exercise that in turn led to an improved muscle perfusion. In a recent review of mechanisms associated with warm-up, Bishop, (2003) reported that increased muscle temperature improves central nerve system function and increases the transmission speed of nervous impulses. These studies justify the physiological benefits of warm-up that enhance performance.

1.2.11 Does Warm-Up Prevent the Occurrence of Muscle Injury?

Many reports on muscle injury emphasise the importance of a warm-up period before activity and of maintaining flexibility to prevent injury. Therefore, warm-up routines have been highly recommended (Ekstrand & Gilliquist 1983; Shellock & Prentice, 1985; Hawkins & Fuller 1999). However, the experimental

evidence to support this is weak as no clear evidence was found in the literature. In a study of hamstring muscle injuries Sallay et al. (1996) found no conclusive protective benefit of warm-up. But, they suggest that warm-up and stretching may be protective in some cases. Lack of muscle flexibility was found to be a risk factor by Witvrouw et al. (2003). They found significant association between preseason tightness, flexibility and the development of hamstrings injuries. Shellock & Prentice, (1985) suggested that stretching is an essential component of the warm-up and should take place after the increase in temperature and blood flow. Stretching is widely regarded as an important exercise and is essential for flexibility in terms of injury prevention (Glein & McHugh, 1997). Safran et al. (1988) studied the role of warming-up in muscular injury prevention. They stated that warm-up stretches the muscle-tendon unit and results in an increased length at a given load. This put less tension on the muscle-tendon junction and results in a reduced incidence of strain injuries.

Safran et al. (1988) reported that when warming-up is combined with stretching, the elasticity of muscles is further increased, which means that a greater force or degree of lengthening is required to tear a muscle. Dadebo et al. (2004) conducted a study among 30 professional football clubs in England. They found that the use of a standard stretching protocol was the only factor related to the frequency of hamstring strains. They concluded that the use of sustained stretching may reduce hamstring strains in professional footballers. More research is needed to investigate the links between tissue biomechanics, warm up techniques and the frequency of injuries.

It should be noted that hamstring muscle injuries may occur at any time during exercise. Athletes can be injured in the early and/or late stages of training or competition. Hamstring strains at the beginning of practice could be related to insufficient warm-up, while strains in the late stages may be related to muscle fatigue. Many sports such as rugby, football and athletics require the athlete to rest between warm-up and the event or between first and second halves of a game. This raises the question of how long the benefits of warm-up persist? There is limited scientific evidence in human experiments. Magnusson et al. (2000) investigated the passive energy return after repeated stretches of the hamstring muscle-tendon unit. They found that warm-up elevated intra-muscular temperature significantly. About 80% of the temperature increase occurred in the initial 10 minutes of exercise and that 10 minutes of warm-up may be sufficient preparation for muscle performance.

1.2.12 Near-Infrared Spectroscopy & Blood Flow within Specific Tissues

Several techniques have been developed to enable estimates to be made of local blood flow within the muscle. They include electromagnetic flow meters, plethysmography techniques, ultrasound Doppler flowmeters, magnetic resonance velocity imaging and near-infrared spectroscopy (Rådegran, 1999). Near infrared spectroscopy (NIRS) has been used primarily as a research tool to assess dynamic changes in the status of tissue oxy-haemoglobin (HbO_2), deoxy-haemoglobin (HHb) and total blood haemoglobin (tHb) in brain and muscle. It allows continuous measurements and operates in real-time (Elwell, 1995). Quaresima et al. (2003) suggested that NIRS is a powerful tool. It can evaluate

muscle oxidative metabolism in athletes and its modification following potential therapeutic strategies and specific programs.

NIRS is a non-invasive technique using light that has the ability to penetrate skin, subcutaneous fat and underlying muscles. It is based on the relative ease with which near-infrared light (700-1000 nm) passes through biological tissues (Bhambhani et al. 1998; Boushel & Piantadosi, 2000). When near-infrared light (NIR) passes through tissues, some is scattered, some is absorbed and some is transmitted unaffected. The amount of light absorbed depends on the oxygenation status of haemoglobin (Hb), myoglobin (Mb) and cytochrome oxidase. NIRS is unable to differentiate between the amount of O_2 released by both Hb and Mb because the absorbency signals of these two chromophors overlap in the NIR range. This amount is small and may be considered negligible (Quaresima et al. 2003). The change is non significant and will not affect the tHb readings.

Absorbance of NIR light by water and lipids in the field of study remains constant and contributes to absorption uniformly. The absorption of light can penetrate up to 8cm of tissue with sensitive instrumentation (Elwell, 1995). Changes in the NIRS signal attributed to Hb saturation emerge primarily from the absorption of light in arterioles, capillaries and venules (Boushel, Langberg, Olesen, Nowark, Simonsen, Bülow and Kjaer, 2000). In skeletal muscle, a full range of oxygenation conditions can be exploited to provide both maximum and minimum spectral values during hyperaemia and ischaemia (Boushel & Piantadosi, 2000). Microscopic boundaries between large structures may cause

significant scattering e.g. between healthy and diseased tissues, soft tissue and bone and large blood vessels (Elwell, 1995) and chronic compartment syndrome (Breit, Gross, Watenpaugh, Chance and Hargens, 1997). The extent of light scattering by tissue should not change during any single experiment if the position of the optodes is fixed.

An advantage of the NIRS blood flow method is that blood flow in a specific muscle region can be measured directly. The practical advantages of the use of NIRS technique include ease of use and low consumables cost (Boushel & Piantadosi, 2000). NIRS as a research tool allows continuous measurements of [HbO_2], [HHb] and [tHb] in different muscles (Edwards, Richardson, Vann Der Zee, Elwell, Wyatt, Cope, Delpy and Reynolds, 1993; Elwell, 1995) in addition to the measurements of blood flow. In humans, Bhambhani et al. (1998) stated that NIRS has been used to evaluate muscle oxygenation and provide information regarding trends during exercise and recovery, which enables us to better understand the physiological factors influencing exercise performance.

NIRS allows the non-invasive measurement of local oxygenation, blood flow and oxygen consumption (Ferrari et al. 1997). It was first demonstrated by Fran Jobsis in 1977 and many improvements have been made since then. Based on the Beer-Lambert Law, NIRS uses the principle that photons of near-infrared light are absorbed by human chromophores with the NIRS signal predominately derived from light absorption by haemoglobin, in both its oxidised and reduced forms (Boushel et al. 2000). Oxygenated and deoxygenated haemoglobin absorb light equally at 800 nm, whereas at 760 nm absorption is primarily from

deoxygenated haemoglobin (Mancini et al. 1994) allowing them, along with total haemoglobin to be used as a measure of blood flow. The contribution of myoglobin to the 760 – 800 nm light absorption is believed to be approximately 10%, therefore it is predominantly derived from haemoglobin (Mancini et al. 1994).

Many variables have to be taken into account when calculating tHb, HbO_2 and HHb concentrations. The attenuation of light in a biological tissue is a complex function of the scattering and absorption coefficients of the tissue as well as the geometry of the tissue and measurement optics (Edwards et al. 1993). Therefore, NIRS is programmed with a modified version of the Beer-Lambert Law to take these variables into consideration (see the equation below).

Beer-Lambert Law: $A = \varepsilon [c] LB + G$

Where:

A is the absorption of light expressed as optical density

ε is the extinction coefficient of the chromophore

[c] is the concentration of the chromophore

L is the distance between point of light exit and point of light entry

B is the path length resulting from scattering in the tissue

G is the factor related to tissue and optode geometry

It is possible to use NIRS to study changes in Hb concentration, muscle O_2 saturation and muscle blood flow during exercise. During work, the extent to which skeletal muscles deoxygenate varies according to the type of muscle, type of exercise and blood flow response. Foster, Rudell, Snyder, Stray-Gundersen,

Gerard, Thometz, Broker and Knapp, (1999) investigated blood flow in the quadriceps muscle during speed skating. They observed a restriction in flow in the muscle since there was greater O_2 desaturation. The restriction of blood flow can be attributable to the high intramuscular forces during the long duty cycle of the skating stroke. The results show that the magnitude of desaturation during static contractions in vastus lateralis was progressively greater at flexed knee positions. The reduced muscle blood flow may have physiological or biomechanical disadvantages. More studies are needed to understand the interaction between muscle blood flow, performance and muscle strain. No studies have been found in the literature focusing on the relationship between muscle injury and blood perfusion of the hamstrings. The present study is the first to measure the blood perfusion directly in a specific muscle region.

1.2.13 Reactive Hyperaemia & Muscle Blood Perfusion

The most important circulatory responses are: the autoregulation of flow, functional hyperaemia and reactive hyperaemia. The relation between perfusion pressure and perfusion in skeletal muscle is remarkable, because changes in perfusion pressure over a wide range have little effect on the steady state blood flow.

The hyperaemia during sustained exercise is less pronounced than during dynamic exercise because the sustained rise in intramuscular pressure limits the dilatation of resistance vessels. Conversely, an O_2 debt builds up rapidly and progressively. This leads to the anaerobic production of lactic acid and rapid

fatigue of the muscle. Hyperaemia is achieved through the co-ordinated dilatation of arterioles, terminal arteries, feed arteries and conduit arteries. The mechanisms responsible for the co-ordinated vasodilatation are: a) metabolic vasodilatation of the terminal arteries and arterioles i.e. resistance vessels; b) ascending vasodilatation of the smaller feed arteries; c) flow-induced vasodilatation of the large conduit arteries.

Reactive hyperaemia is defined as the immediate increase in blood flow as a response to contracting muscle when the circulation is re-established after a period of occlusion (Bonde-Petersen et al. 1975; Tschakovsky et al. 1996; (Farouque & Meredith, 2003). For example, if the artery is occluded and then released an increase in flow is produced and blood flow is re-established. Rhythmic actions of muscular contractions help to pump blood to and from the capillary beds.

Tissue ischaemia occurs if a conduit artery is compressed to impair the blood perfusion to a tissue or to reduce perfusion to a point where it cannot meet the tissue O_2 requirement. The blood perfusion upon releasing the compression is many times higher than normal; this is called reactive or post hyperaemia. The value of reactive hyperaemia lies in optimising the supply of O_2 and nutrients to ischaemic tissue.

Perfusion increases with increasing perfusion pressure. A rise in pressure initially raises the perfusion. Arterioles respond by contracting within 30-60 seconds of the increase. This rise in vascular resistance reduces the perfusion to

almost its former level. Conversely, a fall in perfusion pressure evokes vasodilatation, which reduces the resistance and restores the flow.

Two mechanisms have been proposed for autoregulation; the myogenic response and vasodilator washout. In the myogenic response the vascular smooth muscle responds by to stretch by contracting. The vasodilator washout theory proposes that the increased perfusion following increased arterial pressure reduces the concentration of vasodilator metabolites such as acidosis, hypoxia, adenosine, potassium ions, phosphate ions and hyperosmolarity.

During isometric contractions, blood flow decreases and then after contractions it increases. Kahn et al. (1998) assessed muscle oxygenation of elbow flexor muscles during isometric contractions at 25% up to 100% MVC. They found that blood flow was strongly reduced during contractions at 50% MVC. This decrease is caused by intra-muscular pressure during contraction (Bonde-Peterson et al. 1975).

Foster et al. (1999) observed an increase in the blood flow in quadriceps muscles after isometric contractions at 30% MVC. Daley et al. (2003) noticed an enhancement of blood flow after rhythmic handgrip exercise at 40% MVC. Tschakovsky, Shoemaker and Hughson, (1996) suggest that both a functional muscle pump and rapid vasodilation act in concert to initiate the increase in blood flow during the first 5 seconds of exercise in human skeletal muscle. It can be seen that contractions between 30% and 50% MVC may be enough to increase blood flow after exercise

In rhythmically exercising skeletal muscle the mean blood perfusion increases but the perfusion oscillates. The perfusion falls during each contraction phase because the vessels within the contracting muscle are compressed. The perfusion is increased during phases of muscle inactivity. Myoglobin within the muscle fibres holds a small O_2 reserve for use during the poorly perfused contraction phase.

Doppler ultrasound techniques have been used to study the perfusion of blood in the femoral and brachial arteries during isometric muscle contraction in human volunteers (Tschakovsky, Shoemaker, and Hughson, (1995). They demonstrate that at the onset of exercise there is a very rapid elevation in the blood velocity and thus blood flow. The arterial perfusion occurred almost between contractions.

Depending on the intensity of activity, the blood perfusion stabilised within 30 – 90 seconds and a minor further increase occurred during very intense exercise (Saltin, Rådegran, Koskolou, and Roach, 1998). They estimated that during dynamic knee-extensor exercise about 90% of the measured femoral arterial flow blood perfuses muscle.

A variation in [Hb] of the blood affects the tissue perfusion. A lowering of the [Hb] is compensated for by an increase in blood perfusion (Koskolou, Roach, Calbet, Rádegran and Saltin, 1997). Andersen & Saltin, (1985) observed that peak muscle perfusion was 200 – 220 mL/100g/min. The muscle perfusion in well trained bicyclists reached 380 mL/100g/min (Blomstrand, Rádegran, and

Saltin, 1997). Considering the size of the knee-extensor muscles, perfusion during peak effort may amount to 2 – 3 L/Kg, i.e. approximately 100-fold elevation from rest. The onset of hyperaemia is very fast at the start of exercise. Its magnitude is related to the power output. The muscle pump brings about the very first increase in blood perfusion (Saltin, Rádegran, Koskolou and Roach, 1998).

Blood flow is known to be low during rest and when activity begins it increases in the exercising muscles as the arterioles dilate. A rapid increase in physical work increases the potential of opening the capillary cross-sectional area (Grant et al. 2003). Above a certain force of contraction there is a decrease in flow, in spite of increasing demands for O_2 (Bonde-Petersen et al. 1975). Different degrees of force output can be developed during exercises which depend on the muscle group and type of contraction. The question arises here, at what force level the blood perfusion decreases in the hamstrings.

The muscle pump theory states that muscle contraction aids muscle perfusion by emptying the venous circulation, this lowers venous pressure during relaxation and so increases the pressure gradient across the muscle. This facilitates an increased arterial inflow (Laughlin, 1987). The skeletal muscle pump can be considered as a rapid localised mechanism by which blood flow could be increased to active skeletal muscle (Hamann, Valic, Buckwalter and Clifford, 2003). Blood flow is determined by two factors: perfusion pressure and vascular conductance. If maximal vasodilation is attained, then blood flow becomes a function of perfusion pressure (Laughlin, 1987). The enhanced blood flow

response to a single contraction or rhythmic exercise when the limb is positioned below the heart is attributed to the muscle pump (Tschakovsky et al. 1996). Laughlin, (1987) suggested that muscle pump may be more effective in dynamic exercise than during stimulated contractions due to sequential fibre activation than simultaneous activation of all fibres. The muscle pump may itself increase local flow through sudden release of veins and increase the pressure gradient across muscle and flow would be enhanced through the rhythmic cycle of contraction and relaxation (Maughan 1999). When a muscle contracts, it compresses the vessels in it if it develops more than 10% of its maximal tension; when it develops more than 70%, blood flow is completely stopped. Between contractions, flow is greatly increased. Because venous blood is under relatively low pressure, veins are easily compressed by the smallest muscular contractions (William & Wilkins, 1994).

Muscle pump is responsible for the immediate rise in blood flow seen at the onset of contractions (Joyner & Proctor, 1999). The marked increase in blood flow during recovery compensates for the reduced flow during sustained contraction. Most of reactive hyperaemia studies focused on the forearm muscles. No studies were found investigating blood perfusion in the hamstrings. Does warm-up exercise, which is a type of muscle contraction, change the blood perfusion?

1.3 Aims

The main aim of this thesis is to examine the influence of activity of the hamstring muscles on their blood perfusion. The main aim will then be subdivided to investigate the following:

1) To measure the magnitude and the time course of changes in hamstrings blood perfusion during isometric contractions at a series of muscle lengths.
2) To compare the magnitude of the changes in muscle forces and muscle blood perfusion in the left and right hamstrings.
3) To investigate the effects of specific warm-up contractions on hamstrings blood perfusion.
4) To measure the size and duration of the increased blood perfusion after specific warm up contractions.
5) To investigate hamstrings blood perfusion during periods of induced muscle damage.
6) To investigate hamstrings blood perfusion in a series of case studies of athletes recovering from injury.

Chapter Two

General Methods

2.1 Participants

Forty six male volunteers aged between 15 and 48 years participated in the experiments reported in this PhD thesis. The Faculty Ethics of the University of Glasgow approved the study. All volunteers were recruited from the University of Glasgow staff and students. All volunteers were informed of the nature of the experimental procedure prior to starting the experiment. They were free to withdraw from the tests at any stage. None from the subjects withdrew from any of the experiment stages. All tests took place in the exercise physiology laboratory in the West Medical Building of Glasgow University.

The inclusion criteria were as follows: (1) the volunteers rated themselves as being in good physical health; (2) they had no skeletal muscle disorders; (3) they had not suffered from hamstring injuries in the last 12 months. The exclusion criteria were as follows: (1) a current history of hamstring injury in the last 12 months; (2) who had not completed the experimental protocol. These criteria were applied to the studies of healthy volunteers. However, the study of cases of hamstring strains different criteria were employed. These were: (1) the participants rated themselves as being in good physical health and pain free at the day of experiment; (2) they had suffered from mild to moderately severe hamstring injuries in the last 3 months. The exclusion criteria were: (1) a

hamstring injury more than 3 months old and (2) those who had not completed the experiment for both legs.

2.2 Equipment

The following major instruments were used during these studies:

- A Kin-Com Dynamometer (Chattanooga Group, Inc. USA) was used to measure torque at different knee positions.
- A near infrared spectroscope (NIRO 500 SRS, Hamamatsu Photonics, Japan), was used to measure the changes in the concentration of total haemoglobin [tHb] in the hamstrings.
- An electromyography system (Cambridge Electronic Design, UK) records the surface electromyogram of the hamstrings.
- In addition to other devices will be introduced in the following pages.

2.2.1 Kin-Com Dynamometer

A Kin-Com Dynamometer, (Chattanooga Group, Inc. USA) equipped with a computer system was used for measuring forces produced by muscles during a variety of types of contractions and movements. The system allows the force produced by the contracting muscle against the dynamometer arm during MVC and sub-maximal contractions. The screen of the dynamometer enables the volunteer to perform the required force for a specified time. The set up is shown in figure 2.1.

Figure 2.1: A volunteer seated on the Kin-Com Dynamometer

In this study, a Kin-Com was used to measure torques during isometric contractions and to control the position of the knee. It was also configured to allow left and right limbs to be tested. The dynamometer was adjusted to suit the height and leg length of each volunteer so ensuring safety and minimal injury risk. The correct position was comfortable for the volunteer and their body position was adjusted to ensure the axis of rotation of their knee which was coincident with axis of rotation of the dynamometer. The body was secured firmly with crossover straps to minimise additional movements. This is shown in figure 2.1.

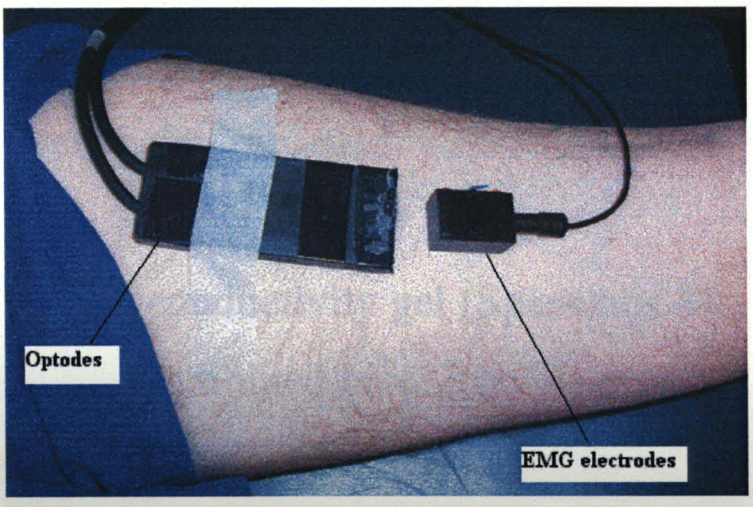
The axis of rotation of dynamometer was carefully aligned with the point of the lateral femoral. The lower leg under observation was also strapped to a shin pad supported above the ankle so that there was no leg movement within the dynamometer's pad. The system records the force produced as the hamstrings contracts and pulls the lower leg against the dynamometer arm.

The purpose of the experiment was described to the volunteers before starting the test. They were taught how to observe the Kin-Com screen to enable them to perform the required force for a specified time. The torque generated by the hamstrings during sub-maximal contractions was displayed to the volunteer during the contraction. This helped the volunteer maintain their contraction at a steady level.

2.2.2 Electromyography (EMG): Application and Measurement

EMG signals were recorded from the skin over the belly of the BF muscle as shown in figure 2.2. The volunteer lay prone on a bench. The location of the BF muscle was identified by asking the volunteer to pull his lower leg backward to about 70° at the knee with an eversion of the foot against resistance from the researcher. The belly of the muscle was identified by palpating and marked to ensure good positioning of both optodes and electrodes. A small patch of the skin at the recording sites was prepared very carefully before attaching the electrodes. The areas were shaved, cleaned with alcohol and allowed to air dry for 60 seconds. The electrodes were placed on the long axis of the muscle. The position of the electrode was not altered during any test. Figure 2.2 shows the placement of both NIRS optodes and EMG electrodes on the belly of the long axis of the BF muscle.

Figure 2.2: The placement of the NIRS optodes and EMG electrodes



2.2.3 Near Infrared Spectroscopy: Application of Optodes and Measurement

These readings were made using laser tissue blood oxygen monitor (NIRO 500 SRS, Hamamatsu Photonics, Japan). The equipment is shown in figure 2.3. The NIR probe contains a light emitting optode and a light detecting optode for measurement of light attenuation in the tissue. The two optodes are housed together in a small cuboidal, flexible black rubber holder at a fixed spacing, shielded them from ambient light and allowed secure attachment onto the skin with inter-optode distance of 4 cm. The NIRS was turned 'ON' at least 15 minutes before the test, as it requires a short amount of time to warm-up to stabilise. The electrical gain was set to the same value before the test for all volunteers. The optodes were placed along the long axis of the BF muscle covers the belly approximately 12-18 cm from the knee joint depends on the size and length of volunteer's thigh. The location was identified previously with a marker when the electrodes were placed. The optode was secured on the skin

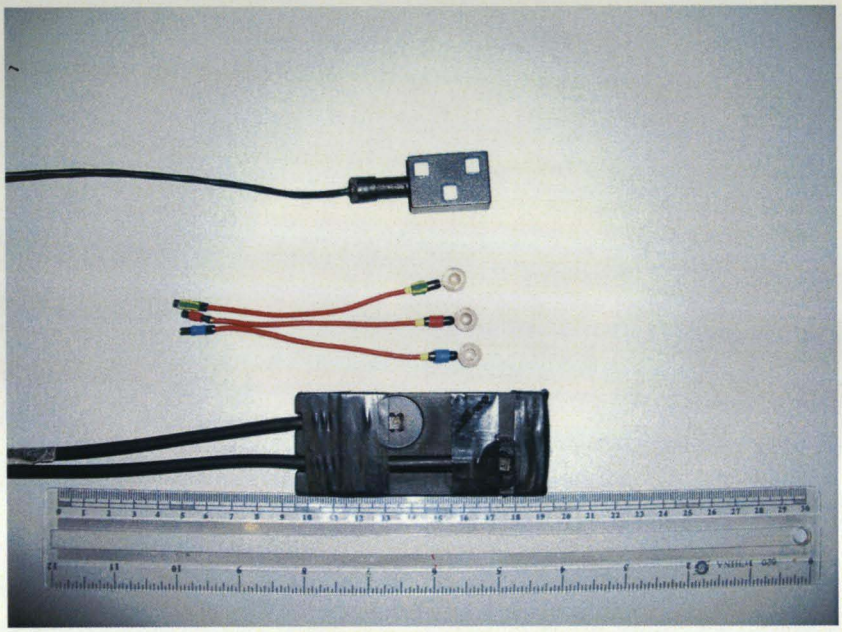
surface with tape, wrapped with an elasticised bandage and then covered by a black cloth held in place with Velcro tabs. This eliminated any ambient light entry and minimised movement of the optode while still permitting freedom of movement. The optode placement was 2 cm above the EMG electrodes directly on the belly of the BF muscle and not in the gap between BF muscle and the other hamstrings muscles.

Figure 2.3: The near-infrared spectrometer

The volunteer was positioned in the Kin-Com close to the NIRS, as the length of the optode cables is 2 metres. The EMG amplifier was close to the volunteer to keep the cables as short as possible. The changes in concentration of tHb are calculated and displayed on the front panel of the NIRO unit.

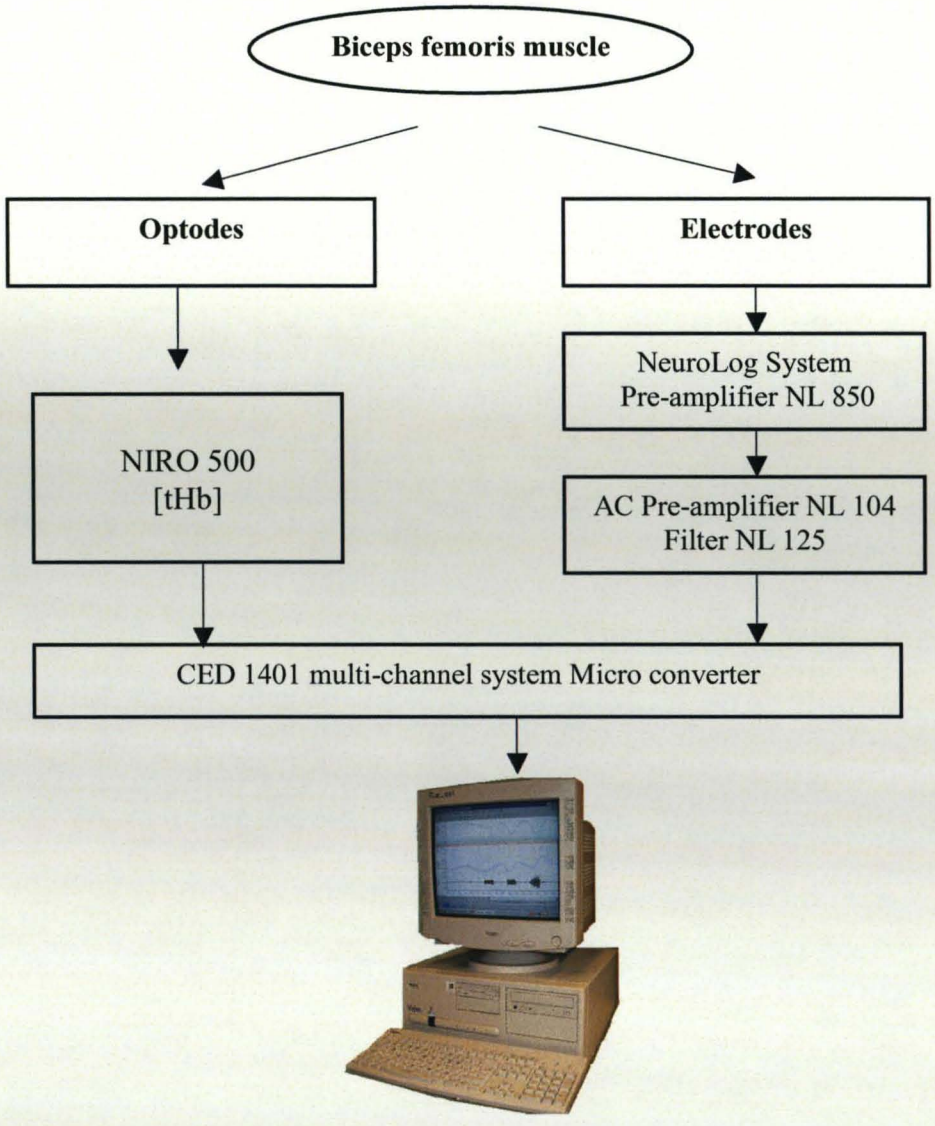
The raw NIRS and EMG data was collected, digitised by a CED 1401 (Cambridge Electronic Design, Cambridge, England) multi-channel analogue/digital converter and transferred to a PC computer for analysis by CED Spike 2 software. One measurement was performed before the real test to ensure that all instruments and signals are in the right position. Once this has been done, the test is started immediately with sub-maximal contractions.

Figure 2.4: EMG single & combined electrodes and NIRS optodes



The top black box is the skin mounted EMG preamplifier. In the middle, there are three silver chloride EMG electrodes of 8 mm diameter with fly leads. The three electrodes connect to the amplifier. The bottom is the NIR probe showing the two optodes mounted in a black rubber holder. The optodes are fixed at a spacing of 4 cm.

Figure 2.5: A block diagram is showing how the equipment is connected



The above block diagram shows the connections for recording EMG and NIRS signals from the BF muscle. The electromyogram was recorded via three electrodes attached to the skin over the BF muscle. The signal from surface electrodes was passed through an NL 850 isolated pre-amplifier, (Neurolog Systems, Digitimer Ltd, England), then through an NL 104 AC pre-amplifier (Neurolog System, Digitimer Ltd, England). This had a range of gains from × 100 to × 20, 000. The total gain in the recording system was typically ×1000.

The EMG signal was then bandpass filtered between 10 and 1000 Hz. A 50 Hz notch filter could be switched into the recording circuit when required.

Both EMG and NIRS signals were digitised with a CED 1401 A/D converter (C.E.D. Cambridge, England). All data were recorded, transmitted and displayed on personal computer (PC) for data analysis via Spike 2 software (version 3.15 and later version 5.03). Two versions of Spike 2 software were used during the study. All the experiments were recorded using version 3.15. The data were converted from this version to the latest version 5.03 for smoothing. The tHb channel was smoothed by using the channel process with settings of 1 or 5 seconds.

The EMG was digitised at 1000 Hz and the three NIRS channels were digitised at 2 Hz. The NIRS has an output frequency of 2 Hz. Thus the maximum time resolution of the NIRS is slow, at 0.5 seconds, but it was operated at the maximum resolution of which it is capable. The maximum time resolution of the EMG is very much faster and so the onset of muscle activity can be identified within a millisecond.

The 1401 is a 12 bit A/D converter. Thus the maximum input voltage range of ± 5 volts is converted into at most 4096 separate levels. The EMG signals were typically more than 4 volts in amplitude when presented for digitisation and so they are well resolved. The NIRS signals were typically rather smaller. The range of the tHb signal was typically about 1 volt. These tHb signals can be

resolved into more than 475 levels. This affords a satisfactory resolution for the experiments.

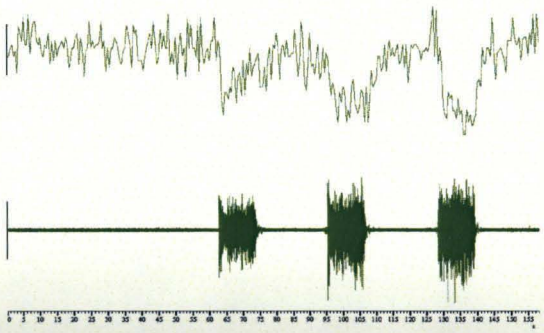
2.3 Measurement of Maximum Voluntary Contraction

All volunteers were given a period of familiarisation with the experimental equipment. They started with a series of contractions to establish their maximum knee flexion torque. This was followed by: EMG electrodes placement, optode placement and data sampling from both EMG electrodes and NIRS optodes during sub-maximal contractions.

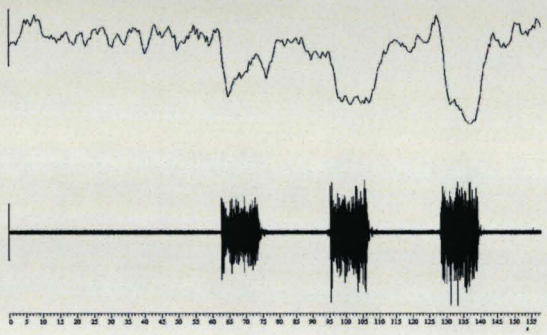
The MVC protocol consisted of 3 maximal repetitions of the knee flexors. Each contraction lasted 3 seconds. During each contraction, volunteers were encouraged strongly to produce their maximal effort for each angle position. Between each contraction they were given a 15 seconds rest. The greatest torque of the three trials was chosen as the MVC and any subsequent sub-maximal contractions were expressed as percentage of the MVC at that position. At least a 5 minute rest was given after determining MVC at 3 muscle lengths.

Figure 2.6: The effect of smoothing on NIRS data

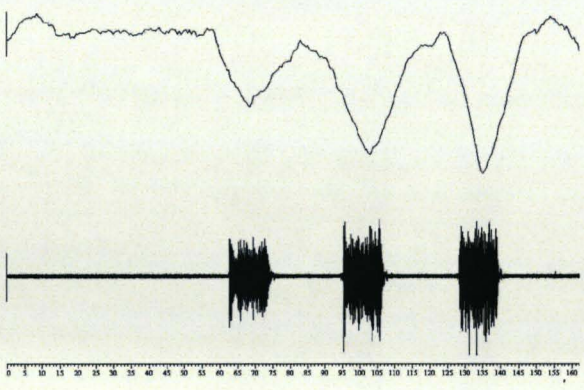
A



B



C



Figures 2.6A, B and C show the effect of smoothing on the raw data. Figure 2.6A shows the raw data before smoothing. Figure 2.6B shows the data after smoothing over 1 second. Figure 2.6C shows the data after smoothing over 5 seconds.
The vertical calibration bar for the Y axis shows 0.1 volt which is equivalent a [tHb] of 12.4 micromoles.

The upper panel shows an experiment that begins with one minute of relaxation followed by isometric contractions at 50°, 70° and 90°. Each contraction is at 50% MVC of the left limb. The upper trace shows the [tHb] signal. The lower trace shows the EMG recorded concurrently. The [tHb] signal is reduced during each contraction. The lower panel shows the same data after smoothing of the [tHb] signal within 1 second.

The smoothing function in Spike 2 version 5 calculates the mean of series of data points and substitutes the running average. The average value is obtained by calculating the mean of a number of data points before and after the value to be replaced. For example, in chapter 3 the most commonly used smoothing period is 1 second. This is obtained by averaging points between 0.5 seconds before and 0.5 seconds after each data point. This succeeds in smoothing the trace and making changes easier to measure but it also introduces a time shift between smoothed and un-smoothed data recorded concurrently. This is seen in figure 2.6. The top panel 2.6A shows the unprocessed data and the tHb trace starts to fall after the contraction begins, shown by the EMG activity. Even this contains and element of misalignment since the tHb trace is sampled at 2 Hz, the output frequency of the NIRS, whilst the EMG is sampled at 1000 Hz. The effect of smoothing is shown clearly in figures 2.6B and C. Progressively longer smoothing times appear to move the fall in [tHb] earlier ahead of the onset of EMG. This is a result of the data points after the fall being included in the average of points before the contraction begins.

This artefact did not cause any significant problems since the temporal relationships were not measured.

2.4 Statistical Methods

During experiments, all values were collected as numerical outputs by pair cursors, which were used for measurement. Data were analysed and saved as Excel files.

Following this, data could be transferred to the Minitab version 13 for statistical analysis. The data were analysed using a one-way analysis of variance (ANOVA). Results were considered to be significant at $P < 0.05$ level of confidence.

The main aim in the experiments described in this thesis is to test if some intervention or a series of interventions changes the value of the [tHb]. In some cases, like chapter 5, the measurements are made several times in the same individuals over a period of one week. The statistical analysis would be easier if all the data for each of the repeated measurements had the same standard deviation.

In general, this cannot be assumed and the data often showed large changes in standard deviation. The values of creatine kinase concentrations in table 5.1b show the changes day by day very clearly. The changes in standard deviation of repeated measurements may result from differences between measurement conditions, the effects of time or the intervention. In these circumstances it is essential to use ANOVA tests with repeated-measures models.

Some experiments produced only two sets of data. The data in chapter 4 is an example of this. In these cases the problems of changes in standard deviation are smaller and t tests were used.

Chapter Three

Blood Perfusion in the Hamstrings at Different Limb Positions

The causes of hamstrings injury are important in terms of injury prevention. The aim of the present study was to look at one of the associated risk factors: e.g. how the hamstrings torque developed at different knee angles influences the blood perfusion during sub-maximal contractions.

During sustained isometric contractions the intra-muscular pressure can rise high enough to obstruct blood flow through the contracting muscle (Bonde-Peterson et al. 1975). The data concerning the intensity of contraction at which blood flow is impaired by sustained contractions is still not clear. However, studies suggested that blood flow appeared to be occluded by approximately 20 to 45% MVC. It was hypothesised that blood flow in the hamstrings may be occluded during sub-maximal contractions between 25% and 50% MVC.

Depending on the exercise involved the intensity and duration of contraction, different degrees of force output can be developed (Boushel, Langberg, Olsen, Gonzales-Alonzo, Bülow and Kjær, 2001). This typically depends on the body parts, muscle group and type of contraction. Small muscles may require low intensity exercise while major muscle groups may require higher exercise intensity. Kahn et al. (1998) reported that perfusion stops above 25% MVC depending on the muscle being studied. For example, blood flow was strongly

reduced in the forearm muscles during 30% MVC (Bonde-Petersen et al. 1975; Hicks et al. 1999), while in elbow flexor muscles, it reached 50% MVC (Kahn et al. 1998). In the quadriceps muscles, blood flow was reduced at 50% MVC (Thorsson, Hemdal, Lilja and Westlin, 1987). It appears from the previous studies that contractions between 30% and 50% MVC are enough to reduce the blood flow in either lower or upper limbs.

No previous study has investigated the relationship between torque and blood flow of the hamstring muscles during different knee angles. Previous studies have shown different outcomes. For example, a direct linear relationship exists between muscle length and force of isometric contraction; a drop in muscle activity as a muscle shortens; an increase in EMG activity in the shortened muscle. As the torque increases, the EMG activity decreases (Lunnen et al. 1981).

It was hypothesised that perfusion in the hamstrings may be different at a series of muscle lengths, at different levels of intensity and between left and right limbs. The aim was to measure the magnitude and the time course of changes in hamstrings perfusion during isometric contractions at a series of muscle lengths, to compare the magnitude of the changes in muscle forces and muscle perfusion in the left and right hamstrings.

3.1 Materials & Methods

3.1.1 Participants

Fourteen adult male volunteers aged between 18 and 42 years (mean 27.5 years) participated in this experiment. Their anthropometric details are given in appendix 9.1. They were not specially selected to represent any particular group of sports people.

3.1.2 Equipment

The Kin-Com, NIRS and EMG instruments used during this study were described in detail in chapter 2.

3.1.2.1 Kin-Com Dynamometer

In this study, a Kin-Com dynamometer was used to measure torques during isometric contractions and to control the knee position. It was also configured to allow left and right limbs to be tested. Volunteers were seated upright position. The axis of rotation of dynamometer was carefully aligned to be coincident with that of the knee at 3 different angles 50°, 70° and 90°. This is illustrated in figure 3.1. The hip position was fixed at 90° for all tests.

Figure 3.1: The three knee angle positions controlled by the Kin-Com Dynamometer

Knee at 50° Knee at 70° Knee at 90°

Volunteers were asked to look at the computer screen to provide them with feedback. This enabled each volunteer to maintain the requested constant torque by keeping the height of the bar graph at the pre-selected level within ± 5% of the desired value.

3.1.2.2 Electromyography: Application and Measurement

EMG signals were recorded from the BF muscle using 3 single silver, silver chloride electrodes, see figure 2.4. Both the EMG electrodes and NIRS optodes were placed on the skin over the belly of the muscle. The 3 electrodes (2 recording and 1 earth) were attached and secured on the skin surface with tape. The electrode diameter was 8mm and the distance between the centres of the recording electrodes was ~ 1 cm. A small amount of conducting gel was put on the electrodes and then they were placed on the long axis of the muscle to obtain good contact between the sensor and the skin. This was done for one leg. After the experiment finished with the first leg, the same procedure was applied to the other leg.

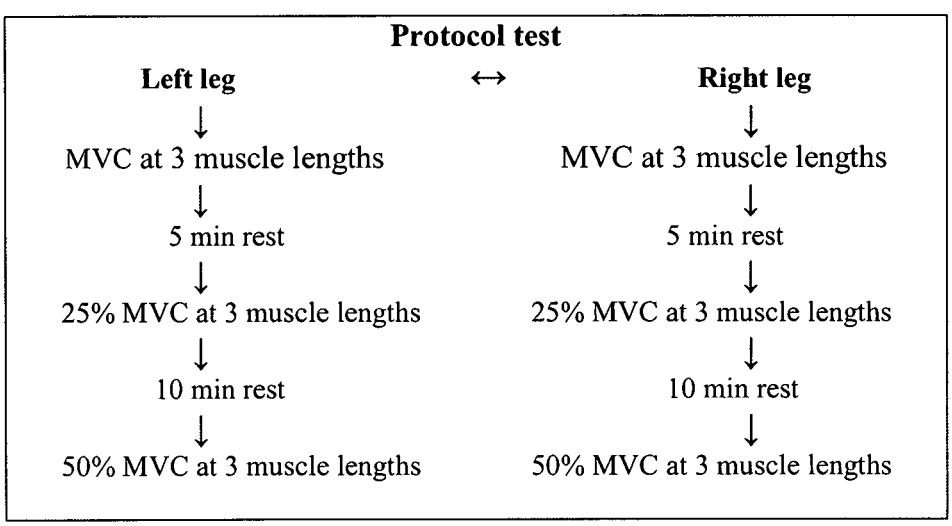
3.1.2.3 Near Infrared Spectroscopy (NIRS)

In this experiment the NIRS was used to measure the concentration of [tHb] during sub-maximal isometric contractions at 25 and 50 % MVC.

3.2 Experimental Procedure

In this series of experiments the left and right legs of the volunteers were tested. The order of testing, left first or right first, was randomised. The maximum voluntary contraction was established for each leg. Subsequently, contractions were made at 25%, 50% and 75% of maximum voluntary contraction (MVC). After a few pilot experiments, the 75% contraction was excluded from the experiment to reduce problems with muscle fatigue. The test lasted about one hour for each leg. The volunteer visited the laboratory on two occasions.

Figure 3.2: Order of performing randomised left and right leg test



3.2.1 NIRS Measurement during Isometric Contractions at 25% MVC

The volunteer was seated in the Kin Com with the NIRS optodes and the EMG electrodes attached. The experiment started with the first exercising leg. NIRS measurements started with a settling time of approximately 60 seconds of baseline data recorded under resting conditions. This was followed by the onset of first sub-maximal isometric contraction of hamstrings. It lasted for 10 seconds at an intensity of 25% MVC at 50° of knee flexion. This was followed by return to relaxation for 15 seconds. Following this the dynamometer arm moved to the next knee position at 70° of flexion where the sequence was repeated. The dynamometer arm then moved to 90° of flexion and the sequence was repeated again. There were 3 sets of 3 isometric contractions giving a total of 9 contractions. After these contractions were completed and while the recording was still running, approximately 25 seconds of recovery was allowed. At this time, the testing of the first leg of 25% MVC was completed.

3.2.2 NIRS Measurement during Isometric Contractions at 50% MVC

After 5 minutes of recovery, the volunteer again performed the same procedure, but this time with a torque of 50% MVC. At the completion of the exercise protocol, the volunteer moved from the Kin-Com dynamometer and electrodes and optodes removed carefully. Throughout the entire experiment, EMG and NIRS signals were recorded simultaneously on a PC using Spike 2 software version 3.15 and stored for further analysis. This whole procedure was repeated

on the other leg. On some occasions the tests followed on the same day. Other volunteers preferred to return to the laboratory for a second testing session.

Figure 3.3: Smoothed data recordings of [tHb] and EMG at 3 positions

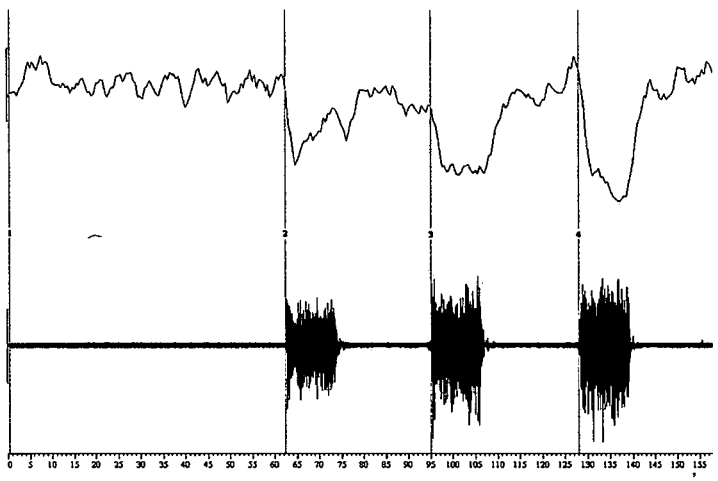


Figure 3.3

This figure illustrates the data of NIRS signal showing [tHb] and EMG activity in the BF muscle. The experiment started with 1 minute of relaxation (between cursor 1 and 2) followed by 3 contractions (cursors 2, 3 and 4) in 3 positions at 50% MVC. The top signal is the [tHb]. The bottom signal is the EMG activity of the BF muscle. The NIRS signals have been smoothed by averaging data points over 1 second as described in the Methods chapter. Cursor (2) is at the beginning of the contraction at 50° of flexion. Cursor 3 is the beginning of the contraction at 70°. Cursor 4 is the beginning of the contraction at 90°.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

3.3 Analysis of the NIRS Traces

The changes in NIRS output were calculated by the use of 'cursors' feature of the Spike 2 software. The term change in this study is defined as; the difference between the [tHb] baseline, mean of [tHb] before contraction, and the lowest trough during contraction. The mean and trough of [tHb] was measured for each contraction. This was done for each position during each sub-maximal effort from these 3 positions (50°, 70° and 90°). İn addition, the area under or above the baseline flow could be measured.

Following this, a separate Excel spreadsheet was used for data capture for each volunteer and then transferred to a Minitab statistical package for further analysis. Finally, the data were statistically analysed using a one-way ANOVA Statistical Package for the Minitab version 13. Results were considered to be significant at $P < 0.05$ level of confidence.

3.4 Forces of the Left and Right Hamstrings

14 male volunteers whose ages ranged between 18 and 42 years were tested. Their age, height, weight and maximum knee flexion torque at three positions are shown in table 3.1. The values include their minimum, maximum, mean and standard deviation. The best MVC force output was chosen from each volunteer at each knee positions. This was done for both limbs. The highest torque in both legs was at 50°, while the lowest was at 90°.

Statistically significant differences were found between mean maximum voluntary contractions at 70° and 90° ($P < 0.01$ left side, $P < 0.001$ right side) and 50° and 90° ($P < 0.001$ left side, $P < 0.001$ right side) when tested with an ANOVA. However, no significant difference was found between mean maximum voluntary contractions at 50° and 70° ($P = 0.083$ left side and $P = 0.101$ right side). The comparisons between maximum voluntary contractions at the three knee positions are shown in table 3.2 A and B.

Table 3.2C shows a comparison between mean maximum voluntary contractions produced by the left and right hamstrings at 3 knee positions. At all three positions tested, no significant differences were found between the maximum voluntary contractions in the left and right limbs. All the ANOVA tests performed produced P values > 0.05.

Table 3.1: age, height, weight and maximum knee flexion torque

No.	Age	Height (cm)	Weight (kg)	MVC (Nm)					
				Left			Right		
				50°	70°	90°	50°	70°	90°
1	29	165	80	306	266	197	396	374	235
2	35	170	65	294	201	157	392	267	205
3	21	169	65	262	217	168	290	255	205
4	23	178	83	450	398	330	523	432	304
5	36	174	105	420	338	224	468	422	324
6	27	165	80	230	210	163	301	308	248
7	27	173	61	317	242	196	403	328	229
8	23	174	75	531	462	361	538	487	367
9	20	176	87	448	352	211	462	425	326
10	40	172	72	339	317	255	381	315	266
11	42	176	74	338	275	229	343	250	192
12	23	166	69	413	347	257	374	380	281
13	21	182	84	500	433	304	439	412	267
14	18	180	60	303	252	134	343	326	290
Min	18	165	60	230	201	134	290	250	192
Max	42	182	105	531	462	361	538	487	367
Mean	**28**	**173**	**76**	**368**	**308**	**228**	**404**	**356**	**267**
St Dev	**8**	**5**	**12**	**92**	**84**	**68**	**75**	**74**	**52**

Table 3.1

The left panel shows the anthropometric details of the volunteers. The heights and weights of the volunteers are typical for the normal population. The middle and right panels show the torques produced by the left and right hamstrings during isometric contractions at each of the three knee positions.
No significant difference was found between the torques developed by the left and right limbs when the positions were matched. Details of the results of the statistical tests are given in tables 3.2A, B and C.

Table 3.2A: MVC of left hamstrings at 3 positions

Position	Mean (Nm)	St Dev	*P* value
50°	368	92	0.083
70°	308	84	
70°	308	84	0.010
90°	228	68	
50°	368	92	0.001
90°	228	68	

Table 3.2B: MVC of right hamstrings at 3 positions

Position	Mean (Nm)	St Dev	*P* value
50°	404	75	0.101
70°	356	74	
70°	356	74	0.001
90°	267	52	
50°	404	75	0.001
90°	267	52	

Table 3.2A and B

A summary of the results of ANOVA tests comparing the magnitude of the knee flexion torques at three positions of the left (table 3.2 A) and right (table 3.2B). The results show that the mean torques were not statistically significant different at 50 and 70 degrees of flexion. The difference in mean torques was statistically significant at other positions.

Table 3.2C: MVC of left & right hamstrings at 3 positions

Positions	Side	Mean (Nm)	St Dev	P value
50°	Left	368	92	0.269
	Right	404	75	
70°	Left	308	84	0.121
	Right	356	74	
90°	Left	228	68	0.095
	Right	267	52	

Table 3.2C

A summary of the results of ANOVA tests comparing the magnitude of the left and right knee flexion torques at three positions. The results show that the mean torques were not statistically significant different at 50, 70 and 90 degrees of flexion.

3.5 [tHb] of the Biceps Femoris Muscle

This section shows NIRS data recorded during sub-maximal isometric contractions. Figure 3.4A shows the smoothed NIRS output during one isometric contraction at one position. This contraction is at 50° knee flexion during 50% MVC. This figure shows baseline recordings for [tHb] signal during the 60 seconds before the contraction starts. The start of the contraction can be seen clearly in the EMG trace. The contraction causes a reduction in the [tHb]. This is probably a result of veins emptying as a result of increased intra-muscular pressure. The results are consistent with earlier observations that report that the muscle blood flow is restricted at contractions above 25% of MVC (Laaksonen et al. 2003; Kahn et al. 1998).

Figure 3.4B shows data from a similar experiment but recorded in another volunteer. Again there is a stable recording during 60 seconds before the contraction. The [tHb] trace did not return to the resting level as quickly after the end of the contraction. The pattern of NIRS traces seen in figure 3.4A was found in 11 of the participants, while the pattern in figure 3.4B was found in very few volunteers.

Figure 3.4A: Data from subject 8 showing [tHb] in left hamstrings during a contraction at 50% MVC at 50°

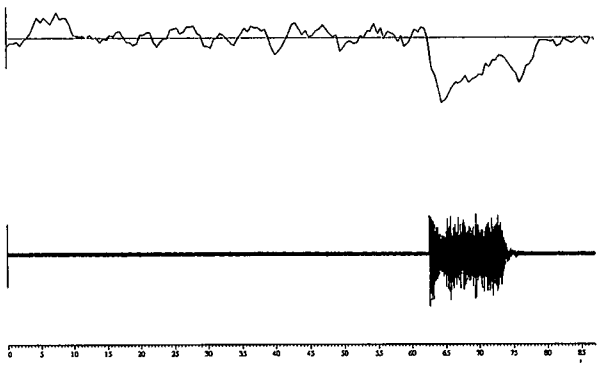


Figure 3.4A
This figure shows the [tHb], and EMG recorded concurrently. The NIRS signals have been smoothed by averaging data points over 1 second. The first 60s show stable recording as the volunteer sits at rest. At 62s the volunteer makes a voluntary contraction to 50% MVC. The lower trace shows the hamstrings EMG activity while the knee held at 50° of flexion. During the contraction [tHb] falls and then rises. After the contraction, [tHb] value returned to the resting level.

In figures 3.4 A, B the vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 3.4B: Data from subject 6 showing [tHb] in left hamstrings during a contraction at 50% MVC at 50°

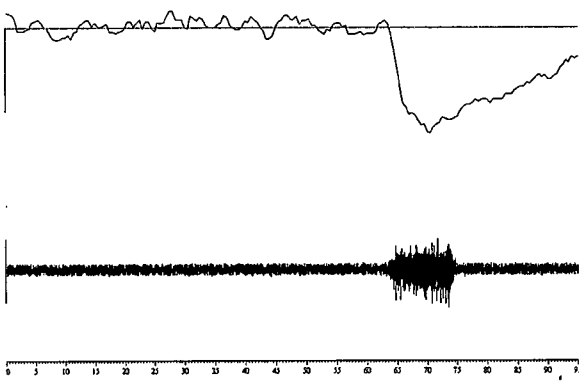


Figure 3.4B
This figure shows the [tHb], and EMG recorded concurrently. The NIRS signals have been smoothed by averaging data points over 1 second. This data was recorded from a second volunteer. The first 60s show stable recording as the volunteer sits at rest. At 60s the volunteer makes a voluntary contraction to 50% MVC. The lower trace shows the hamstrings EMG activity while the knee held at 50° of flexion. Unlike figure 3.4A the fall of [tHb] signals during the contraction continued and did not return to the resting level.

The previous figures 3.4A and 3.4B show recordings during one isometric contraction at 50% MVC. The two figures 3.5A and 3.5B below show data from the same volunteers, but with longer recordings of three contractions at 50% MVC at 50°, 70° and 90° of knee flexion.

In figure 3.5A the size of changes in [tHb] concentrations become progressively bigger as the angle of knee flexion increases towards 90°. After the contraction the recordings return to the resting values. It appears that the flow restriction is greater at the more flexed positions. However, in figure 3.5B the sizes of changes in total haemoglobin concentrations do not change in a systematic way.

Figures 3.6A and 3.6B show even longer recordings from the same two individuals. These figures show continuous records of a series of nine contractions at 50% MVC. There are three repetitions of each contraction at three positions: 50°, 70° and 90° of knee flexion.

Figure 3.6A shows consistent changes NIRS signals during repeated contractions and relaxations. The smallest changes always occur at 50°. There are intermediate sized changes at 70° and the largest changes always occur at of knee flexion 90°.

Figure 3.6B does not show consistent changes in the NIRS signals during contractions. The biggest changes occur at 50° and some times at 70°.

Figure 3.5A: Data from subject 8 showing [tHb] in left hamstrings during a contraction at 50% MVC at 50, 70° and 90°

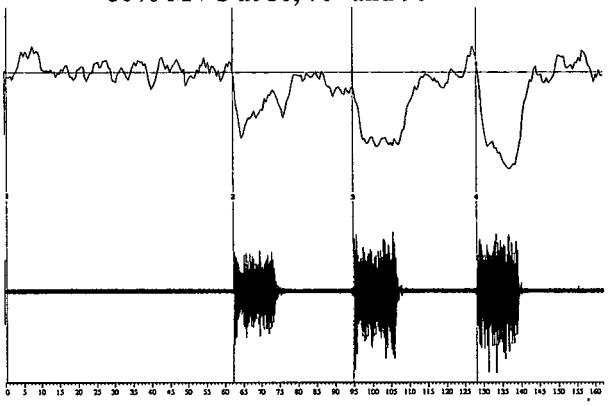


Figure 3.5A

This figure shows the [tHb] and EMG recorded concurrently. The NIRS signals have been smoothed by averaging data points over 1 second. The lower trace shows the hamstrings EMG activity during knee flexion. The first 62s which is between cursor 1 and 2 show stable recording as the volunteer sits at rest. Cursor 2 at 63s the volunteer makes a voluntary contraction to 50% MVC. Cursor 3 at 94s the volunteer makes a voluntary contraction at 70°. Cursor 4 at 129s the volunteer makes a voluntary contraction at 90°. During the contraction [tHb] falls then rises. After the contraction [tHb] values return to the resting values. For figure 3.4 A, B the vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 3.5B: as above but for volunteer 6

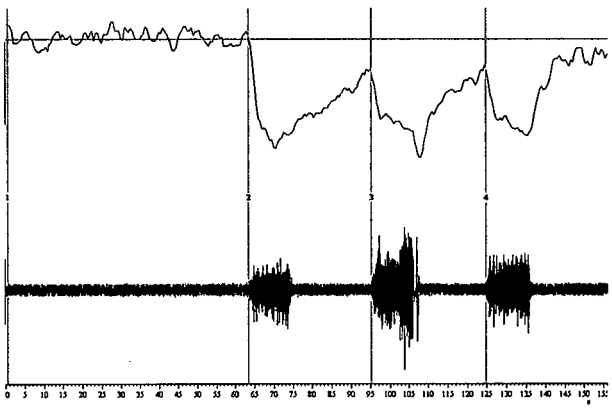


Figure 3.5B

This figure shows the [tHb] and EMG recorded concurrently. This data was recorded from a volunteer 6. The lower trace shows the hamstrings EMG activity during knee flexion. The first 63s show stable recording as the volunteer sits at rest. At about 64s the volunteer makes a voluntary contraction to 50% MVC at 50°. At 95s the volunteer makes a voluntary contraction at 70°. At 125s the volunteer makes a voluntary contraction at 90°. Unlike figure 3.5A all three signals fall during the contraction.

Figure 3.6A: Data from volunteer 8: [tHb] during contractions at 50% MVC at 50°, 70° and 90°

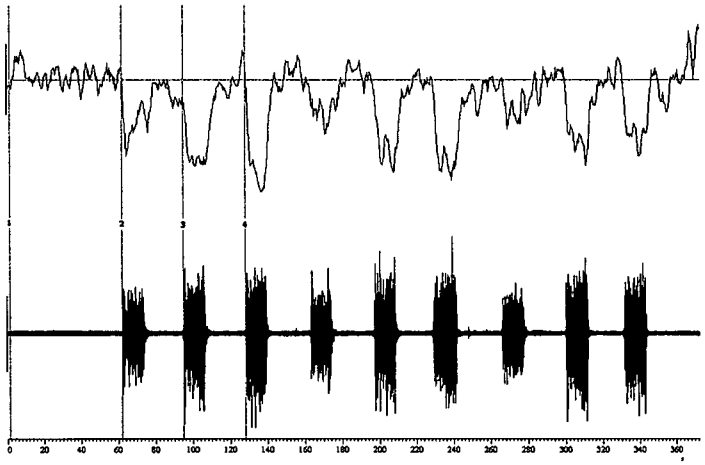


Figure 3.6A

This figure shows the [tHb] and EMG recorded concurrently. The NIRS signals have been smoothed by averaging data points over 1 second. The lower trace shows the hamstrings EMG activity during knee flexion. The first 62s which is between cursor 1 and 2 show stable recording as the volunteer sits at rest. Cursor 2 at 63s the volunteer makes a voluntary contraction to 50% MVC at 50°. Cursor 3 at 95s the volunteer makes a voluntary contraction at 70°. Cursor 4 at 129s the volunteer makes a voluntary contraction at 90°. Here the volunteer makes three contractions at each knee position making a total of nine contractions. During the contraction [tHb] falls and then rises. After the contraction [tHb] values return to the resting values.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 3.6B: as above but for volunteer 6

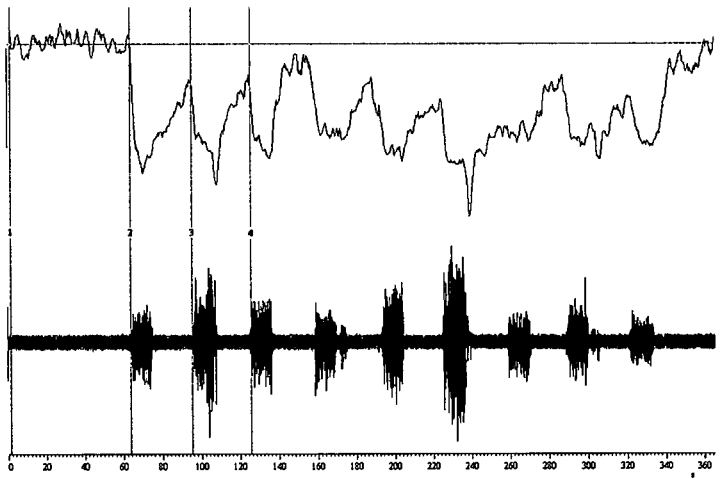


Figure 3.6B

This figure shows the [tHb] and EMG recorded concurrently. The NIRS signals have been smoothed by averaging data points over 1 second. This data was recorded from a volunteer 6. The lower trace shows the hamstrings EMG activity during knee flexion. The first 63s show stable recording as the volunteer sits at rest. At about 64s the volunteer makes a voluntary contraction to 50% MVC at 50°. At 95s the volunteer makes a voluntary contraction at 70°. At 125s the volunteer makes a voluntary contraction at 90°. Here the volunteer makes three contractions at each knee position making a total of nine contractions. Unlike figure 3.6A the [tHb] signal fall during the contraction but did not return to the resting levels between the contractions. However, at the end [tHb] signal returned to the resting levels.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Tables 3.3 and 3.4 show individual values of the changes in [tHb] during contractions for the 14 volunteers. The changes at each of the three knee positions are shown separately along with the means and standard deviations. Table 3.3 shows the values of [tHb] recorded in the left and right BF muscles during contractions at 25% MVC at 3 limb positions. Table 3.4 shows the equivalent values during contractions at 50% MVC.

There was no significant difference between the mean values of [tHb] during contractions at 25% of MVC at each position in either limb. All the *P* values were > 0.05 when tested with an ANOVA.

Table 3.3: Changes in [tHb] during contractions at 25 % of MVC at 3 knee positions

25%	Left knee angle			Right knee angle		
Volunteer	**50°**	**70°**	**90°**	**50°**	**70°**	**90°**
1	-5.637	-3.758	-2.505	5.548	0.627	1.969
2	-1.074	-0.984	-1.789	1.521	2.058	0.358
3	1.342	-1.342	0.090	4.027	3.311	2.685
4	2.506	0.179	-2.953	-1.432	-0.447	-3.221
5	-1.163	-7.427	-5.637	-11.006	-10.827	-14.496
6	3.311	-1.342	-1.968	1.432	0.090	2.237
7	3.132	2.953	1.790	3.937	0.537	-1.432
8	0.358	-2.774	-4.921	4.474	4.743	1.700
9	2.237	-0.358	-1.700	3.937	2.774	1.432
10	-12.706	-13.691	-13.780	-11.991	-13.243	-11.722
11	3.132	2.148	2.416	-2.058	1.342	-0.626
12	9.575	7.696	6.085	0.806	2.506	2.953
13	-1.432	-1.700	-0.805	2.595	1.879	0.716
14	0.984	-3.042	-3.132	7.338	3.669	0.269
Mean	**0.326**	**-1.674**	**-2.058**	**0.652**	**-0.070**	**-1.227**
St Dev	**5.059**	**4.919**	**4.541**	**5.744**	**5.291**	**5.333**

Table 3.3

Values of [tHb] in micromoles during contractions at 25% MVC at 3 limb positions recorded in the left and right BF muscles. The means and standard deviations are also shown.

Similar data were recorded during contractions at 50% of MVC. These data are shown in Table 3.4. Again there were no significant differences between the mean values of [tHb] during contractions at 50% MVC at each position in either limb. All the *P* values were > 0.05 when tested with an ANOVA.

Table 3.4: Changes in [tHb] during contractions at 50% of MVC at 3 knee positions

50%	Left knee angle			Right knee angle		
Volunteer	**50°**	**70°**	**90°**	**50°**	**70°**	**90°**
1	-7.069	-5.458	-4.653	7.517	2.774	2.595
2	-3.579	-2.953	-2.147	0.448	0.716	0.716
3	-2.505	-3.221	-1.253	2.237	1.879	1.163
4	-0.626	-2.863	-7.248	-3.042	-6.801	-5.458
5	-4.921	-9.396	-9.038	-11.454	-24.160	-20.223
6	-1.432	-0.895	-0.358	-3.132	-3.490	-3.758
7	-0.179	0.358	1.790	1.521	-2.505	-3.042
8	-0.895	-4.385	-5.458	2.595	0.000	-0.895
9	-0.895	-2.058	-2.416	3.132	1.342	0.537
10	-18.254	-23.176	-21.297	-21.744	-21.476	-16.107
11	4.027	4.027	4.206	-2.863	-2.863	0.716
12	11.543	6.174	7.338	-3.937	-7.606	-2.416
13	-4.295	-2.595	-2.953	2.864	1.700	0.000
14	-3.579	-8.680	-6.353	5.369	3.043	-1.253
Mean	**-2.333**	**-3.937**	**-3.560**	**-1.464**	**-4.103**	**-3.387**
St Dev	**6.416**	**6.941**	**6.781**	**7.516**	**8.619**	**6.671**

Table 3.4

Values of [tHb] in micromoles during contractions at 50% MVC at 3 limb positions recorded in the left and right BF muscles. The means and standard deviations are also shown.

A comparison between the changes in [tHb] during contractions at 25% and 50% MVC was made for the three knee angles. These data for the left leg are shown in table 3.5 and for the right leg in table 3.6. The changes in the [tHb] during contractions at 50% MVC were greater than those during the 25% MVC in both the left and right limbs. At each of the three knee angles there is clear difference between 25% and 50% in the left BF muscle. The changes in [tHb] were found to be statistically significant when tested with paired t tests.

The same result was found for the changes in [tHb] in the right limb.

Table 3.5: Changes in [tHb] for the left limb during contractions at 25 and 50% of MVC at 3 knee positions

Volunteer	50°		70°		90°	
	25%	50%	25%	50%	25%	50%
1	-5.637	-7.069	-3.758	-5.458	-2.505	-4.653
2	-1.074	-3.579	-0.984	-2.953	-1.789	-2.147
3	1.342	-2.505	-1.342	-3.221	0.090	-1.253
4	2.506	-0.626	0.179	-2.863	-2.953	-7.248
5	-1.163	-4.921	-7.427	-9.396	-5.637	-9.038
6	3.311	-1.432	-1.342	-0.895	-1.968	-0.358
7	3.132	-0.179	2.953	0.358	1.790	1.790
8	0.358	-0.895	-2.774	-4.385	-4.921	-5.458
9	2.237	-0.895	-0.358	-2.058	-1.700	-2.416
10	-12.706	-18.254	-13.691	-23.176	-13.780	-21.297
11	3.132	4.027	2.148	4.027	2.416	4.206
12	9.575	11.543	7.696	6.174	6.085	7.338
13	-1.432	-4.295	-1.700	-2.595	-0.805	-2.953
14	0.984	-3.579	3.490	-8.680	-3.132	-6.353
Mean	**0.326**	**-2.333**	**-1.208**	**-3.937**	**-2.058**	**-3.560**
St Dev	**5.059**	**6.416**	**5.087**	**6.941**	**4.541**	**6.781**
T test	**0.001**		**0.008**		**0.023**	

Table 3.5

This table shows the values of the change in [tHb] in micromoles during contractions at 25 and 50% of MVC in the left BF muscles at 3 positions. In this table the means and standard deviations are shown.

Table 3.6: Changes in [tHb] for the right limb during contractions at 25 and 50% of MVC at 3 knee positions

Volunteer	50°		70°		90°	
	25%	50%	25%	50%	25%	50%
1	5.548	7.517	0.627	2.774	1.969	2.595
2	1.521	0.448	2.058	0.716	0.358	0.716
3	4.027	2.237	3.311	1.879	2.685	1.163
4	-1.432	-3.042	-0.447	-6.801	-3.221	-5.458
5	-11.006	-11.454	-10.827	-24.160	-14.496	-20.223
6	1.432	-3.132	0.090	-3.490	2.237	-3.758
7	3.937	1.521	0.537	-2.505	-1.432	-3.042
8	4.474	2.595	4.743	0.000	1.700	-0.895
9	3.937	3.132	2.774	1.342	1.432	0.537
10	-11.991	-21.744	-13.243	-21.476	-11.722	-16.107
11	-2.058	-2.863	1.342	-2.863	-0.626	0.716
12	0.806	-3.937	2.506	-7.606	2.953	-2.416
13	2.595	2.864	1.879	1.700	0.716	0.000
14	7.338	5.369	3.490	3.043	0.269	-1.253
Mean	**0.652**	**-1.464**	**-0.083**	**-4.103**	**-1.227**	**-3.387**
St Dev	**5.744**	**7.516**	**5.281**	**8.619**	**5.333**	**6.671**
T test	**0.007**		**0.002**		**0.002**	

Table 3.6

This table shows the values of the change in [tHb] in micromoles during contractions at 25 and 50% of MVC in the right BF muscles at 3 positions. In this table the means and standard deviations are shown.

3.6 Discussion

The maximum knee flexion torque was measured at three positions in 14 male volunteers. The highest torque in both legs was at 50°, while the lowest was at 90°, see table 3.1. However, no significant difference in mean torque was found between 50° vs. 70° in the left and right limbs, see table 3.2A and 3.2B. Peak torque decreased significantly as knee positions increased towards 90°. When tested with an ANOVA, statistically significant differences were found between mean maximum voluntary contractions at 70° vs. 90° and 50° vs. 90° in both sides. This is in agreement with Lunnen et al. (1981). However, the mean maximum torques in the left and right limbs were not significantly different. These data are shown in table 3.2C. These results are consistent with those published by Orchard et al. (1997) and Kannus & Yasuda, (1992).

The present study is the first to quantify blood perfusion in human hamstring muscles during isometric exercise with NIRS. The effect of isometric contractions at 25% and 50% of MVC on [tHb] was compared at the three knee positions. As can be seen in the results in tables 3.3 and 3.4 no significant difference was found in the mean changes in [tHb] in the biceps femoris muscle at the three positions at either 25% or 50% MVC. This is discussed more fully in section 3.6.3.

3.6.1 Torque and Knee Position during MVC

The body position has an influence on injury occurrence either in team or individual sports. For example, the hamstrings muscle is at risk when extending the knee and flexing the hip. It was hypothesised that such knee position could have an influence on hamstring muscle strains. The question raised here is that is there any relationship between hamstring muscles and its action in particular knee position? The present experiment showed that the highest MVC value in both legs was found at 50°, while the lowest was at 90°. In other words, while the degree of the knee flexion increases the torque value decreases (table 3.1).

Peak torque decreased significantly as knee flexion increased towards 90°. This is in agreement with previous studies using different joints and muscle lengths. For example, Lunnen et al. (1981) investigated the relationship between muscle length and torque in various hip positions. They found that during maximal muscle contraction a decrease in torque occurred as the muscle was shortened. They also indicate that the BF muscle developed a greater amount of torque in the lengthened state than in shortened position. When torque at each hip position was compared during MVC, the 3 angle positions provide a longer muscle length were not significantly different. However, the shortened muscle length developed significantly less force than the two lengthened muscle positions. It should be noted that similarities in these results is because the axis of the knee joint was held constant during the three muscle lengths. However, changing the joint angle may provide different results. The knee joint was held constant in Lunnen's study, while in the present study the hip joint was constant.

In the present study, hamstrings generated less force at 90° than at 50°. In sports requiring high amount of knee flexion such as rowing and sprinting, the flexion of the knee usually exceeds 90°. In this case, the hamstring muscles are at the shortest position that cannot produce high forces. The study of the influence of strength, flexibility, warm-up and fatigue of hamstring muscle injury by Worrell & Perrin (1992) indicated that since the ability of connective and muscle tissue to absorb force is directly proportional to both passive and active components. It seems that a stronger hamstring muscle group can absorb greater forces in a lengthened position.

During sports activities the knee moves forward and backward in different angles that may have an influence on hamstring muscle oxygenation. It was hypothesised that the tension in the hamstring muscles increases with increasing the degree of knee flexion i.e. from 45° to 90°. Therefore, it was decided to choose three knee positions as follows; 50°, 70° and 90°. Assuming as the degree of knee flexion increases the hamstrings would show greater tension, influencing the blood flowing in the contracted muscle. Also, it was thought that 50% MVC would occlude the blood flowing to the hamstrings, which may result in muscle strain. It seems that forces more that 50% MVC are required to influence the blood flow in the hamstrings.

3.6.2 MVC in the Left and Right Legs

It was thought that there might be a difference in the maximal force between left and right hamstrings. The comparison between left and right hamstrings shows

no significant difference. Orchard et al. (1997) assessed the relationship between the isokinetic peak torque and side-to-side comparisons of hamstring muscle ratios. They found that the peak torque values for the hamstring muscle strength were not significantly different between the dominant and non-dominant legs. Kannus and Yasuda, (1992) assessed the relationship between the isokinetic peak torque and the angle-specific torques at different degrees of knee flexion of the quadriceps and hamstrings muscles. They found that the average of peak torques and angle-specific torques of the quadriceps and hamstrings muscles were almost equal in both legs. The results of maximum force of the hamstrings in the present study and the comparison between left and right muscles show no significant difference between them. Accordingly, it is suggested that during any experiment, one limb can be tested instead of both limbs.

3.6.3 Changes in [tHb] during Contractions of Biceps Femoris

The changes in BF muscle oxygenation were recorded during rest and isometric contraction. It was found that during the contractions [tHb] signals decreased below the baseline. Those signals then returned to the baseline in 11 out of 14 volunteers after the contraction stopped, figure 3.5A. This means that, on average, blood volume in the BF muscle decreased during isometric contractions.

During moderate to high forces, blood flow would be totally occluded due to mechanical compression. Blood perfusion was expected to be impaired at or above 25% MVC. In the present study during 25% MVC contractions, there was

a small decrease in [tHb] of the BF muscle. These changes were greater at 50% compared to 25% MVC. Kahn et al. (1998) assessed muscle oxygenation during isometric contraction in different forces 25% up to 100% MVC. They found that blood flow of elbow flexor muscles was strongly reduced at 50% MVC.

Greater changes of [tHb] signals were found during higher force with sustained contraction. This resulted in reduced blood flow perfusion and O_2 supply with a chance for blood flow to be occluded. The rapid decline in BF muscle oxygenation during contractions especially during 50% MVC was due to the need for the release of O_2 in order to meet the metabolic demands of the muscles. Also, the situation was similar for the rapid increase in BF muscle de-oxygenation to meet the muscle's need for O_2.

The reduction in [tHb] during contractions at low to moderate forces suggest that blood flow reduced during contractions as a result of forces applied by contracting muscle. Kahn et al. (1998) found that during isometric contractions of elbow flexor muscles beyond 25% MVC, for each force level, muscle oxygenation decreased immediately after the beginning of the contraction and remained low during the whole contraction. The results show that blood flow of exercising muscle decreases during contractions and then increases during relaxation periods. This may be due to O_2 demand and supply to BF muscle during contraction and relaxation periods. The situation is similar during exercise activities where the exercising muscles contract and relax. Bonde-Peterson et al. (1975) demonstrate that above a certain force level there is a decrease in flow in spite of increasing demands for O_2 which is related to

occlusion of the muscular vascular bed caused by the increase in intramuscular pressure during contraction with increasing force. Also, they found that muscle blood flow is more or less impaired when isometric contraction intensity exceeds 25% MVC. The changes in [tHb] during contractions increased and the circulation of blood was temporary impaired but not to the extent to damage or injure the hamstring muscles.

Muscle blood flow reduces during contractions and this reduction may be greater in some extreme body positions. For example, Foster et al. (1999) found that a reduction in blood flow of the quadriceps was seen at a low skating position with the knee flexed compared to a high position with the knee pre-extended during sustained contractions. They suggest that the long duration of the gliding of the skating stroke might lead to restriction of muscle blood flow.

In summary, several authors have reported that during the period of contraction, blood flow will be limited or occluded due to an augmented intramuscular pressure Laaksonen et al. (2003), Kahn et al. (1998) and others. The percentage of MVC at which perfusion stops depends on muscle being studied but it is usually above 25% MVC.

In the present study, in some volunteers the flow restriction was greater with the knee flexed towards 90°. From the group of 14 volunteers, there were 8 who showed the greatest restriction at 90° as illustrated in figure 3.6A. The others showed no clear effect of limb position on flow restriction. This is consistent

with Foster et al. (1999). They found in skaters that the more the knee flexes, the greater the restriction in muscle blood flow.

Boushel et al. (2001) reported that changes in blood flow during exercise depend on the work intensity, degree of activation of the muscle group and level of training. Body position may be added to these factors as it restricts the blood flowing to the working muscles during contractions. This effect can be clearly seen in some volunteers, see figure 3.6A, but it is clearly absent in others, see figure 3.6B. This supports the hypothesis that insufficient blood flow could be a cause of muscle injury. It is open to question if those athletes with the more severe restriction of perfusion at particular body positions are more likely to incur injuries at that position.

Chapter Four

Blood Perfusion after Specific Warm-Up

Most athletes perform a warm-up before training or competing. It is generally thought that warming-up prior to activity is a physical and mental preparation for the athlete (Bishop, 2003). Warm-up is believed to aid performance and reduce the risk of injury via temperature-related and non-temperature-related mechanisms (Safran et al. 1988; Sallay et al. 1996). Although the majority of athletes perform a warm-up, the scientific understanding of the process and its benefits is still poor. The athlete from rest starts some type of physical exercise. This results in higher core temperature, higher heart rate and more blood flow throughout the body, especially to the exercising muscles (Bergh & Ekblom, 1979). The effect of increasing muscle temperature on metabolism during such exercise depends on the type of the warm-up used (Gerbino et al.1996).

Shellock & Prentice, (1985) described three main types of warm-up: passive, general and specific. These are described in detail in section 1.2.10 of the Introduction. Most athletes start their activity with general warm-up including jogging and stretching. This is followed by a specific warm-up including activities similar to the main sports event. This is mainly focussed on the muscles to be used during the activity. A parallel aim is to reduce the chance of injury.

The general and specific warm-up exercises may increase muscle temperature and improve O_2 delivery of the exercising muscles (Koga et al. 1997). Blood

flow in resting skeletal muscle is known to be low at about 4 ml/100g/min (Barcroft & Swan, 1953; Laaksonen et al. 2003). During exercise, muscle blood flow increases by about 65 ml/100g/min (Harms et al. 1997). During maximal exercise, blood flow increases in the range of 50-150 ml/100g/min (Laughin, 1987).

Much of the literature concerning warm-up focuses on its perceived benefits in enhancing performance, which can be described as physiological, psychological and injury prevention. The hypothesis of this experiment was that specific warm-up consisting of intermittent contractions would increase the concentrations of haemoglobin in the biceps femoris muscle. Therefore, the aim of the experiments described in this chapter was to investigate whether specific warm-up increases perfusion of the hamstring muscles. In addition, how intense these warm-up contractions have to be to cause a flow increase and for how long the increase persists.

4.1 Materials and Methods

4.1.1 Participants

Fourteen male volunteers aged between 20 and 42 years participated in this experiment (mean age 27 years). Their anthropometric details are given in appendix 9.2. They were not specially selected to represent any particular group of sports people.

4.1.2 Equipment

The instruments, which have been used during this experiment, were similar to those described in the first study.

One major difference is that all experiments were done in the right limb with the knee position fixed at 60° of flexion. Volunteers lay in a prone position on a flatted seat on the Kin-Com dynamometer. In the experiments described in chapter 3 the volunteers sat upright. In these experiments the volunteers lay prone. Moving to a prone position avoided any problems caused by compression of the hamstrings muscles by the weight of the limb. Their body position was adjusted to ensure the axis of rotation of their knee and was coincident with axis of rotation of the lower arm. The dynamometer's lever arm was also adjusted to meet the volunteer's leg length ensuring safety and preventing injury during contractions. The volunteer's peak torque was determined at the beginning of the test. This is illustrated in figure (4.1).

Blood pressure and heart rate were monitored at intervals throughout the test using a Colin NET BP-88 automatic monitor. In each experiment nine values were taken. The first three were taken as baseline values before exercise started. The second three were made immediately after exercise and the last three were made during recovery phase approximately 10 minutes after the end of exercise. The mean of the three measurements was used in the analysis to investigate if there were any significant changes in blood pressure (BP) and heart rate (HR).

Figure 4.1: volunteer in prone position and the knee at 60° flexion

Figure 4.1

This figure shows a volunteer in the prone position with the right knee at 60° flexion. The cuff on the left arm measures blood pressure and heart rate. Other devices can be seen behind the volunteer: for example the NIRS, PC and screen of the Kin-Com.

4.2 Experimental Procedure

Each volunteer performed 3 MVC contractions as outlined in the general methods chapter section 2.3. The highest torque value was chosen and any sub-maximal contraction was expressed as percentage of this. The NIRS recorded the muscle perfusion during sub-maximal contractions. In a pilot study, contractions were made at 25%, 30%, 35%, 40% and 45% of MVC. In practice, the measurements at each force level e.g. 30% MVC took about one hour to complete. This made the whole experiment too long for the volunteers to sustain. A modified protocol that tested warm-ups with 30% and 40% MVC contractions was adopted.

The warm-up consisted of 3 sets of 5 repetitions of isometric contractions at 30% and 40% MVC. Each contraction lasted 5 seconds with 10 seconds intervals. The 3 sets were separated by 1 minute rest period. The recording session for one force level lasted approximately 15 minutes. The whole measurement of one session took about one hour to complete. Depending on the recovery time after a single session volunteers were tested over one or two sessions. The volunteers were given visual feedback about the force of contraction by allowing them to see the computer screen of the Kin-Com. After a familiarisation period the volunteers could hold the contraction forces at the specified value.

During each tests there were simultaneous recordings of EMG and NIRS signals using the CED 1401 and PC as described in the general methods section.

Figure 4.2 shows the sequence of activities during the experiment.

Figure 4.2: Order of specific warm-up at 30% and 40% MVC

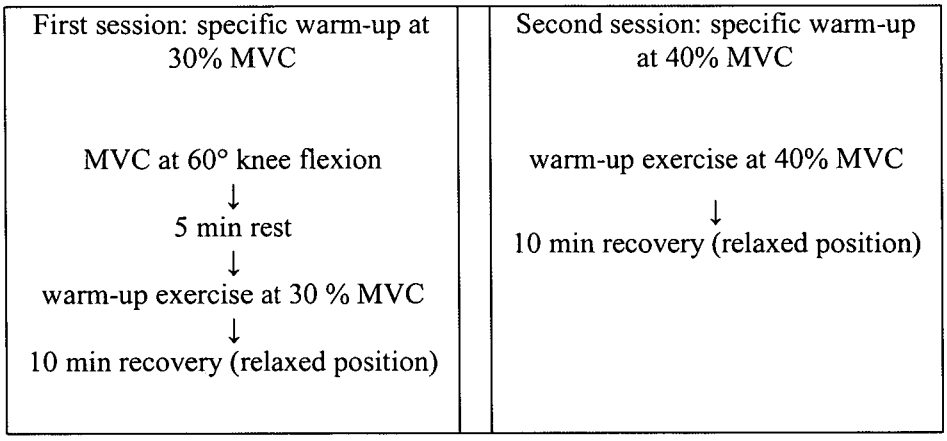


Figure 4.2

This figure shows the experimental protocol of warm-ups at 30% and 40% MVC contractions. The experiment consisted of two sessions. At session one, the volunteer started with MVC of knee flexion at 60°. A period of 5 minutes rest was given. This was followed by the warm-up exercise at 30% MVC. The volunteer stayed in the same position for about 10 minutes as a recovery period of reactive hyperaemia. At the second session, the same protocol was repeated at 40% MVC.

4.3 Analysis of the NIRS Traces

The data were analysed by measuring the size of hyperaemia and their duration periods. The size of hyperaemia was defined, as the period that [HbO_2] value was above the mean value of baseline. There was a period of hyperaemia following each set of contractions at 30% and 40% MVC. The values were taken from [HbO_2] signals. The duration of hyperaemia was defined as the period that [HbO_2] signal was higher than the mean baseline value. The change in [HbO_2] was deemed to be significant if its magnitude was greater than two standard deviations above the mean [HbO_2] in the 150 seconds before warm-up.

The analysis was started with measuring the mean value of [HbO_2] for 150 seconds before contractions start. The mean value for this period was calculated along with the standard deviation. Figure 4.3 shows the specimen data of means and confidence interval. The middle dashed line is the control mean. The upper and lower dashed lines are the 95% confidence intervals calculated as mean ± two standard deviations. These control values are extrapolated forward in time. Any excursion of the trace above or below these confidence intervals shows a significant change in HbO_2 concentration. The duration of the change in flow was calculated from the time spent above or below the confidence interval. The magnitude of the response was calculated as the area above or below the mean value during this time. The Minitab statistical package version 13 was used for statistical analysis. One-way ANOVA tests were used.

Figure 4.3: Specimen data showing means and confidence interval

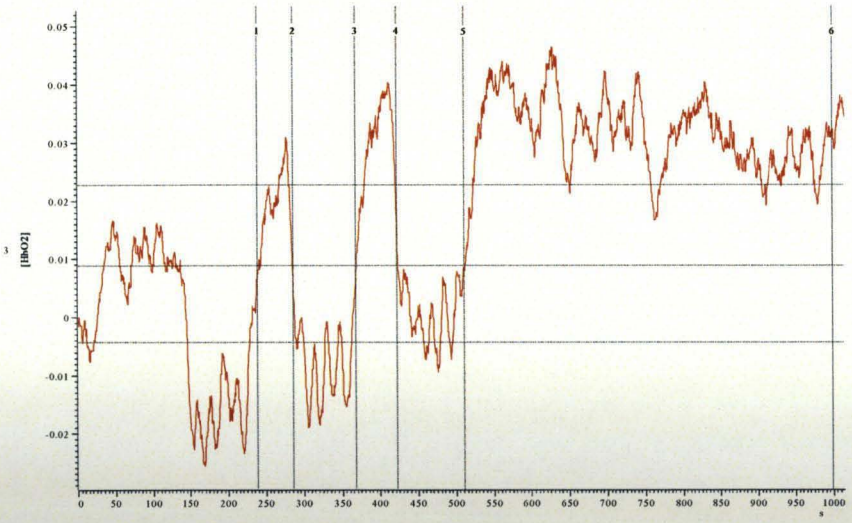


Figure 4.3

This figure shows specimen NIRS data showing [HbO_2]. The data has been smoothed using a 5 second averaging period. There is a period of resting flow followed by three sets of contractions at 30% MVC. The [HbO_2] is reduced during the contractions. The contractions are followed by three hyperaemias. These can be seen as [HbO_2] above the 95% confidence interval. The first area is between cursor 1 and 2 above the upper horizontal line. The second area is between cursor 3 and 4 above the upper horizontal line. The third area is between cursor 5 and 6 above the upper horizontal line. It can be seen that the hyperaemia in the first area is smaller than the second area. Also, the hyperaemia in the third area is much bigger than the second area. Each of these areas has its duration period.
For these plots a voltage change of 0.01 volt equals 5.3 micromoles of HbO_2

4.4 Results of Reactive Hyperaemia after Specific Warm-Up

This section shows NIRS data recorded during sub-maximal intermittent isometric contractions. Figure 4.4A and 4.4B show the NIRS output recorded as two volunteers make intermittent isometric contractions at 30% MVC. This recording lasts for 1000 seconds, approximately 16 minutes. The recordings show very stable baselines for all the signals during the 150 seconds before the first set of contraction starts. This is followed by 2 further sets of contractions. These can be clearly seen in the lowest trace of EMG.

It is interesting to see that the EMG trace in figures 4.4A, 4.4B shows that the volunteers were able to relax their hamstrings completely during the baseline recording and between the sets of contractions. Both volunteers show short bursts of EMG activity after the contractions. This is particularly clear in figure 4.4B at about 460 seconds. These periods of activity are not surprising given the duration of the recordings. However, they can have an effect on the NIRS output. It can be seen in figure 4.4B that the small contraction clearly reduced the [tHb] and the [HbO_2]. A similar but smaller effect can be seen later in figure 4.4A.

The sets of contractions illustrated in figures 4.4A and 4.4B cause reductions in the [tHb] and [HbO_2]. These were accompanied by rises in the [HHb]. These changes probably reflect a relative under-perfusion of the muscle during the sets of contractions. These observations are consistent with the results in chapter three. The effects are now much larger since they follow three sets of 5

contractions, each of which lasts 5 seconds. The single contractions reported in chapter 3 lasted for 10 seconds. The magnitudes of the contractions in the experiments described in chapter 3 were 25 or 50% of MVC. Those reported in this chapter were at 30 or 40% of MVC.

The hyperaemia which followed the contractions is best seen in the [HbO_2]. This is easy to see in figures 4.4A and 4.4B. There is a clear increase above the horizontal line, indicating the control mean, following these 3 sets of contractions. The general pattern was the increase in [HbO_2] was greater more during the interval between the second and third sets than it was between the first and second sets. The hyperaemia after the third set was still bigger in all volunteers.

Figure 4.4A: NIRS & EMG data from volunteer 7

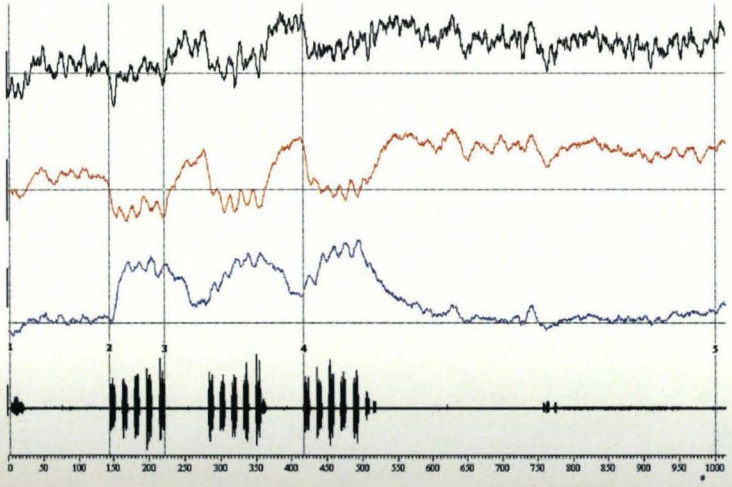


Figure 4.4B: NIRS & EMG data from volunteer 2

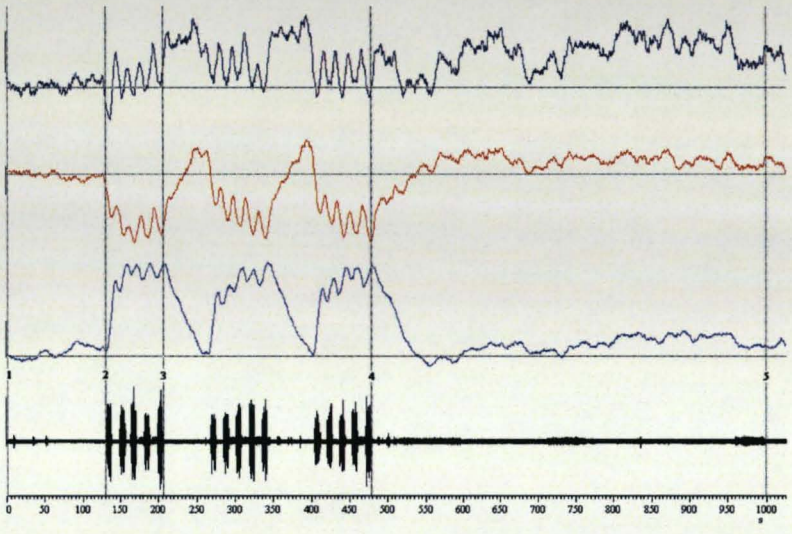


Figure 4.4A and B

These two figures show NIRS and EMG data in volunteers making intermittent isometric contractions at 30% MVC. The NIRS signals have been smoothed over 5 second periods. This recording lasts for 1000 seconds approximately 16 minutes. It starts with a resting period of about 150 seconds. This is between cursor 1 and 2. The beginning of the first set of 5 intermittent isometric contractions is at cursor 2. There are 3 sets of 5 contractions. There is long recovery between cursor 4 where the exercise finishes and cursor 5. The biggest hyperaemia was found during this period.

The [tHb], top trace, and [HbO_2], middle trace decrease during the sets of contractions. Clear hyperaemia can be seen after these sets. The [HHb], lower trace increases during the contractions. The lower trace shows the hamstrings EMG activity during knee flexion. All these traces were recorded concurrently.

The vertical calibration bar for the top trace shows 0.05 volts, 8 micromoles of tHb, the calibration for HbO_2 shows 0.01 volt equals 5.3 micromoles. The calibration for the EMG is 1 millivolt.

Figure 4.5 shows the NIRS output recorded as volunteer 4 makes contractions at 30% MVC. This data is similar to figure 4.4 A and B but recorded from another volunteer. The recordings show a very stable baseline for all signals during the first 150 seconds before the first set of contraction starts. The volunteer in figure 4.5 shows unstable recordings in baseline of the NIRS traces. The hamstring muscles were active during the relaxation period before contractions. The NIRS output is affected by the contractions in the hamstrings.

This volunteer is unable to relax the hamstrings. The bursts of EMG activity during the relaxation period before the sets of contractions and between set one and set two have an effect on the NIRS output. The volunteer is able to relax for about 25 seconds at about 100 seconds into the recording. This is accompanied by a substantial increase in all three NIRS signals. These prolonged contractions before this may have affected the apparent baseline values. The activity between set one and two depresses the [tHb] and probably restricts the size of the hyperaemia indicated by the [HbO_2] after set one.

These disturbances in the NIRS signal emphasise how important it is to examine the concurrent EMG activity. Any involuntary muscle contractions can have strong effects on the NIRS signals.

Figure 4.5: NIRS & EMG data from volunteer 4

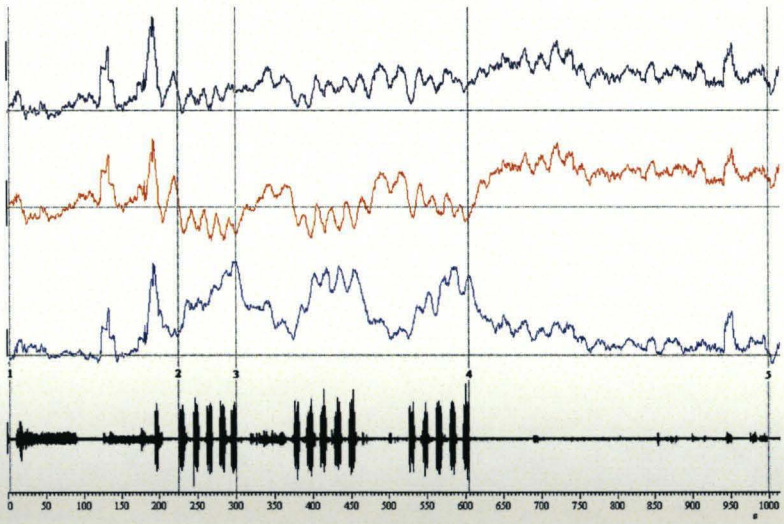


Figure 4.5

This figure shows NIRS and EMG data from volunteer 4. The recordings show unstable baseline during the relaxation and between contractions at 30% MVC for all signals. The EMG activity means that the hamstrings were active during the control period and the hamstrings were unable to relax between contractions. These involuntary contractions affect the NIRS outputs.
The vertical calibration bar for the top trace shows 0.05 volts, 8 micromoles of tHb, the calibration for HbO_2 shows 0.01 volt equals 5.3 micromoles. The calibration for the EMG is 1 millivolt.

Figure 4.6A and 4.6B show the [HbO_2] trace that has been converted from Spike 2 to a spreadsheet. The middle dashed line is the control mean extrapolated across the whole record. The upper and lower dashed lines are the 95% confidence intervals calculated as mean ± two standard deviations. Whilst about 5% of the data points should lie outside this interval, any prolonged excursion of the trace above or below these intervals shows a significant change in HbO_2 concentration.

These two figures show clear reduction in the [HbO_2] during the contractions at 30% of MVC, figure 4.6A and at 40% of MVC, figure 4.6B. Three periods of hyperaemia can be clearly seen above the horizontal line. The magnitude of the hyperaemia is much bigger after the third set of contractions. This can be seen in figure 4.6B.

Figure 4.7A and 4.7B show the [tHb] trace that has been exported from Spike 2 to an Excel spreadsheet. These data were recorded from the same volunteer in figure 4.6 but showing [tHb] instead of [HbO_2]. The data show that the pattern of [HbO_2] is almost similar to the pattern of [tHb].

Figure 4.6A: volunteer 7 at 30% MVC

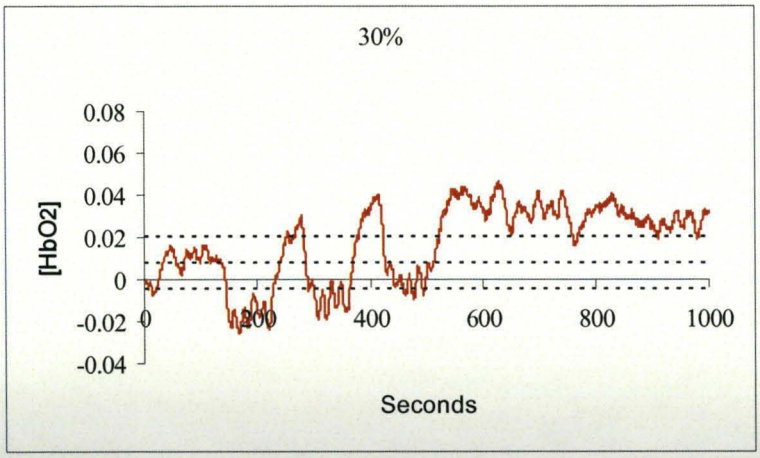


Figure 4.6B: volunteer 7 at 40 % MVC

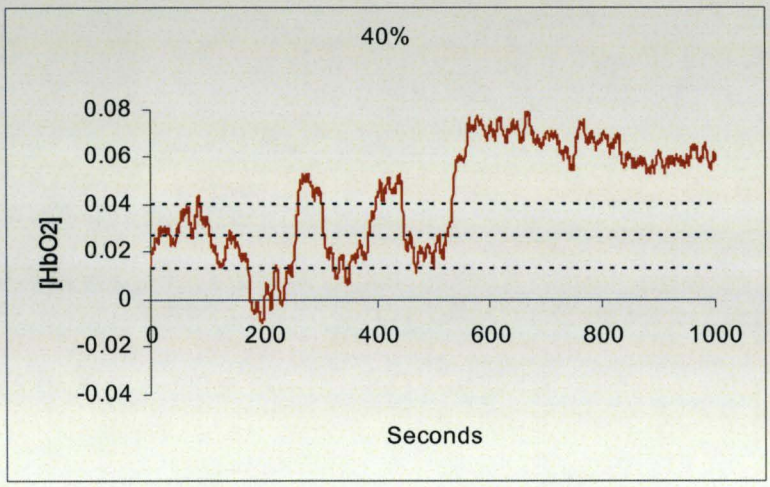


Figure 4.6

These two figures illustrate the hyperaemias after sets of contractions at 30 and 40% MVC for volunteer 7. The duration of the experiment is 1000 seconds. There are three horizontal lines in this figure. The middle line is the mean of $[HbO_2]$. The other 2 outer lines show ± 2 standard deviations. In all volunteers and at both intensities the $[HbO_2]$ declined during contractions and increased above the confidence interval of the mean during recovery.
The vertical calibration bar for the $[HbO_2]$ shows trace 0.01-volt equals 5.3 micromoles.

Figure 4.7A: [tHb] for volunteer 7 at 30% MVC

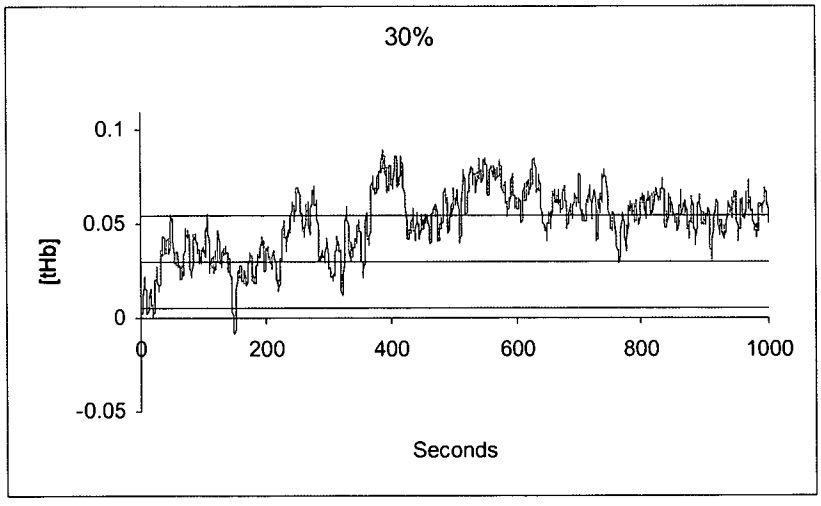


Figure 4.7B: [tHb] for volunteer 7 at 40% MVC

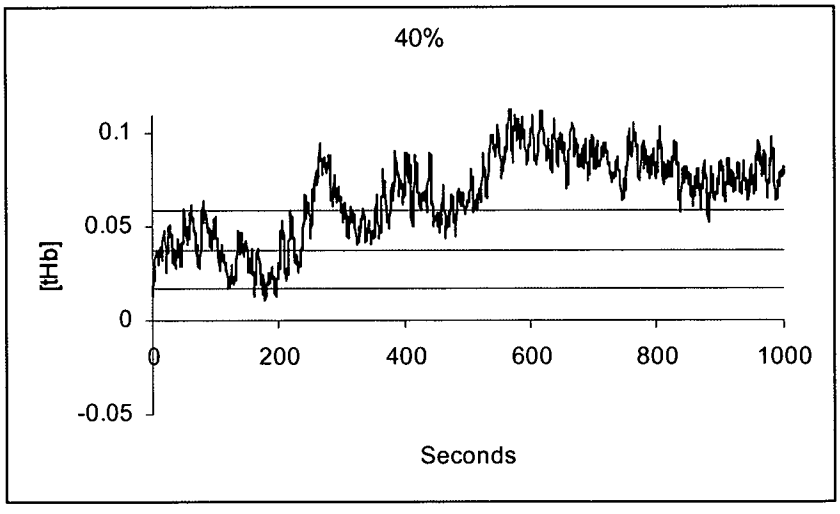


Figure 4.7

These two figures illustrate the hyperaemias of [tHb] after sets of contractions at 30 and 40% MVC for volunteer 7. There are three horizontal lines in this figure. The middle line is the mean of [tHb]. The other 2 outer lines show ± 2 standard deviations.

The duration of the experiment is 1000 seconds. The third set of contractions stops at 500 seconds in both cases. The hyperaemia starts at this point where the [tHb] rises above the upper confidence interval.

In all volunteers and at both intensities the [tHb] declined during contractions and increased above the confidence interval of the mean during recovery. The contractions are followed by three hyperaemias. The first, second and third areas were found significantly above the 95% confidence interval. This is similar to the figure 4.6 of [HbO_2] where the hyperaemia in the third area is much bigger than the first and second areas. The calibration bar for the tHb shows 0.05 volts is equivalent to 8 micromoles.

4.4.1 Size of Hyperaemia at 30% and 40% MVC

It was of interest to compare the magnitude of the hyperaemias following sets of contractions at 30 and 40% of MVC. This allows a comparison to be made of the effectiveness of specific warm-up at two different intensities.

All 14 volunteers completed sets of contractions at both intensities. All volunteers had a significant hyperaemia in both tests. Tables 4.1 and 4.2 show individual values of the sizes of the hyperaemia after the three sets of contractions at 30% and 40% MVC. There was a substantial variation in the size of the hyperaemia. For example volunteer 5 shows a very large response and volunteer 14 has a very small, but still statistically significant, response after the 30% contractions. The sizes of the hyperaemias at 30% and 40% were not statistically significantly different when tested with an ANOVA ($P = 0.427$) or with a paired t-test ($P = 0.099$).

Table 4.1: MVCs and sizes of hyperaemias at 30 and 40% MVC

No	MVC (Nm)	Sizes of hyperaemia at	
		30%	40%
14	493	419.9	3194.9
8	252	829.2	5805.0
7	307	1249.2	1892.4
10	450	1493.7	3545.7
6	314	2094.4	1504.4
3	426	2535.7	1844.6
4	376	2604.8	722.9
1	317	2891.8	3147.0
12	229	2907.8	5331.9
9	298	2913.1	2684.5
2	269	2918.4	4093.3
11	306	3279.9	1185.4
13	416	5002.3	4906.6
5	421	5108.6	4040.1
Mean		**2589.2**	**3135.6**
St Dev		**1361.6**	**1585.9**

Table 4.1

This table shows the MVC and sizes of hyperamias at 30% and 40% of 14 volunteers. This table is sorted out in ascending order for values at 30% MVC. The magnitude of the hyperaemia is calculated as the area under the [HbO_2] curve. It is expressed as the product of micromoles multiplied by seconds. There is a considerable variation in the MVC and size of the hyperaemia among the volunteers.

The volunteers' MVC forces are also shown in table 4.1 above. This table is sorted in ascending order by the size of hyperaemia after contractions at 30% MVC. The highest MVC was 493 Nm while the lowest value was 173 Nm and the mean was 330 Nm.

Figure 4.7 shows the MVC data plotted against the size of the hyperaemias. No obvious relationship can be seen between the forces produced by 14 volunteers and the sizes of hyperaemias at either 30 or 40% MVC. Figure 4.8 shows the magnitude of the hyperaemias following the sets of contraction intensities plotted against each other. Again, there is no obvious pattern in the responses.

Figure 4.8: size of hyperaemia at 30% and 40% MVC

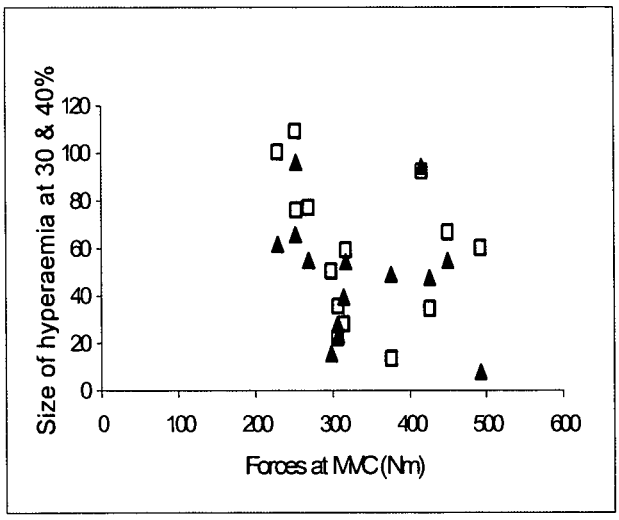


Figure 4.8

This figure shows the relationship between the size the hyperaemias after contractions at 30% and 40% MVC. This Δ symbol represents the size of hyperaemia at 30% MVC, while this □ symbol represents the size of hyperaemia at 40% MVC. The distribution of these symbols indicates that the force did not affect the area of hyperaemia.

Figure 4.9: relationship between 30 and 40%MVC of hyperaemia

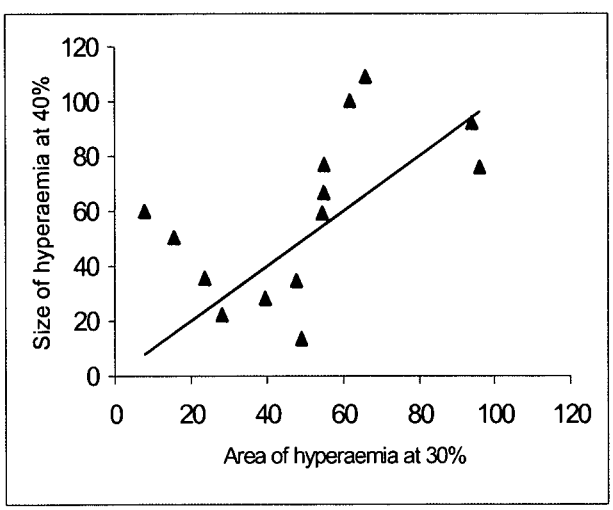


Figure 4.9

This figure shows the relationship between the size the hyperaemias after contractions at 30 & 40% MVC. The distribution of these symbols indicates that there is no difference in the sizes of hyperaemias at both intensities. The line of identity, y = x is also shows.

4.4.2 Duration of hyperaemia at 30 and 40% MVC

The duration of a hyperaemia was defined as the period that [HbO_2] signal was significantly higher than the mean value of the control period i.e. when it was above mean plus two standard deviations. All values of duration were calculated individually. All 14 volunteers were tested. The data can be seen in table 4.2. This table is sorted out in ascending order for duration of hyperaemias after sets of contractions at 30% MVC.

Table 4.2: MVCs and durations of hyperaemias at 30 and 40% MVC

No	MVC (Nm)	Duration of hyperaemia (s) at	
		30%	40%
4	376	386	183
3	426	423.5	373.5
13	416	430	430
11	306	439.5	555.5
9	298	441	500.5
10	450	449.5	390
2	269	466	457
5	421	471	552.5
14	493	480	440.5
1	317	487.5	433.5
7	307	490	478
6	314	507.5	486.5
8	252	546.5	487
12	229	611	473.5
Mean		**474**	**446**
St Dev		**134**	**145**

Table 4.2

This table shows the MVC and durations of hyperaemias at 30% and 40% of 14 volunteers. This table is sorted out in ascending order for the magnitude of the hyperaemia at 30% MVC. There is a considerable variation in the MVC and duration of the hyperaemia among the volunteers.

The duration of hyperaemia during the recovery period lasted between 183 and 611 seconds. Although the mean duration of hyperaemia after sets at 30% MVC was higher than after 40% MVC, the difference was not statistically significant when tested with an ANOVA, ($P = 0.307$) or with a paired t-test ($P = 0.114$).

Figure 4.10: duration of hyperaemia at 30 and 40% MVC

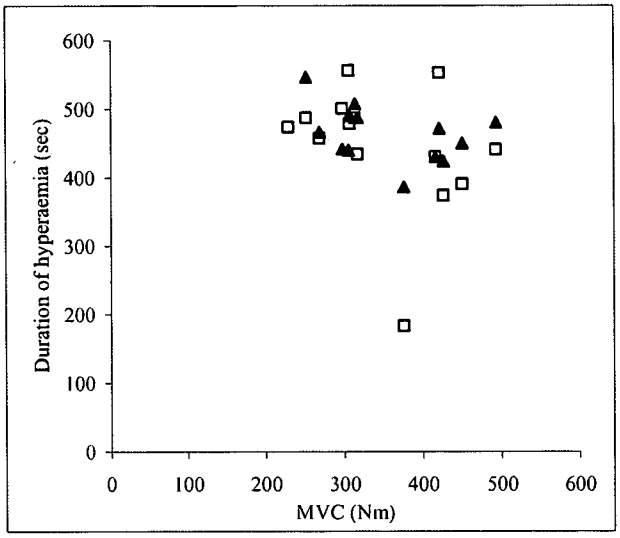


Figure 4.10

This figure shows the relationship between the duration of hyperaemias after contractions at 30 and 40% MVC. This Δ symbol represents the duration of hyperaemia at 30% MVC, while this □ symbol represents the area of hyperaemia at 40% MVC. The distribution of these symbols indicates that the force did not affect the duration of hyperaemia.

4.4.3 Blood Pressure Changes during the Warm-Up

The perfusion of the muscles may be affected by the state of the cardiovascular system. The arterial blood pressure (BP) and heart rate (HR) were recorded at intervals throughout the experiment.

Table 4.3 shows the values of systolic and diastolic blood pressures at several points during the experiment. The column headed before contains values measured just before the warm up contractions i.e. taken during the baseline rest period in 150 seconds prior to start of experiment. The column headed during contains values measured the average of three readings taken immediately after last set of contractions" at 30% MVC. The final sets of readings were taken at the end of the recording session. A similar set of data for the same volunteers contracting at 40% of MVC are shown in table 4.4.

No significance difference in either systolic or diastolic blood pressure was found. The results of a series of ANOVA tests are given in table 4.5.

4.4.4 Heart Rate Changes during the Warm-Up

The heart rates were measured at the same time as the blood pressure was recorded. The heart rate data are shown in tables 4.6. The heart rates showed no statistically significant changes over the duration of the test.

This stability of the BP and HR means that there have been no significant changes in the cardiovascular system as a result of the specific warm-up. Thus changes in BP and HR are unlikely to have caused the NIRS observations.

Table 4.3: Systolic & Diastolic BP before, during and after exercise at 30% MVC

BP 30%	Systolic Pressure (mm Hg)			Diastolic Pressure (mm Hg)		
No	**Before**	**During**	**After**	**Before**	**During**	**After**
1	104	110	93	62	65	67
2	124	119	119	69	63	65
3	137	135	133	72	64	72
4	*	*	*	*	*	*
5	130	132	132	73	70	78
6	125	131	125	66	75	67
7	133	140	136	76	76	84
8	135	150	146	88	90	93
9	133	141	129	61	64	67
10	119	128	125	62	71	67
11	*	*	*	*	*	*
12	126	105	126	81	44	50
13	123	124	123	63	59	53
14	122	128	119	64	67	70
Mean	**126**	**129**	**126**	**70**	**67**	**69**

Table 4.3

This table shows the values of the systolic and diastolic blood pressure in 14 volunteers. These values were recorded before, during and after the specific warm-up exercise. "Before" was defined as an average of three readings of systolic and diastolic values taken before the start of experiment. "During" was defined as an average of three readings of systolic and diastolic values taken immediately after the three sets of contractions. "After" was defined as an average of three readings of systolic and diastolic values taken at the end of the recording session. The intensity of the contractions was 30% MVC. The * means that no data available from these tests due to technical problems.

Table 4.4: Systolic & Diastolic BP before, during and after exercise at 40% MVC

BP 40%	Systolic Pressure (mm Hg)			Diastolic Pressure (mm Hg)		
No	**Before**	**During**	**After**	**Before**	**During**	**After**
1	105	107	114	55	44	60
2	*	*	*	*	*	*
3	138	142	143	72	72	74
4	120	144	128	68	64	67
5	132	131	125	70	60	67
6	128	127	129	70	83	65
7	138	140	137	69	77	82
8	135	160	136	86	78	89
9	139	149	143	69	76	73
10	143	142	138	83	75	73
11	132	68	133	71	135	77
12	129	129	125	78	73	78
13	124	124	120	64	55	62
14	122	124	128	63	60	75
Mean	**130**	**130**	**131**	**71**	**73**	**72**

Table 4.4

This table shows the values of the systolic and diastolic blood pressure in 14 volunteers. These values were recorded before, during and after the specific warm-up exercise. The intensity of the contractions was 40% MVC. The * means that no data available from these tests due to technical problems.

Table 4.5: *P* values of BP before, during and after exercise

30%	*P* value	
Before vs. During	0.561	N.S.
During vs. After	0.561	N.S.
Before vs. After	0.927	N.S.
40%	***P* value**	
Before vs. During	0.983	N.S.
During vs. After	0.893	N.S.
Before vs. After	0.774	N.S.

Table 4.5

This table shows the *P* values of a series of ANOVA tests comparing the blood pressure before, during and after contractions at 30% and 40% MVC. No statistically significant difference was found after the analysis.

Table 4.6: HR before, during and after exercise at 30% and 40% MVC

No	HR (bpm) at 30% MVC				HR (bpm) at 40% MVC		
	Before	During	After		Before	During	After
1	73	75	73		78	108	102
2	79	73	70		*	*	*
3	59	63	55		64	67	64
4	*	*	*		104	114	102
5	60	67	64		54	51	50
6	61	61	54		69	66	64
7	69	69	69		69	70	67
8	77	71	69		74	75	71
9	63	64	70		78	76	71
10	76	73	63		74	76	70
11	*	*	*		62	76	60
12	88	87	72		81	81	78
13	69	72	66		66	67	70
14	57	62	67		55	57	63
Mean	**69**	**70**	**66**		**71**	**76**	**72**

Table 4.6

This table shows the values of the heart rate in 14 volunteers. These values were recorded before, during and after the specific warm-up exercise. The intensity of the contractions was 30% and 40% MVC. The * means that no data available from these tests due to technical problems.

Table 4.7: *P* values of HR before, during and after exercise

30%	*P* value	
Before vs. During	0.887	N.S.
During vs. After	0.185	N.S.
Before vs. After	0.334	N.S.
40%	***P* value**	
Before vs. During	0.486	N.S.
During vs. After	0.541	N.S.
Before vs. After	0.956	N.S.

Table 4.7

This table shows the *P* values of the test of ANOVA for the heart rate before, during and after contractions at 30% and 40% MVC. No statistically significant difference was found after the analysis.

4.5 Discussion

The reactive hyperaemia was investigated after specific warm-up contractions in the hamstrings blood perfusion in 14 male volunteers. The size and duration of the hyperaemias were measured after set of contractions at 30% and 40% MVC. The results show that there was significant increase in [HbO_2] after specific warm-up at 30% and 40% MVC in al 14 volunteers. No significant difference in the size of the hyperaemia was found after sets of contractions at 30% and 40% MVC.

The duration of hyperaemia was measured after sets at 30% and 40% MVC. The hyperaemias lasted about 7 to 8 minutes for both intensities of contraction. See table 4.2. During the recovery period, the hyperaemias in all 14 volunteers were returned to within ±2 standard deviation of mean value. It is clear that these warm-up exercises increase the blood perfusion in the hamstrings. Kagaya & Homma, (1997) observed that post contraction hyperaemia after isometric handgrip exercises was greater and lasted longer as exercise intensity increased. The protocols are different in that they asked their volunteers to maintain a steady contraction for one minute and they used forces up to 70% of MVC. The intermittent contractions used in this experiment and narrow range of forces employed may have concealed any force related effect.

All of these hyperaemia occurred at a time when there was no overall change in arterial blood pressure or heart rate and so cannot be secondary to an overall change in the state of the cardiovascular system. This can be clearly seen in

table 4.3, 4.4, 4.5, 4.6 and 4.7. It can be concluded that the exercising muscle mass is too small or the intensity of contractions too low to have a significant pressor effect.

In more intense exercise blood pressure increases as the contraction force increases (Kagaya & Honna, 1997). More specifically, systolic BP can increase during maximal isometric contractions to high values that may be a danger in some cases. BP rises are smaller in individuals with lower cardiovascular fitness (Tzemos, Lim and MacDonald, 2002).

4.5.1 Methods of Warm-Up

Shellock & Prentice, (1985) described three types of warm-up: passive, general and specific. Kato et al. (2000) stated that specific warm-up appears to be the most desirable type as it increases the temperature of specific muscles that will be used in subsequent event.

Athletes usually start their training or competition with general warm-up which consists of jogging and stretching. Then depending on their sports event, they perform specific warm-up. During jogging the heart rate increases and the core temperature of the body start to rise. These are usually followed by dynamic and sustained stretching to the major muscles and joints. The final stage of warm-up takes the athlete from general to specific exercises similar to the requirements of sport events. When this has been done properly, it helps the athlete to perform

better and may prevent him having an injury, at least in the first stages of strenuous sports.

4.5.2 Size & Duration of Hyperaemia

In the experiments described in this chapter reactive hyperaemias were measured in the biceps femoris after specific warm-up exercises. This protocol focused on light to moderate intensity contractions at 30% and 40% MVC. These were chosen to allow completion of the experiments in a reasonable time and to avoid muscle fatigue. In the present experiment, significant hyperaemia was identified after specific exercise. The rapid increase in [HbO_2] was due to vasodilation in the hamstrings.

Andersen & Saltin, (1985) measured the quadriceps muscle perfusion. They concluded that muscle blood flow is closely related to the O_2 demand of the exercising muscles. The increment of blood flow to exercising muscles may be related to the mechanical interactions between the contracting and relaxing muscles that is 'the muscle pump'. This type of rhythmic contractions increased perfusion in the exercising muscles. The appearance of exercise hyperaemia may be associated with O_2 delivery that has been enhanced following specific warm-up. It appears that after a period of O_2 extraction during contractions, O_2 was delivered into the hamstrings during relaxation periods.

Blood flow during exercise is not steady, which may explain the difficulty in identifying the specific mechanism of exercise hyperaemia. In a review article

Tzemos et al. (2002) reported that in human limbs, the hyperaemia can be divided into four phases: rapid early vasodilatation, beginning of active exercise, steady-state and recovery. Tschakovsky et al. (1996) in their experiment showed that blood flow of the human forearm is increased after repeated cuff inflation and deflation, which may explain the effect of the neural mechanism. However, during the steady-state phase of exercise, rhythmic muscle contractions and metabolic factors ensure a constant blood supply.

When intra-muscular pressure increases, the blood flow to the exercising muscle will be impaired as a result of vasocompression. The sets of contractions illustrated in figures 4.4 A and B cause reductions in the [tHb] and [HbO_2]. The amount of this change depends on the force and duration on the contraction and the length of recovery periods. Hicks et al. (1999) studied muscle blood flow of the forearm during isometric contractions. They stated that blood flow appeared to be occluded by contractions between 20% and 45% MVC.

The hyperaemia was observed between the contractions, while this was significantly observed after the sets of contractions. Khan et al. (1998) found that immediately after the release of the maintained force muscle blood flow increased to peak flow level. It appears that mild warm-up has positive effects and may contribute in enhancing the performance as a result of increased blood flow in the exercising muscle. Specific warm-up increases the temperature of the body parts involved in the activity (Kato et al. 2000). Any muscle vasodilation associated with increased temperature may facilitate muscle perfusion allowing an increase in muscle blood flow (Koga et al. 1997). Thus, it

is important to perform at least light warm-up before strenuous exercises as preventative procedure. It could therefore be concluded that mild specific warm-up exercise at 30% MVC increased the overall blood flow and O_2 supply to the hamstrings.

Chapter Five

Perfusion of the Hamstrings during Delayed Onset Muscle Soreness

DOMS is frequent at the beginning of the season when athletes return to training after a period of reduced or no activity. The unfamiliar exercise intensity provokes muscle pain. The post-exercise soreness or delayed-onset muscle soreness (DOMS) reaches its maximum intensity 2-3 days after the training session (Ernst, 1998). This intensity of DOMS is affected by the intensity, duration and type of exercise. Both concentric and eccentric exercise can cause DOMS, but the latter is the more potent cause (Nosaka & Newton, 2002). The outcome of eccentric exercise is fibre damage; leading to pain and tenderness. These symptoms recover after about one week (Clarkson & Tremblay, 1988).

McHugh et al. (1999) listed the symptoms of DOMS after eccentric exercise as follows; strength loss, pain, muscle tenderness and elevated Creatine Kinase (CK) activity. These symptoms provide indirect evidence of muscle damage. DOMS has been related to possible damage to connective tissue (High & Howley, 1989). Cheung et al. (2003) reported that DOMS is classified as type I muscle strain injury. These changes are commonly accepted as associated with muscle damage that may affect sport performance. DOMS may increase the risk of further injury if athletes attempt an early return to sport. The chemical and

mechanical changes can be useful indicators of muscle damage in order to seek prevention of muscle injury.

It was hypothesised that perfusion in the hamstrings would be reduced during an episode of DOMS due to oedema following damage to the muscle fibres. The aim of this study was to investigate changes in the total haemoglobin [tHb] in the hamstrings during rest, exercise and recovery periods tested during an episode of DOMS. A search of the literature revealed that there have been no previous studies of hamstring muscle perfusion during DOMS.

5.1 Materials and Methods

5.1.1 Participants

The experimental protocol was approved by the Glasgow University Research Ethics Committee. The purpose of the study and the expected risks that associated with the procedures were explained to the participants.

Twelve male volunteers aged between 18 and 42 years participated in this experiment (mean age 22 years). Their anthropometric details are given in appendix 9.3. They were not specially selected to represent any particular group of sports people.

Volunteers were asked to not participate in any strenuous physical activity for the duration of the study. All volunteers were evaluated three times during the course of the experiment. They visited the laboratory 3 times within 1 week. Volunteers visited the laboratory at day 0, day 2 and day 7.

5.1.2 Equipment

The testing instruments used were similar to those described before. A hamstring curl machine was used to exercise the right hamstrings.

5.2 Experimental Procedure

In these series experiments the right leg of the volunteer was tested at three visits. The following measurements made each day: 5 ml blood sample taken from ante-cubital vein to allow measurement of [CK], recordings of BP and HR, measurements MVC of the hamstrings, measurements of [tHb] at 10, 20, 30 and 40% MVC of isometric contractions at 60° flexion. The body position for these tests is identical to that illustrated in figure 4.1.

At the end of the first experimental session the volunteer performed a vigorous exercise programme with their right hamstrings. Details of this are given below in section 5.2.3. The order of the experimental protocol is shown in figure 5.1.

Fig 5.1: DOMS test

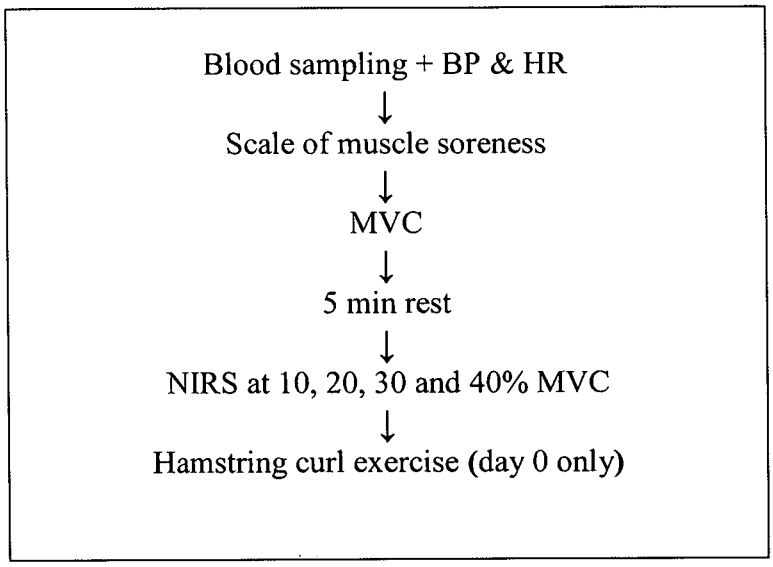


Figure 5.1

This figure shows the experimental protocol of DOMS experiment. The experiment consisted of blood sampling, BP and HR recordings, muscle soreness and MVC of knee flexion at 60°. A period of 5 minutes rest was given. This was followed by the contractions at 10, 20, 30 and 40% MVC. After 2 days, the same session was repeated. The same protocol was repeated after 7 days. The hamstring curl exercise was performed at day 0 only.

5.2.1 Blood Sampling

At each visit approximately 5 ml of venous blood was drawn from the ante-cubital fossa by qualified phlebotomists using standard venipuncture technique. Blood samples were collected at 3 time points; at day 0, a baseline sample before exercise, on day 2, 48 hours after exercise and at 7 days after exercise. Blood was withdrawn and allowed to clot for 30 minutes. It was then centrifuged for 15 minutes to separate the serum. All serum samples were frozen at -80°C until subsequent analysis for CK activity.

Total CK activity was determined at 30°C by using a hexokinase/glucose-6-phosphate dehydrogenase-coupled enzyme system. 200 µl aliquots of blood serum were added to 1.3 ml of CK assay buffer at 30°C (containing 130mM KCl, 10mM Tris (pH 7.4), 1mM MgCl2, 2mM AMP, 50µM diadenosine pentaphosphate, 5mM glucose, 0.7mM NADP, 1.5mM ADP, 9mM PCr, 1.3 units of hexokinase, and 0.5 units of glucose-6-phosphate dehydrogenase). CK activity was determined from the increase in absorbance at 340 nm (using a Cecil double beam UV spectrophotometer). The average of the assays was used for statistical analysis (Gregor, Mejsnar, Janovská, Žurmanová, Benada and Mejsnarová, 1999).

5.2.2 Measurement of MVC and Sub-Maximal Isometric Contractions

MVC of right hamstrings was measured three times at every visit. The method was described in the general methods chapter, section 2.3.

5.2.3 The Hamstring Curl Exercise

Volunteers were seated in a hamstring curl chair, which was adjusted for the right leg. The seat position was adjusted to ensure that the centre of rotation of the machine and the centre of rotation of the volunteer's knee were coincident. The MVC of the knee flexors was tested by lifting weights over a range of knee angles between full knee extension and 90° knee flexion. Volunteers were required to move the leg pad from starting position of 180° downward

concentrically by shortening the hamstrings and upward eccentrically to the end position of 90°.

A 5 minutes rest was given after MVC measurement. They were instructed to exercise by lifting and lowering with a load of 75 % of their MVC. The exercise consisted of 3 sets of 10 repetitions. Each contraction lasted about 5 seconds, with a rest period of about 5 seconds. In addition there was a 2 minute rest between sets. All volunteers performed the same pattern of exercise on day 0 only. This intensity was chosen to induce muscle damage (Whitehead 1998; Heikki, Timo and Paavo, 1998).

5.2.4 Subjective Measurement of Muscle Soreness

Muscle soreness was assessed subjectively in all participants on each visit. They used a visual analogue scale (VAS) to rate their soreness (Grant et al. 1999). The scale ranged form 0 (not sore) to 10 (very sore). More specifically: 0 = no pain at all, 1-2 = light pain felt only when touched, 3-4 = light pain felt when walking/stretching, 5-6 = moderate pain when walking/stretching, 7-8 = moderate pain, stiffness and very painful when walking and 9-10 = severe pain limits the daily movements. The assessment was done by the volunteer during self-palpation and movement.

5.2.5 [tHb] NIRS Measurements

The reflected light from the BF muscle was analysed to give the change in the [tHb], similar to that described in the previous experiments. Measurement of [tHb] was undertaken during isometric contractions of the hamstrings at 10, 20, 30 and 40% MVC.

Measurements of the baseline values were determined in day 0 before exercise. The procedure of measurement of [tHb] of day 0 was repeated in day 2 and 7. Measurements of continuous reading of [tHb] and EMG activity were started with a settling time of 1 minute under resting conditions. Each contraction lasted for 10 seconds followed by 30 seconds at rest.

The size of change in the [tHb] was analysed by measuring the mean of resting time before each contraction and the minimum value of each contraction (10, 20, 30 and 40% MVC). The values of day 0, day 2 and day 7 were compared at both 10 and 40% MVC. Values are expressed as means, standard deviation and a P value of 0.05 or less was considered significant.

5.2.6 Arterial Blood Pressure Measurement

The protocol for measuring the arterial blood pressure was described earlier in chapter 4. In these experiments the mean blood pressure at rest was calculated at diastolic plus one third of pulse pressure.

5.3 Results of Muscle Soreness, Muscle Strength, [CK] and [tHb]

This section reports the measurements of muscle soreness, muscle strength, [CK] and [tHb] during 3 visits over a period of one week. The measurements were made at day 0, day 2 and day 7. The hamstring muscle was heavily exercised in day 0. Twelve volunteers completed this experiment.

The results in table 5.1A show that all participants experienced DOMS after 48 hours of the exercise. None of the volunteers reported any muscle soreness at their first visit. All volunteers reported soreness 2 days after the exercise. Volunteer 12 reported only a very small increase whilst others, like volunteers 1 and 7 reported considerable increases. After one week all the volunteers except one, reported that the soreness had gone. There is no doubt that the exercise protocol succeeds in provoking DOMS.

The values for the concentrations of CK are given in table 5.1B. The mean plasma [CK] before exercise was 224 ± 64 U/L. This was increased to 847 ± 262 U/L after 48 hours. The mean of [CK] fell to 180 ± 90 U/L after one week. The increase in [CK] at day 2 is highly significant ($P < 0.0001$). There is no significant difference between day 0 and day 7 when tested with a paired test ($P = 0.090$). These observations confirm those of the changes in table 5.1A and also support the assertion that the exercise protocol succeeds in provoking DOMS.

Interestingly, volunteer 12 hardly perceived any muscle soreness, see table 5.1A and he has a 424% increase in [CK]. This is the highest post exercise value. Thus he has significant muscle damage. His rating of soreness suggests either he is very insensitive to muscle pain or reluctant to report it.

The maximum knee flexion torques in each volunteer on each day is reported in right hand panel of table 5.1B. The mean torque before exercise was 325 ± 58 Nm. This fell to 267 ± 68 Nm after 48 hours. The mean torque rose to control values after one week. The drop in torque at day 2 is significant ($P = 0.0012$). There is no significant difference between day 0 and day 7 when tested with a paired test ($P = 0.285$). This is consistent with the data above.

No change in the BP and HR were observed over the three days. These data are shown in table 5.2 A and B.

5.3.1 The [tHb] at 10% and 40% MVC during 3 Visits

Figures 5.3 A, B and C shows NIRS data recorded during a series of contractions at 10 to 40% of MVC in one volunteer on the three days of the experiment. This is a clear set of data. Each contraction on each day shows reductions in [tHb] and [HbO_2]. These were accompanied by rises in the [HHb]. These observations are consistent with the results in chapter three and four. As the intensity of the contraction increases the changes in the NIRS signals becomes larger. This is best seen in the [HbO_2] and [HHb] signals in figure 5.3B

The volunteer was also able to relax the hamstrings between the contractions on each day and so the NIRS data was not affected by persistent low-level contractions.

In contrast, other volunteers found it difficult to relax their hamstrings between and after contractions. This is illustrated in figure 5.4 A, B and C. The NIRS recordings in figure 5.4A, B and C show stable baseline for all signals during the first 60 seconds before contractions start. This volunteer, number 5, has difficulties during the relaxation periods and his hamstrings were active. NIRS outputs were affected by the activity of the hamstrings and inability to relax. In figure 5.4A there is a long period of EMG activity after the last contraction. This appears to have reduced the post contraction hyperaemia. Figure 5.4B, recorded on day 2 when the volunteer reported moderate muscle soreness, the volunteer cannot relax at the end of the 10% contraction or at the end of the 20% contraction. There is a large burst of EMG activity between the 20 and 30% contractions, which has a clear effect on all the NIRS signals. Of the 12 volunteers tested, five volunteers had the problems with relaxation of their hamstrings.

One of the aims of these experiments was to investigate if muscle perfusion was changed during DOMS. The first stage of the analysis was to compare the changes in NIRS signals during contractions at 10% of MVC over the three days. The values of the [tHb] are given in the left hand panel of table 5.3. The means and standard deviations are shown at the foot of this table. The values varied between the volunteers. The mean on the day before exercise was – 0.56

± 0.77. The mean on day 2 increased to – 0.02 ± 0.93. The mean at day 7 was -0.11 ± 0.96. The means from all twelve volunteers were compared with a series of ANOVA tests. The *P* values ranged between 0.137 and 0.819. These are all volts and will be shifted to [tHb]. There is no significant difference in the changes of [tHb] during 10% contractions over the three visits.

One possible complication here is the data from volunteers who could not relax completely. Even when those five volunteers are excluded from the analysis, the result is still not statistically significant. The *P* values ranged between 0.093 and 0.577.

This analysis was repeated for the contractions at 40% MVC. The mean values of changes in mean [tHb] during 40% contractions are given in the right hand panel in table 5.3. The mean before exercise was – 0.32 ± 0.61. This increased to 0.02 ± 0.89 after 48 hours. The mean at day 7 increased to 0.10 ± 0.88. There is no significant difference in the changes in mean [tHb] over the three visits. The *P* values were between 0.186 and 0.820. Thus there was no significant difference in the changes of [tHb] during contractions at 40% MVC over the three visits. When the five volunteers are excluded from the analysis, the result is still not statistically significant. The *P* values ranged between 0.053 and 0.417.

The results show no statistically significant difference in [tHb] changes during contractions at 10 and 40% MVC. All *P* values were > 0.05. This suggests that no change occurred in blood perfusion during the period of DOMS.

The changes at 20 and 30% of MVC were not analysed. It seemed unlikely that the intermediate forces would yield significant results if smaller and larger forces had not.

Table 5.1A: muscle soreness before and after exercise

No.	Day 0	Day 2	Day 7
1	0	7	0
2	0	3	0
3	0	6	0
4	0	6	0
5	0	6	0
6	0	6	0
7	0	7	0
8	0	6	3
9	0	6	0
10	0	3	0
11	0	5	0
12	0	1	0
Mean	**0**	**5**	**0**

Table 5.1A

Table 5.1A shows the muscle soreness of the 12 volunteers at 3 visits. There were variations in the rating of muscle soreness between the volunteers. For example volunteer 1 experienced moderate pain, while volunteer 12 experienced light pain. The mean value of muscle soreness was 5. The results show significant difference between day 0 and 2. This value returned to normal level at day 7.

Table 5.1B: [CK] and MVC before and after exercise

No.	[CK] (U/L)				MVC (Nm)		
	Day 0	Day 2	Day 7		Day 0	Day 2	Day 7
1	178	787	200		285	229	207
2	217	1004	178		273	226	295
3	183	622	209		330	289	323
4	239	804	278		255	217	412
5	243	683	183		266	244	379
6	196	735	304		397	400	426
7	317	813	52		297	143	190
8	257	609	204		308	260	343
9	243	1230	139		391	371	396
10	78	1057	113		290	273	341
11	217	474	13		388	284	388
12	317	1343	287		417	269	350
Mean	**224**	**847**	**180**		**325**	**267**	**338**
St Dev	**64**	**262**	**90**		**58**	**68**	**75**

Table 5.1B

The left panel of table 5.1B shows the [CK] and the right panel the MVC of 12 volunteers. There were variations in the [CK] values among the volunteers at day 2. The results show significant differences in the mean values between day 0 before exercise and day 2 after exercise ($p<0.001$, paired T test).

Figure 5.2A: muscle soreness before and after exercise

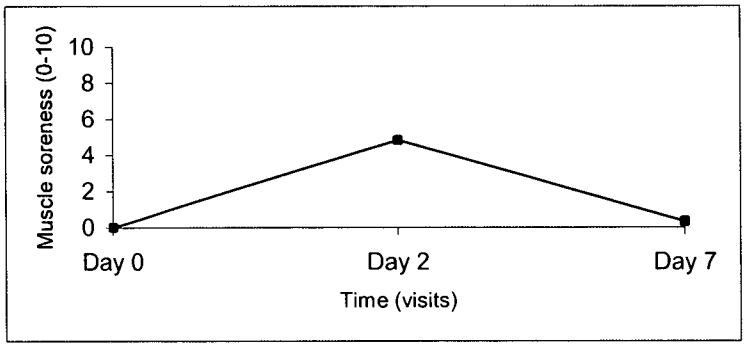


Figure 5.2B: [CK] before and after exercise

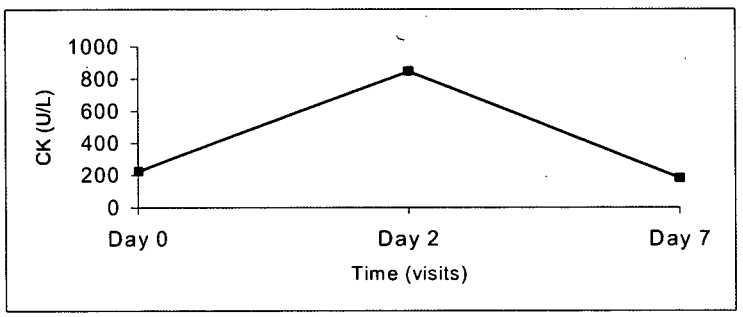


Figure 5.2C: MVC before and after exercise

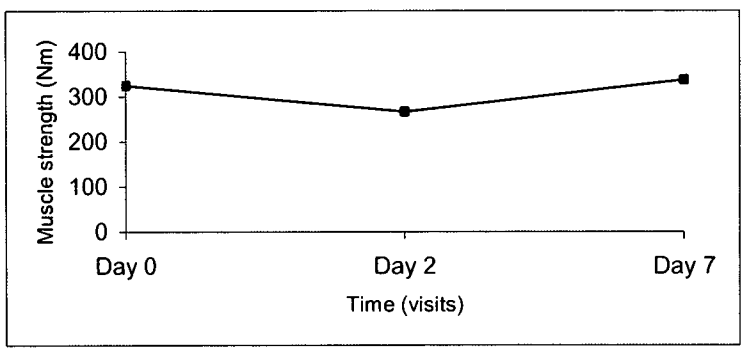


Figure 5.2A, B and C

The 3 figures above show the muscle soreness, [CK] and MVC of 12 volunteers.

Figure 5.2A shows the increase in muscle soreness at day 2 after exercise. Figure 5.2B shows the increase in [CK] at day 2. Figure 5.2C shows the decrease in the MVC at day 2. These changes in the mean values between day 0 and 2 were significant. The change in [CK] was significant, $p<0.001$, paired T test. The change in MVC was also significant $p<0.01$.

Table 5.2A: Mean BP Before and After Exercise

No.	Mean BP (mm Hg) before Exercise			Mean BP (mm Hg) after Exercise		
	Day 0	Day 2	Day 7	Day 0	Day 2	Day 7
1	98	96	100	111	115	116
2	98	96	95	114	124	110
3	100	94	100	114	110	100
4	93	96	96	101	95	87
5	98	95	93	102	94	92
6	91	92	94	91	87	82
7	101	95	97	99	97	88
8	93	98	93	98	88	89
9	95	96	100	75	84	83
10	96	94	100	101	99	97
11	94	100	97	98	98	93
12	102	104	99	91	92	78
Mean	**97**	**96**	**97**	**100**	**99**	**93**
St Dev	**4**	**3**	**3**	**11**	**12**	**11**

Table 5.2B: HR before & after exercise

No.	HR (bpm) before Exercise			HR (bpm) after Exercise		
	Day 0	Day 2	Day 7	Day 0	Day 2	Day 7
1	72	82	70	68	77	65
2	90	84	81	80	100	70
3	51	59	72	54	61	70
4	88	77	93	93	71	96
5	64	85	70	64	68	73
6	90	76	75	72	78	84
7	70	69	74	76	75	68
8	77	87	72	81	78	79
9	50	57	52	61	58	61
10	65	59	71	61	61	70
11	70	66	80	83	71	77
12	76	75	72	80	75	78
Mean	**72**	**73**	**74**	**73**	**73**	**74**
St Dev	**14**	**11**	**9**	**11**	**11**	**9**

Table 5.2

The 2 tables show the values of BP and HR of 12 volunteers at 3 visits. The means and standard deviations are also seen in these tables. The left hand panel of table 5.2A shows the mean BP before exercise and the right hand panel shows the mean BP after exercise. The left hand panel of table 5.2B shows the mean HR before exercise and the right hand panel shows the mean HR after exercise. No significant changes were found in either BP or HR before and after exercise. All the ANOVA tests performed produced P values > 0.05.

Figure 5.3A: NIRS & EMG data from volunteer 2

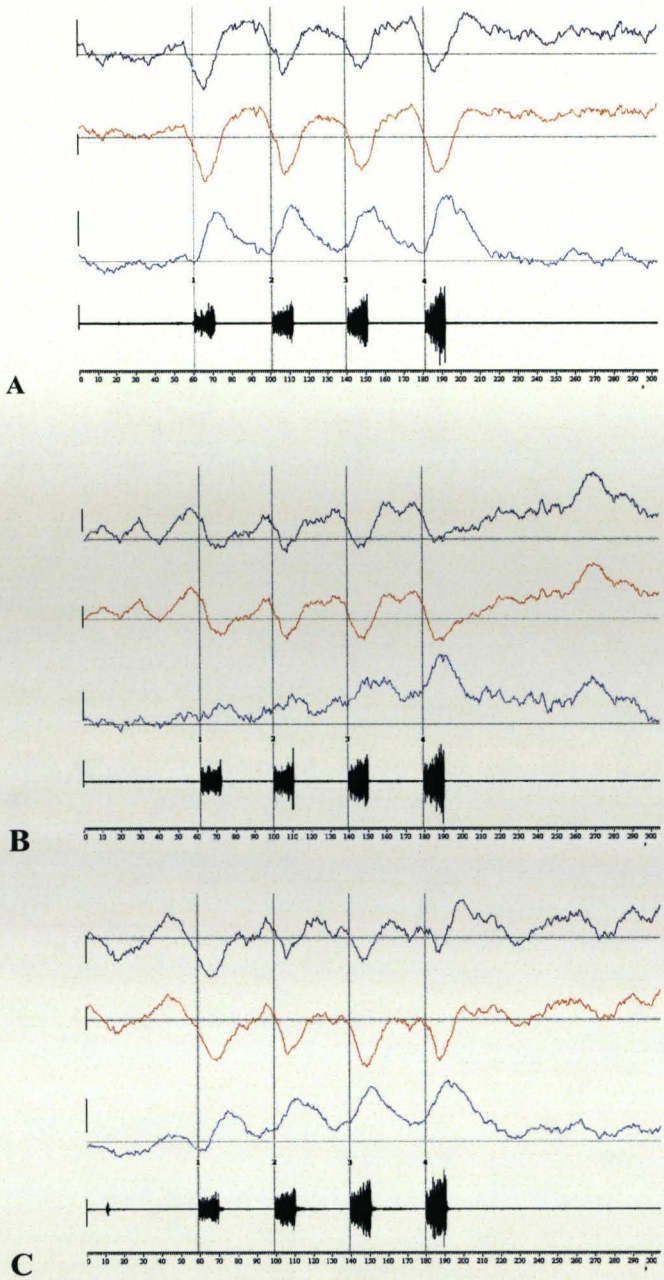


Figure 5.3

These figures show the [tHb], top trace, [HbO_2], middle trace and [HHb], lower trace recorded concurrently on day 0 (A), day 2 (B) and day 7 (C). The NIRS signals have been smoothed by averaging data points over 1 second. In each case the bottom trace shows the hamstrings EMG activity during knee flexion. The first 59s the volunteer is at rest position. Cursor 1 at 60s the volunteer makes a voluntary contraction to 10% MVC. Cursor 2 at 100s the contraction is at 20% MVC. Cursor 3 at 140s the contraction is at 30% MVC. Cursor 4 at 180s the contraction is at 40 MVC. During the contraction [tHb] and [HbO_2] falls and [HHb] falls and then rises. After the contraction Hb values return to the resting values.

The vertical calibration bar for the tHb trace is 0.05 volts, equivalent to 8 millimoles. The calibration bar for the EMG shows 0.5 millivolts.

Figure 5.4: NIRS & EMG data from volunteer 5

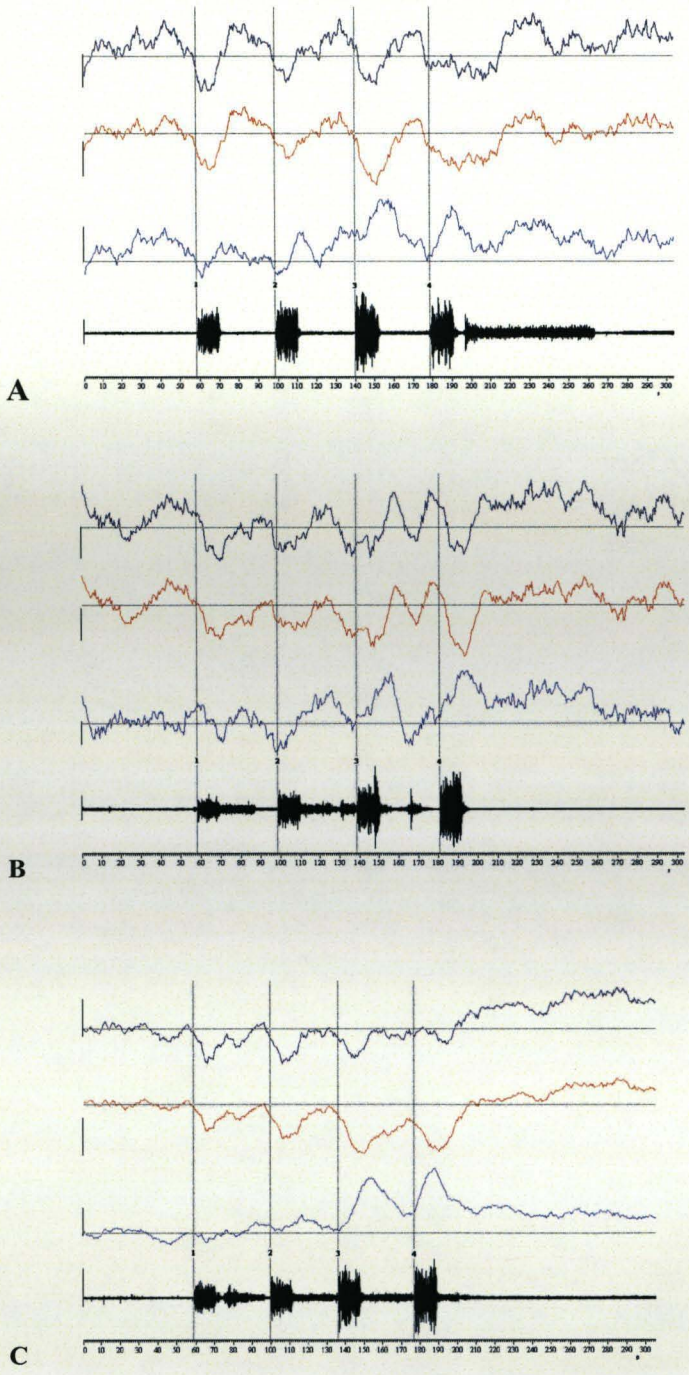


Figure 5.4

Figures 5.4A, B and C show NIRS and EMG data from volunteer 5. The NIRS signals have been smoothed by averaging data point over 1 second. The data are similar to figure 5.3. The difference is that the recordings show unstable EMG and NIRS signals between and after contractions. Figure 5.4A shows good EMG during relaxation and contraction until 197s. The hamstrings were active during the recovery period between 198s and 265s. In figure 5.4B and C, the hamstrings were unable to relax between contractions. The activity of the hamstrings affects the NIRS outputs.

The vertical calibration bar for the tHb trace is 0.05 volts, equivalent to 8 millimoles. The calibration bar for the EMG shows 0.5 millivolts.

Table 5.3: Changes in [tHb] during contractions at 10% and 40% MVC

[tHb]	10% MVC			40% MVC		
No.	**Day 0**	**Day 2**	**Day 7**	**Day 0**	**Day 2**	**Day 7**
1	-215.475	64.159	-70.423	-143.262	127.603	-12.259
2	-20.849	16.912	56.464	-5.816	22.281	85.725
3	-98.521	121.518	138.967	-88.051	102.011	97.716
4	34.362	19.328	-60.490	44.742	23.087	-55.927
5	-44.204	-4.563	-61.206	-13.243	0.716	-33.824
6	7.338	-11.991	93.778	10.738	-11.991	93.778
7	3.222	46.263	-80.266	20.671	53.779	-69.528
8	-34.182	-26.218	-91.541	-15.122	-10.469	-74.002
9	31.230	27.292	138.251	30.245	-12.617	134.941
10	-7.516	-145.947	27.919	20.492	-127.871	70.334
11	-29.619	174.492	51.990	5.817	155.969	118.297
12	10.470	-68.186	-23.981	27.561	-65.054	-8.232
Mean	**-30.872**	**17.195**	**9.395**	**-9.329**	**20.894**	**28.358**
St Dev	**68.709**	**83.063**	**85.527**	**54.326**	**80.006**	**78.397**

Table 5.3

This table shows the mean values of [tHb] in millimoles of 12 volunteers at 3 visits. The left hand panel is the [tHb] at 10% MVC and right hand panel at 40% MVC. The means and standard deviations are shown at the foot of this table.

Figure 5.5: [tHb] at 10 and 40 % during 3 visits

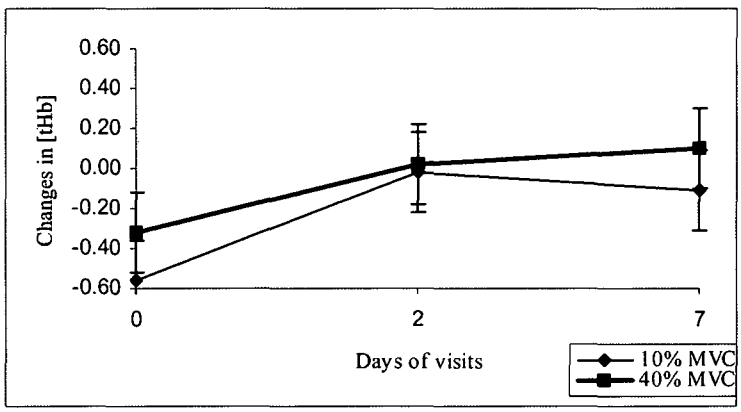


Figure 5.5

Figure 5.5 shows the [tHb] at 10 and 40% MVC at the 3 visits. The Y-axis describes the changes in [tHb]. The X-axis describes the 3 days of the experiments. The light line is the 10% and the bold line is the 40% MVC. These values are means and standard deviations. It can be seen that both intensities were increased at day 2 and day 7.

5.4 Discussion

The aim of this study was to investigate changes in the total haemoglobin [tHb] in the hamstrings during rest, exercise and recovery periods tested during an episode of DOMS. It is clear from the data in tables 5.1A and B that concentric/eccentric exercise at 75% MVC caused DOMS in the hamstrings. All participants experienced significant changes in muscle soreness, levels of plasma [CK] and production of maximal force after exercise. Surprisingly, the size of [tHb] changes during small and moderate contractions did not change significantly over the 3 days. This can be seen for the data in table 5.3. It was thought that perfusion would be changed during DOMS. However, the results show that the change was small and statistically non-significant. This may be explained as physiological and/or technical considerations of optodes positions at day 2 and 7.

In some participants, the CK levels were much higher than in others, which may suggest greater muscle damage, table 5.1 B. Muscle damage is associated with oedema (Kujala, 1997). The oedema raises tissue pressures that may compress blood vessels in the muscle. If the contracting muscle generated enough force, it will also compress blood vessels, causing occlusion in the exercising muscle and leading to ischaemia. Whitehead et al. (1998) reported that the link between muscle damage and DOMS is thought to be provided by the inflammatory process triggered by the damage and it is this, which is thought to be responsible for the muscle swelling.

Previous studies show that muscle damage follows eccentric exercise. Morgan & Allen, (1999) reported that the immediate changes are reductions in muscle force, followed by muscle soreness and rises in plasma [CK].

It was expected that blood flow in biceps femoris muscle might be impaired due to the increased intramuscular pressure during contractions. Van Beekvelt, Colier, Wevers and Van Engelen, (2001) studied the performance of NIRS in measuring local O_2 consumption and blood flow in forearm muscles. They reported that the vessels within the exercising muscle will be compressed when contraction force exceeds 25-30% MVC. This leads to obstruction of the blood flow. NIRS flow reflects an estimation of only the local flow in the NIRS region of interest within one muscle.

In the present study, the differences were not statistically significant. This may be due to changes in the optodes position between recording sessions. Whilst every care was taken to return to the same position, for example the skin was marked clearly, it is not possible to place the optodes in exactly the same point.

The changes in [tHb] by the amount of light reflected by the posterior thigh were individually analysed. With the methods used in the present study, the researcher was unable to detect changes in [tHb] among healthy and damaged hamstring muscles. Although the present study showed no significant difference, other studies have found that NIRS is able to discriminate between normal and pathological states. For example, Van Beekvelt et al. (2001) were able to use the

NIRS to quantify differences in forearm blood flow at rest and during exercise in patients with mitochondrial myopathies and healthy persons.

Calbet, (2000) reported that the influence of blood [Hb] on physical performance remained unclear. The examination of the effect of [tHb] in healthy volunteers was showed that a reduction of [tHb] caused by bleeding decreased physical work capacity. In general, during sub-maximal exercise alterations in [Hb] are counterbalanced by changes in muscle blood flow and cardiac output in such a manner that muscle O_2 delivery is maintained. In contrast, during maximal exercise, especially when performed with a large muscle mass, changes in [Hb] barely affect maximal limb blood flow or cardiac output. In general, studies suggest that muscle vasodilation during exercise is regulated to match O_2 demand and supply. It may also suggest that the natural vasodilator mechanisms are so powerful that they overcome the tissue oedema and blood vessel compression associated with DOMS.

5.4.1 DOMS and Risk of Hamstring Strain Injury

Subsequent eccentric exercise at the same intensity does not elicit DOMS, thus the muscle is more resistant to damage. When adaptation takes place any damage that does occur is repaired at a faster rate (Clarkson & Tremblay, 1988). Excessive eccentric exercise leads to damage of sarcomeres and is associated with localised pain and sensations of general heaviness and weakness in the exercised muscle (Garrett, 1996). Continuing the training programme with the same workload or higher loads may predispose the muscle to risk of more fibres

damage. Therefore, DOMS should not be ignored. Sufficient rest periods or decreasing the intensity of training are important during DOMS as the muscle needs time to return to normal. Reducing the intensity of training during this period is useful because the overstretched muscles are prone to more disruption. This is an attempt to reduce chances of minor injury that may proceed in later stages.

Well-designed training programmes are essential to improve performance without damaging the muscle. The intensity of training should always be monitored and gradually increased especially during the initial stages of sports season.

Chapter Six

An Investigation of Perfusion of the Injured and Non-Injured Hamstrings: Six Case Studies

6.1 Introduction

The musculoskeletal system is often at risk of injury during sports. Hamstring strains are common injuries among different sports e.g. water skiing and Australian football elite clubs (Sallay et al. 1996; Verrall et al. 2001). Approximately 14% of these hamstring strains are re-injuries (Dadebo et al. 2004).

Hamstring muscle injuries have been studied extensively, but the causes of injury are still not clear. It is important to know the major risk factors associated with hamstring strains in order to prevent injury. Factors that are associated with hamstring injuries include lack of flexibility, increased muscle fatigue, hamstring strength imbalance and insufficient warm-up before sports activity (Worrel, 1994; Witvrouw et al. 2003). The age and type of sport are considered to be risk factors of hamstring strains. For example, Matheson, Macintyre, Taunton, Clement and Lloyd-Smith, (1989) found the frequency of injuries in football and racket sports rises as the age of the participants increases.

There are different physical characteristics required in some sports that may place an athlete at risk of injury by exposing the muscle to repeated high force

contractions. Bylak & Hutchinson, (1998) reported that racket sports involve repeated short bursts of activity with quick stop-start and sharp lateral movements and accelerations, which place high demands mostly in the muscle-tendon units. Injuries during sprint events may reflect the type of explosive work of specific muscle groups e.g. hamstrings. Kujala et al. (1997) reported that muscle strains are common in sprinters, but middle distance runners can also be affected.

Muscle strains may result in swelling and muscle weakness (Agre, 1985; Garrett, 1990; Faulkner et al. 1993; Tucker, 1997). The tissue swelling may reduce muscle perfusion. This study investigated a series of cases of hamstring strains in sportsmen of a variety of ages, who participate in different sports. It was hypothesised that perfusion and muscle activity would be different in the injured and non-injured limbs of these volunteers. The main aim of this study was to investigate changes in the total haemoglobin concentration [tHb] during sub-maximal contractions in the hamstrings in a number of athletes with hamstring strains. Another aim was to investigate the EMG activity in the injured hamstrings and compare it with the EMG activity in the non-injured hamstrings.

6.2 Materials & Methods

The experimental protocol was approved by the Glasgow University Research Ethics Committee. The purpose of the study and the expected risks that associated with the procedures were explained to the participants.

Six male volunteers aged between 15 and 47 years participated in this experiment. They were recruited by word of mouth in the university sports teams over three years. They were ranging from different sports but not specially selected to represent any particular group of sports people. This ran in parallel with the other experiments. Volunteers were tested whenever they found available.

Volunteers lay in a supine position on a flatted seat for the active and passive knee extension tests. In the former test the volunteer lies supine with the hip of the leg under study flexed to 90°. Their shank was then extended to stretch the hamstrings until the volunteer felt pain. A goniometer was used to measure the range of pain free active movement. In the passive test, the body position is similar but the shank is moved by the experimenter rather than by the volunteer. For the full knee flexion test they lay in a prone position. All these tests were done while their hip position was at 0°. The range of movement (ROM) of the knee joint was measured using a manual goniometer. The injured and non-injured limbs were evaluated once (appendix 9.7).

NIRS recording were made sequentially with the knee at two positions: 20° and 70° of flexion. Records were made at rest and during isometric contractions which developed 50 Nm of torque. The results of the previous experiments show no difference between intensities of sub-maximal contraction so the 50 Nm was chosen. Also, all the volunteers can perform this intensity of exercise. This was about 15% MVC in the uninjured hamstrings.

6.3 Six Cases of Hamstring Strains

This study focused on 6 cases of hamstring strains.

6.3.1 Case Report (1): A 15-year old badminton player injured his right hamstrings during a local competition. Before his injury, he used to train 5 days per week. He usually spent about 5 minutes in warming-up before each session. The injury occurred when he slipped during a sudden change in direction. He continued the game with sustained pain. He had difficulty in walking for about one week. The patient sought a medical care from a physiotherapist in Hampden Sports Injury Clinic. Physical examination revealed acute hamstring muscle strain. Physiotherapy treatment was given but he did not complete the treatment sessions and the rehabilitation program. Two weeks after the injury, the patient decided to jog. He resumed the badminton training after 7 weeks, but there was twinge pain during lunging.

6.3.2 Case report (2): A 19-year-old was injured whilst playing rugby. His normal warm-up consisted of about 15-20 minutes of jogging followed by 20 minutes stretching. During full sprint in a game he experienced a tearing sensation in his left hamstrings. He sought an immediate treatment with rest, ice, compression and elevation (RICE). The patient reported that this was a recurrence of a previous hamstring strain. He was out of training for about 6 weeks during treatment at a sports injury clinic. Five weeks after the injury, he commenced jogging and followed by progressive training. At the time of the test he still felt uncomfortable in the size of injury during sprinting.

6.3.3 Case report (3): A 22-year-old amateur football player experienced a tearing sensation in his left hamstrings when he attempted to kick the ball. He did not follow any warm-up procedure. He did not seek any medical care or RICE application. After a rest period of 3 weeks, he commenced light jogging. He returned to playing football after 10 weeks, but he was not able to return to his previous level of performance. At the time of his test, he was still suffering from pain during fast running and/or changes in directions.

6.3.4 Case report (4): A 28-year-old Gaelic football player suffered from a left hamstring injury during a match. He usually spent 10 to 15 minutes in warm-up. The injury occurred when he suddenly accelerated. RICE was given by the physiotherapist. He did not complete the treatment course. After a rest period of only one week, he decided to participate in another game. This recurrence injury kept him away from sports participation for about 12 weeks. He was unable to run in his previous level of intensity and speed.

6.3.5 Case report (5): A 42-year-old former international sprinter was involved in a football game after a period of detraining. He pulled his left hamstrings. The injury occurred when he suddenly ran fast from a stationary position. He was unable to continue and limped off the field. The patient used the RICE technique 2 hours after injury and continued for 48 hours in addition to ibuprofen tablets from his GP. He started a rehabilitation program he designed himself. Six weeks later he came to the lab for the test.

6.3.6 Case report (6): A 47-year-old recreational distance runner injured his right hamstrings during a period of uphill running. He usually warms up before training. The patient sought medical care from a physiotherapist in a sports injury clinic. He reported that he completed two weeks of physiotherapy treatment. He also reported that he was not able to run in his previous level for both intensity and duration.

6.4 Results of Laboratory Tests

The laboratory assessment was performed in six cases of hamstring strains. All volunteers were pain free at the time of their appearance in the laboratory. Their age, sport, injured side and history of injury are shown in table 6.1.

Among these 6 cases, there were 2 hamstring strains in left side and 4 in the right side. Three cases were classified mild. Three cases were classified moderate. Three of the six had completed the rehabilitation phase.

The immediate medical care was either a treatment with (RICE) or a non-steroidal anti-inflammatory drug (NSAID). Five out of 6 cases sought medical care soon after the injury. Case 3 did not seek any treatment.

Table 6.2 shows the results of laboratory assessments of range of movement (ROM) of injured and non-injured limbs. The differences in the ROM of knee flexion and extension in the injured and non-injured limbs are small and close to the limits of the accuracy of measurement. They are unlikely to be of functional significance.

Table 6.1: History of 6 cases of hamstring strains

No	Age	Sport	Time Since Injury	Injured Side	WU	Med. care	Injury severity	Rehab
1	15	Badminton	12 weeks	R	Yes	Yes	Moderate	No
2	19	Rugby	4 weeks	L	Yes	Yes	Moderate	Yes
3	22	Football	10 weeks	L	No	No	Mild	No
4	28	Gaelic football	6 weeks	L	Yes	Yes	Mild	No
5	42	Athletics	3 weeks	L	Yes	Yes	Moderate	Yes
6	47	Athletics	6 weeks	R	Yes	Yes	Mild	Yes

* **L:** left, **R:** right, **WU:** warm-up, **Med. Care**: medical care, **Rehabil:** rehabilitation

Table 6.1

This table shows the history of 6 cases of hamstring strains including the following; age of patient, sport involved, side of injury, warm-up before the task, medical care either at the same time or later, the severity of the injury, by whom they had been treated and completion of rehabilitation phase.

Table 6.2: Laboratory assessment of 6 cases of hamstring strains

Test	Cases					
	1	2	3	4	5	6
Active extension	5°	No	5°	10°	9°	5°
Passive extension	No	12°	5°	No	5°	No
Full flexion	5°	5°	No	No	15°	No

* **No:** there is no difference between the left and right legs

Table 6.2

This table shows the results of laboratory tests of range of movement at the knee in the six cases of hamstring strains. The injured and non-injured hamstrings were compared. The hamstrings were tested during active extension, passive extension and full knee flexion. The uninjured leg has the greater range of movement.

6.5 Analysis of the NIRS Traces

The changes in [tHb] were calculated by the use of Spike 2 software. This was done by measuring the mean of [tHb] before contraction and the minimum values during contractions. The mean and minimum of [tHb] were measured for each contraction at 20° and 70°. The data were statistically analysed using a one-way ANOVA Statistical Package for the Minitab version 13. Results were considered to be significant at $P < 0.05$.

6.6 Results of NIRS Investigation of Hamstrings Perfusion

Figures 6.1 to 6.6 illustrate NIRS recording of the [tHb] and EMG during isometric contractions of the hamstrings in 6 cases of hamstring strains. Examples of the [tHb] changes in the non-injured hamstrings are given in 'A' figures and the [tHb] changes in the injured examples are given in 'B' figures. These figures show changes in [tHb] at 50 Nm while the knee flexed at 20° and 70°. In cases 2 – 6, figures 6.2 – 6.6, there is a stable recording at the beginning before the contraction. However, this is not the same with case 1, figure 6.1A. There is no obvious cause of the increase in [tHb] about 30 seconds before the first contraction.

Case 1, figure 6.1A and B show larger reductions in the [tHb] during contraction at 20° than at 70° flexion. These reductions are clearly seen in the non-injured limb. The [tHb] falls during contractions and then rises during the intervals between contractions. This case received medical care but he did not complete

the rehabilitation phase. The lab assessment of ROM showed no significant difference between injured and non-injured legs.

Case 2, figure 2A shows clear reduction in [tHb] in the non-injured limb during contractions and then increases during interval between contractions. This was not the case in figure 6.2B in the injured limb. During first and third contractions the reduction in [tHb] is larger than in the other contractions. This case received an immediate medical care and also finished the rehabilitation phase. The lab assessment shows some variation in ROM at passive knee extension between the injured and non-injured legs.

Case 3, figure 6.3A and B, shows a good example of changes in [tHb] during and after contractions. The contraction causes clear reduction in the [tHb]. The lab assessment of ROM showed no significant difference between injured and non-injured legs.

Case 4, figure 6.4A and 6.4B show larger reductions in the [tHb] during contraction at 20° than at 70° flexion. These reductions are clearly seen in the non-injured limb. The [tHb] falls during contractions and then rises during the intervals between contractions. This case received medical care but he did not complete the rehabilitation phase. The lab assessment shows some variation in ROM at active knee extension between the injured and non-injured legs.

Case 5, was the first volunteer tested at the early stages of this project. The protocol was not fully established at this time. The test was carried out at a

single limb position, 20° flexion. Figure 6.5A and 6.5B show large and obvious reductions in the [tHb] during the 3 contractions at 20° flexion. These reductions are clearly seen in both limbs. The [tHb] falls during contractions and then rises during the intervals between contractions. This case received medical care and completed the rehabilitation phase. The lab assessment shows some variation in ROM at active knee extension and full knee flexion between the injured and non-injured legs.

Case 6, figure 6.6A and B shows a different pattern of changes in the [tHb] contractions. No differences can be seen during and after contractions in either leg. This case received medical care and also finished the rehabilitation phase. The lab assessment shows some variation among the volunteers in ROM. The results showed no significant difference between injured and non-injured legs. This could be due to the advantage of the use of medical care soon after the injury or because they had finished the rehabilitation phase and recovered from the injury.

The results in figures 6.1 – 6.6 of EMG records show different patterns of injured and non-injured limbs. Some were able to relax the injured leg whereas others were not able to do so. For example, volunteers 1, 2 and 3 can fully relax their hamstrings in the non-injured leg. Volunteers 4 and 5 had good non-injured relaxation except one burst of EMG. A volunteer 6 was not able to relax the non-injured hamstring at all. In the injured leg, volunteers 2, 3, 4, 5 and 6 were not able to relax the injured hamstrings. Volunteer 1 can fully relax his injured hamstrings.

The EMG in case 1, figure 6.1A and B shows clear relaxation in both injured and non-injured hamstrings. This case was able to relax either the injured or non-injured hamstrings before, between and after contractions. This case had a moderate hamstring injury.

Case 2, figure 6.2A and B shows clear relaxation in the non-injured hamstrings. This case shows clear example of the difficulty in relaxing the injured hamstring. The injured hamstring was not able to relax at all between contractions. This case had a moderate hamstring injury.

Case 3, figure 6.3A and B shows relaxed non-injured hamstrings. This case was not able to relax the injured muscle during the interval periods. The inability of relaxation between contractions can be seen at 100, 122, 135 and 195 seconds. The changes in [tHb] are affected by these contractions during interval periods. This case had a mild hamstring injury.

Case 4, figure 6.4A and B shows clear relaxation in the non-injured leg except between the first and second contractions. The injured leg shows three contractions during the relaxation periods. These are at 74, 166 and 257 seconds. This case had a mild hamstring injury.

Case 5, figure 6.5 shows very clear relaxation in the non-injured hamstrings except between 163 and 173 seconds. The injured hamstring was unable to relax during the interval periods. This is clear at the beginning of the test. There is a

long period of EMG activity after the first contraction at 72 second and 110 seconds. This case had a moderate hamstring injury.

Case 6, figure 6.6A and B shows an unusual pattern of EMG activity. This case was not able to relax either injured or non-injured hamstrings at all. The effect of these contractions is clearly seen in the changes of [tHb]. It is difficult to distinguish between the injured and non-injured muscles when only looking at the NIRS trace. This case had a mild hamstring injury.

The observations on the EMG that some volunteers with sore muscles cannot relax completely are consistent with the results in chapter five.

The analysis of the changes in the [tHb] during contractions at 50 Nm was made at 20° and 70° of knee flexion in either limb. These data are given in table 6.3. The means and standard deviations are shown in this table. The mean change at 20° for the non-injured limb was - 0.11 ± 0.05. The mean for the injured limb 20° was - 0.10 ± 0.07. The means of the injured and non-injured limbs were compared with ANOVA test. The test shows that there is no significant difference in the [tHb] at 20° flexion, P value was 0.713. Similar test was made at 70° flexion. The mean of the non-injured was - 0.06 ± 0.03. The mean for the injured limb was - 0.04 ± 0.04. The comparison between the injured and non-injured limbs shows no significant difference with *P* value of 0.354.

Table 6.3: [tHb] of the injured and non-injured limbs

No.	Flexion at 20°			Flexion at 70°	
	Non-injured	Injured		Non-injured	Injured
1	-15.30	-16.20		-0.03	0
2	-6.35	-0.09		-0.11	-0.03
3	-4.56	-4.56		-0.06	-0.1
4	-3.67	-0.09		-0.06	-0.03
5	-4.56	-1.88		*	*
6	-1.88	-6.35		-0.03	-0.02
Mean	**-6.053**	**-4.862**		**-0.058**	**-0.036**
St Dev	**4.757**	**6.088**		**0.033**	**0.038**
P	**0.713**			**0.354**	

* the test was only at 20° flexion

Table 6.3

This table shows the mean values of [tHb] of 6 cases of hamstring strains. The means, standard deviations and P value are also seen in this table. The left hand panel shows the non-injured and injured hamstrings at 20° flexion. The right hand panel shows the non-injured and injured hamstrings at 70° flexion. No significant changes were found in either 20° or 70° between both limbs.

Figure 6.1A: Non-injured hamstring of case 1 at 50 Nm

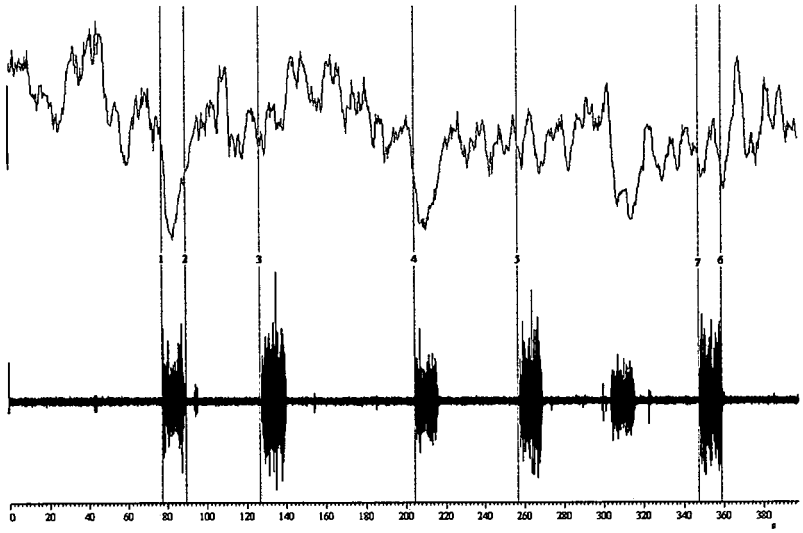


Figure 6.1B: Injured hamstring of case 1 at 50 Nm

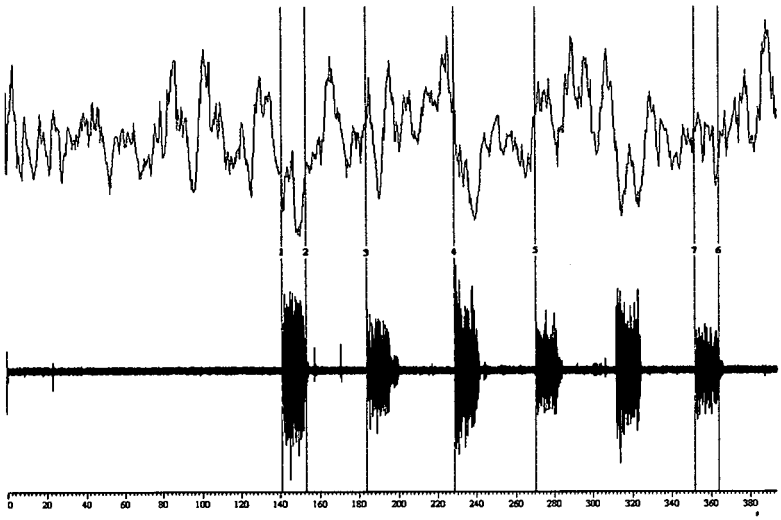


Figure 6.1

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. In both traces the first, third and fifth contractions are at a knee position of 20° flexion. The alternate contractions are with the knee at 70° of flexion. In each case a torque of 50Nm is produced. The NIRS signals have been smoothed by averaging data points over 1 second. During the contractions [tHb] falls and then rises during the relaxation periods. These two figures show how this volunteer was able to relax both the injured and non-injured hamstrings.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 6.2A: Non-injured hamstring of case 2 at 50 Nm

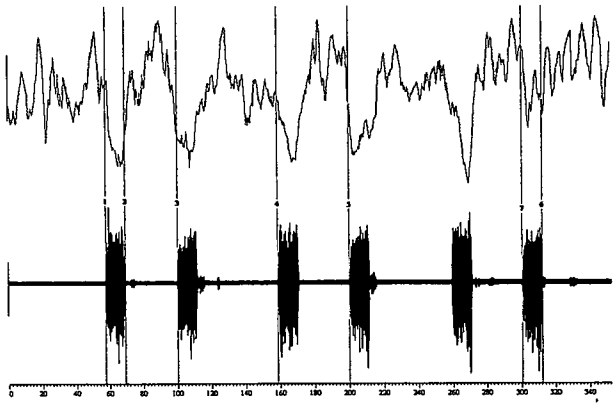


Figure 6.2B: Injured hamstring of case 2 at 50 Nm

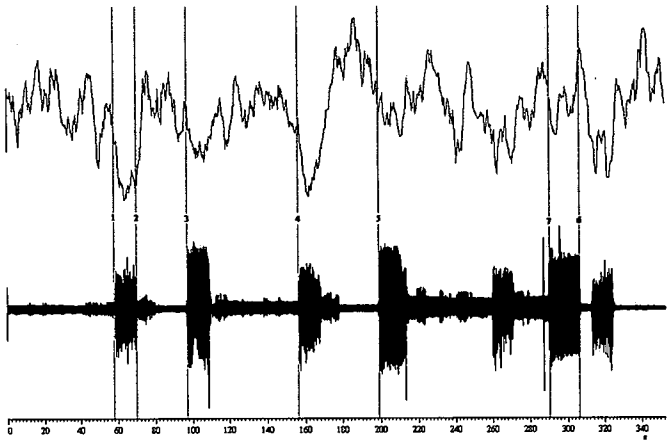


Figure 6.2

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. In both traces the first, third and fifth contractions are at a knee position of 20° flexion. The alternate contractions are with the knee at 70° of flexion. In each case a torque of 50Nm is produced. The first 58 seconds is the resting period. The NIRS signals have been smoothed by averaging data points over 1 second.

Figure 6.2A, shows stable recording of EMG at the beginning of the resting period. The EMG recordings of the non-injured hamstrings show good relaxation between contractions. The [tHb] falls during the contractions and then rises. After the contraction [tHb] values return to the resting values.

Figure6.2B shows unstable EMG recordings of the injured hamstrings. This volunteer is unable to relax the hamstrings between contractions. The [tHb] falls during contractions. These involuntary contractions during rest periods cause reductions in [tHb].

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 6.3A: Non-injured hamstring of case 3 at 50 Nm

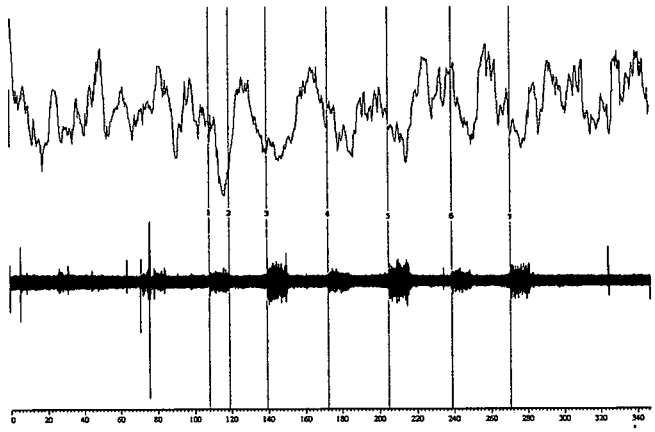


Figure 6.3B: Injured hamstring of case 3 at 50 Nm

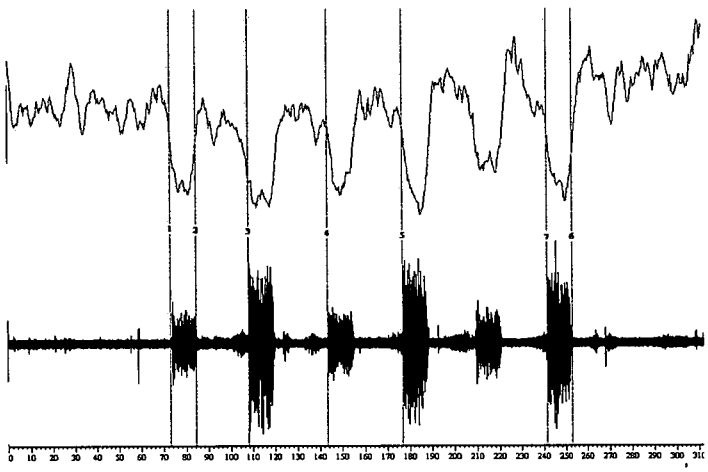


Figure 6.3

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. In both traces the first, third and fifth contractions are at a knee position of 20° flexion. The alternate contractions are with the knee at 70° of flexion. In each case a torque of 50Nm is produced. The NIRS signals have been smoothed by averaging data points over 1 second. During contractions [tHb] falls and after contractions [tHb] values return to the resting values.

Figure 6.3A, shows unstable recording of EMG at the beginning of the resting period. The EMG recordings of the non-injured hamstrings show relaxation between contractions.

Figure 6.3B shows stable EMG recordings at the beginning of the resting period of the injured hamstrings. This volunteer is unable to relax the hamstrings between contractions. These involuntary contractions may affect [tHb] during rest periods.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 6.4A: Non-injured hamstring of case 4 at 50 Nm

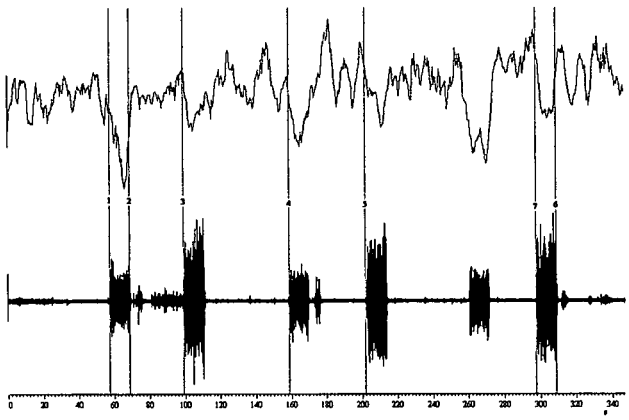


Figure 6.4B: Injured hamstring of case 4 at 50 Nm

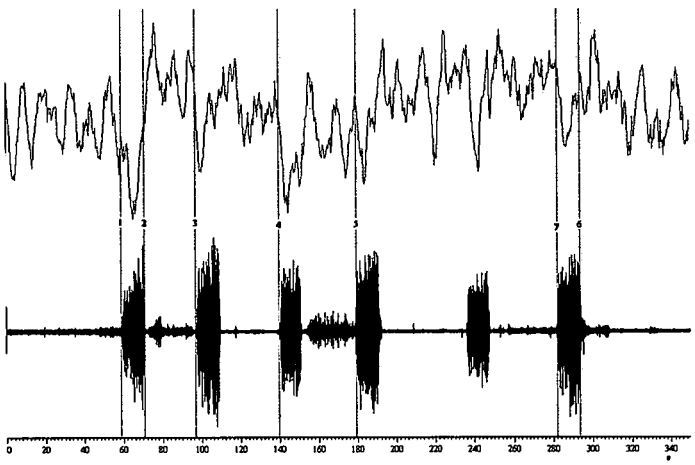


Figure 6.4

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. In both traces the first, third and fifth contractions are at a knee position of 20° flexion. The alternate contractions are with the knee at 70° of flexion. In each case a torque of 50Nm is produced. The NIRS signals have been smoothed by averaging data points over 1 second. During contractions [tHb] falls and after contractions [tHb] values return to the resting values.

Figure 6.4A, shows stable recording of EMG at the beginning of the resting period. The EMG recordings of the non-injured hamstrings show relaxation between contractions. Except between first and second contractions the hamstrings were unable to relax.

Figure 6.4B shows stable EMG recordings at the beginning of the resting period of the injured hamstrings. After this initial rest period this volunteer is unable to relax the hamstrings between contractions. This can be clearly seen after the first and third contractions. This volunteer cannot relax the injured hamstrings after the 20° flexion.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 6.5A: Non-injured hamstring of case 5 at 50 Nm

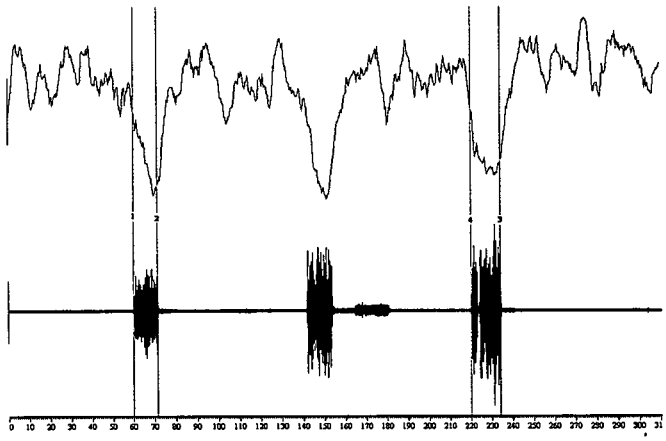


Figure 6.5B: Injured hamstring of case 5 at 50 Nm

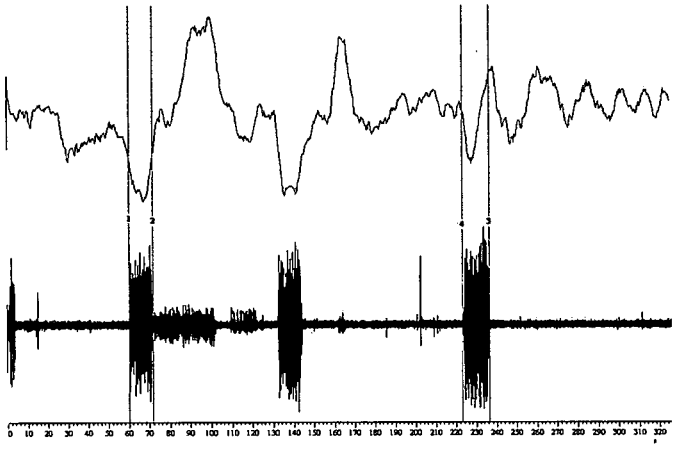


Figure 6.5

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. These three contractions are at a knee position of 20° of flexion. In each case a torque of 50Nm is produced. The first 60 seconds is the resting period. The NIRS signals have been smoothed by averaging data points over 1 second. During contractions [tHb] falls and after contractions [tHb] return to the resting values.

Figure 6.5A, shows stable recording of EMG at the beginning of the resting period. The EMG recordings of the non-injured hamstrings show type of good relaxation between contractions. Except after the second contraction there is a burst of EMG at about 165 seconds where the hamstrings were unable to relax.

Figure 6.5B shows unstable EMG recordings at the beginning of the resting period of the injured hamstrings. This volunteer is unable to relax the hamstrings between contractions. This can be clearly seen after the first contraction.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

Figure 6.6A: Non-injured hamstring of case 6 at 50 Nm

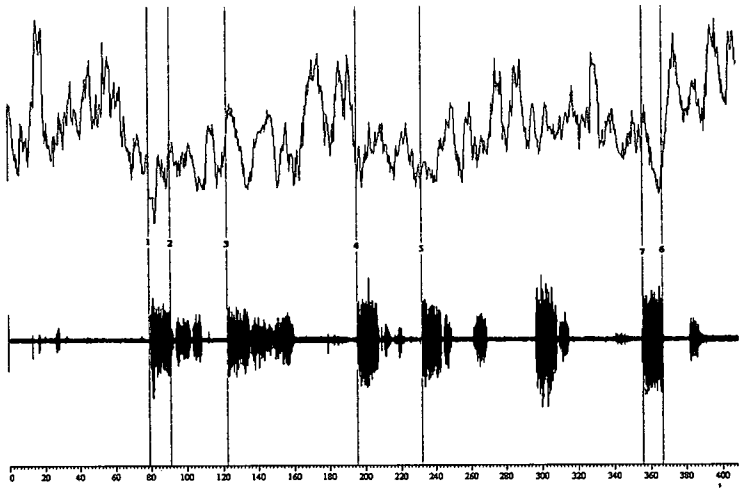


Figure 6.6B: Injured hamstring of case 6 at 50 Nm

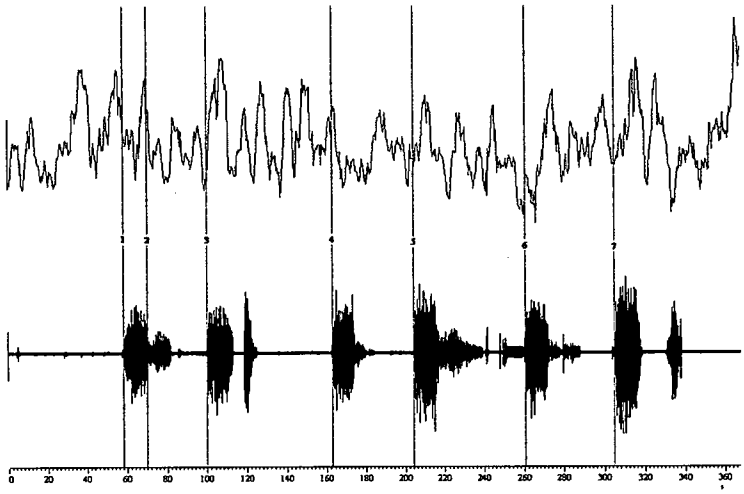


Figure 6.6

These two figures show the [tHb], top trace and EMG activity, lower trace recorded concurrently. In both traces the first, third and fifth contractions are at a knee position of 20° flexion. The alternate contractions are with the knee at 70° of flexion. In each case a torque of 50Nm is produced. The NIRS signals have been smoothed by averaging data points over 1 second. The first EMG recording at the beginning is the resting period. This volunteer is unable to relax the hamstrings between contractions at all in both limbs.

The vertical calibration bar for the upper trace shows 0.1 volt which is equivalent to a [tHb] of 12.4 micromoles. The calibration bar for the lower trace shows 1 millivolt.

6.7 Discussion

The [tHb] was measured at two positions 20° and 70° of knee flexion during contractions at 50 Nm in 6 cases with hamstring strains. Based on data from other experiments reported in chapters 4 and 5, it can be estimated that contractions at 50 Nm are at about 15% MVC. The mean changes in [tHb] in the injured and non-injured limbs were not significantly different. This is consistent with the data in chapter 5. These data are shown in table 6.3. In addition, some of the volunteers found it impossible to relax their hamstrings. This is similar to data in chapter 5.

This study is the first to investigate blood flow in the hamstrings in the post injury period with a NIRS. Successful measurements of the changes in [tHb] before, during and after contractions were made with NIRS in 5 volunteers. Perfusion decreased during contractions and then increased during relaxation periods in 5 volunteers. Case 6 is an exception.

There was no significant difference in the changes in [tHb] during contractions in the pairs of muscles. This might be related to the following: 1) any tissue damage or oedema in the injured muscle may have resolved after the medical care and treatment, 2) optodes were placed over the belly of the biceps femoris muscle and the injury might be in other area in this muscle or in other muscles e.g. semitendinosus and semimembranosus. It seems that individual analysis is the best option in cases with hamstring strains as variations in the behaviour of the exercising muscle were found among the volunteers.

The above case studies give examples of hamstring strains and focus on a number of interesting things. Firstly, athletes of different ages are prone to hamstrings strain. Secondly, hamstring strains can occur at any time in any sport specially those requiring fast or sudden movements. Thirdly, injured athletes usually suffer from muscle soreness and this can last few days to several weeks.

Thorsson et al. (1987) reported that the increased blood flow has significant implications when a muscle is damaged. The increased blood flow can result in more bleeding if no action has been taken. Studies showed that immediate treatment and rehabilitation after muscle strain are essential factors for minimising risks of re-injury (Askling, Karlsson and Thorstensson, 2003).

Five of the cases reported here received medical care after the injury. This included rest, ice, compression and elevation and ibuprofen, a non-steroidal anti-inflammatory drug, to reduce pain and inflammation. RICE is used to minimise pain and swelling allowing faster return to activity. However, returning to training before complete healing and rehabilitation may lead to a further injury. The rehabilitation programme aims to return the athlete to his previous level as soon as possible. Case 3 did not seek any of these treatments. This person was unable to return to his previous level of performance because of recurrence hamstring strains.

As role of injury prevention, it is important to educate athletes the basic principles of immediate first aid and consultation with a specialist in sports injuries for adequate treatment and earlier return to full activity. Delayed

consultation may complicate the diagnosis and treatment. If the injury is left untreated, weakness and loss of function are expected.

The lab assessment of the volunteers was varied between 2 and 12 weeks with an average of 7 weeks after hamstring injury. The results show that there were no significant differences in range of movement between injured and non-injured hamstrings. Bylak & Hutchinson, (1998) described 3 phases of the rehabilitation. First: the acute phase, which includes the initial treatment process to reduce symptoms and control tissue injury. Second: the recovery phase, which involves the process of tissue healing. Third: the maintenance phase, which involves directing therapeutic activities towards promoting the progression of sport-specific gains in function.

Lysens et al. (1991); Lysens, Steverlynck, Auweele, Lefevre, Renson, Claessens and Ostyn, (1984) considered muscle weakness and variation in range of movement in the injured and non-injured limbs as factor associated with re-injury. Orchard & Best, (2002) reported that the most popular and safe approach is to return an injured athlete to a full range of movement. They concluded that there appears to be a transaction between quick return to play, rate of recurrence and perhaps athletic performance. Hamstring strain is a complex injury, which may associate with more than one risk factor. Identifying any predisposing factors may prevent recurrence injuries.

The number of cases studied here is too small to be sure if injured muscles have more restriction to blood flow than non-injured muscles. It opens the question

of the possibility of testing the perfusion of muscles as an aid in identifying when full recovery from hamstring strains has occurred. The results also show that it is difficult to relax injured hamstring muscles. An ability to relax and produce a silent EMG might also be an indication of when recovery is completed.

Chapter Seven

General Discussion

Forty six male volunteers participated in the four series of experiments described in this thesis. This study is the first to investigate blood perfusion in the hamstrings during isometric exercise with a NIRS. The aims were:

1) To measure the magnitude and the time course of changes in hamstrings blood perfusion during isometric contractions at a series of muscle lengths.
2) To compare the magnitude of the changes in muscle forces and muscle blood perfusion in the left and right hamstrings.
3) To investigate the effects of specific warm-up contractions on hamstrings blood perfusion.
4) To measure the size and duration of the increased blood perfusion after specific warm up contractions.
5) To investigate hamstrings blood perfusion during periods of induced muscle damage.
6) To investigate hamstrings blood perfusion in a series of case studies of athletes recovering from injury.

The results of the experiments performed in pursuit of these aims are reported in chapters 3 to chapter 6. In general terms, aims 1 to 5 were successfully achieved. A series of case studies were performed to investigate perfusion during the recovery from hamstrings injuries. It is hard to draw any major conclusions from these because of the small number of cases and the varied nature of the injuries.

Changes in the concentration of total haemoglobin were measured in the hamstrings during rest and sub-maximal isometric contractions. The contractions produced reduction in the concentrations of total haemoglobin, (figure 3.4A, 3.5A and 3.6A). The easiest way to interpret these changes is that perfusion of the hamstrings is restricted during the contraction. Joyner & Halliwill, (2000) reported that muscle contraction compresses the veins resulting in changes in blood flow. This agrees with the views previously published by Breit et al. (1997). Their view was that intra-muscular pressures rose above perfusion pressures when forces exceeded 20% of MVC. The results reported in this thesis do not provide any information about which blood vessels are most compressed by the contractions. However, it is clear that changes in flow are not a secondary result of overall changes in the cardiovascular system brought about by the contractions. The arterial blood pressure and heart rate were very stable throughout the experiments (table 4.3, 4.4 and 4.5)

The nature and time course of these changes also indicates that the NIRS and the data capture equipment operated well. Previous studies used a NIRS to measure muscle blood flow in the forearm, quadriceps and calf muscles (Bonde-Peterson et al. 1975; Jensen et al 1993; Foster et al 1999; Kowalckhuk, Rossiter, Ward and Whipp, (2002). No previous study has investigated the hamstrings.

One issue in these experiments is the volume of tissue illuminated by the NIRS. In particular, does the light path go through the biceps femoris and does the light path include other muscles? The hamstrings are large enough to allow easy identification of the belly of biceps femoris muscle by palpation. The optodes

were securely attached to skin at the beginning of each test and the position at the end of the experiment was confirmed. The author is confident that there was no significant optode movement. Any optode movement might interfere with the recording since it may influence the readings by changing the angle of reflection or the length of the light path. Stable recording can be clearly seen at the beginning of the test followed by changes in NIRS signals during contractions.

7.1 Isometric & Dynamic Contractions

Most sports are characterised by dynamic muscle activity e.g. jogging, cycling and swimming. However, some sports e.g. weightlifters have clear phases of isometric muscle activity. The protocol used in the present project required the use of isometric contractions. These are not representative of the athletes' movements. However, isometric contractions were chosen to minimize the relative movement between optodes and muscles during the experiments. The NIRS signals are sensitive to changes in light path. The strategy was successful in that in 40 (87%) of volunteers the NIRS signal returned to baseline after the contractions.

A second issue concerns the relative speed of movement of the athletes' limb and response time of the NIRS. The NIRS is characterized a slow output frequency of 2 Hz. In athletic competition such as sprinting or jumping, the hamstrings activity only lasts for 100 to 400 msec (Ashkanani, 2005) i.e. the contraction will be finished before the NIRS makes even a single measurement

of [tHb]. It would be very interesting to investigate high speed movements but this is presently impossible with the current state of NIRS technology.

7.2 Prone & Seated Positions

Volunteers were seated upright during the experiments described in chapter 3. In later experiments they were tested in a prone position. Both positions have their advantages and disadvantages. The seated upright position resulted in some problems with the placement of optodes and electrodes. However, the researcher was conscious of this and care was taken to ensure good placement of these items. The prone position allowed much access to electrodes and optodes. In addition, it is important to consider the weight of the thigh in the seated position as it may affect the results by compressing the hamstrings.

Whilst individual contractions show reductions in the concentrations of total haemoglobin, oxy-haemoglobin and increases in the reduced haemoglobin, the size of these changes was not systematically different at different muscle lengths (table 3.3, 3.5, 3.8 and 3.9) or during periods of muscle soreness elicited during an episode of DOMS (figure 5.5). This may indicate that there are no positions of the limb where perfusion of the hamstrings is particularly restricted. Neither is perfusion especially poor during episodes of DOMS.

The interpretation of the experiments described in chapter 5 is particularly difficult. Measurements of muscle soreness, [CK] and MVC of the right hamstrings were made at day 0 before a vigorous bout of concentric/eccentric

exercise and then repeated after 2 and 7 days. The results (table 5.1A and B) show that all participants experienced significant increases in muscle soreness and plasma [CK]. There were concurrent reductions in maximal force. There is no simple relationship between the magnitudes of these changes in some individuals. For example, those who reported greatest elevation in [CK] and the biggest force reduction did not have the greatest pain (volunteer 2, 10 and 12 in tables 5.1A and B). The extent of any flow reduction probably depends on the development of tissue oedema in the damaged muscle. The signs of DOMS clearly suggest muscle damage but either oedema was not a problem or any oedema did not affect local perfusion.

A period of warm-up is thought to improve performance and prevent injury by physical and psychological preparation (Inbar & Bar-Or, 1975; Bishop et al. 2001; Thacker et al. 2004). Warm-up is also widely believed to increase blood flow in the exercising muscles (Daley et al. 2003). The results reported in chapter 4 show clear hyperaemias in the biceps femoris after sets of sub-maximal contractions. These were statistically significant in all 14 volunteers tested because the NIRS signals rose above the 95% confidence intervals calculated from the pre warm-up period.

The data in chapter 3 shows that the changes in blood perfusion in the hamstrings were significantly greater during contractions at 50% MVC than during contractions at 25% MVC. Thus the magnitude of the contraction can be thought to affect the size of the flow response. In chapter 4 the size and duration of the hyperaemias were measured after sets of warm-up contractions at 30%

and 40% MVC. The magnitudes and durations of the hyperaemias were similar after either set of contractions, i.e. they were both equally effective at increasing the perfusion of the biceps femoris. The hyperaemias lasted about 8 minutes (figure 4.6A and B and table 4.2). A statistically significant increase in blood perfusion was reported in all volunteers after warm-up exercise.

Some studies using the NIRS are able to make absolute measurements of perfusion. In these experiments a blood pressure cuff is used to stop venous flow out of a muscle (Breit et al. 1997) and the NIRS measures the increase in [tHb] (Nielsen, Boesen and Secher, 2001). It is not possible to use such an approach in a study of hamstrings perfusion. The anatomy of the thigh makes the use of the cuff impossible. The hamstrings muscles derive their blood supply from the femoral artery and are drained by the femoral veins. These cannot be compressed by a cuff. These results reported here are all relative flow measurements and changes in perfusion are recorded. In this respect the techniques are similar to Edwards et al. (1993), Nielsen et al. (2001) and Kowalchuk et al. (2002). These results still provide useful information on relative perfusion.

Chapter 6 reported data on perfusion changes in hamstrings in sportsmen recovering after injury. The perfusion changes were very varied probably as a result of the different injuries, the different recovery times and the different management of the injuries. However, the EMG data showed that five of the six cases had persistent hamstrings EMG which they could not silence. A similar inability to relax the hamstrings was seen in five of the 12 volunteers who

experienced DOMS in the experiments reported in chapter 5. The inability to relax the muscle might explain their sense of stiffness and soreness. It is also possible that these contractions any impair perfusion and delay recovery. One might speculate on the value of including EMG in the assessment of hamstrings injury.

7.3 Advice to Athletes on Warm-Up

It is clear from section 1.2.10 in the literature review that there is a great variety in the ways in which athletes warm-up. There is little or no scientific data available to inform this discussion. The most appropriate intensity and duration of warm-up are still not clear. One aim of this project was to examine the effects of sets of sub-maximal contractions on hamstrings blood flow.

The protocols used to investigate perfusion in this project have several important differences for the warm up routines used in athletics. Most athletes use dynamic exercises in their warm up and these experiments used longer duration, isometric contractions. The reasons for this have been described earlier. The intensity of warm up is also quite different. The athlete will usually exercise a larger muscle mass and an intensity sufficient to increase their heart rate substantially. In these experiments, only the hamstrings in one limb was exercised and the intensity of contraction was modest, in the range 10-40% of MVC.

Whilst the conditions of the warm up differs for that before athletic competition, the results in chapter 4 show that an intermittent exercise lasting 4 minutes at 30% MVC is enough to increase blood flow in the hamstrings significantly in all the volunteers. This flow increase lasted for approximately 8 minutes on average. This intensity of exercise clearly produces a warm-up effect. There was no significant advantage in warming-up at 40% of MVC. It seems that mild intensity exercise at about 30% MVC is enough to prepare the athlete. The effects of warm-up contractions at intensities above 40% were not tested. They offer the potential of larger or longer lasting increases in muscle perfusion. However, the higher intensity warm-up probably carries a higher risk of injury during the warm-up.

The results in chapter 4 show a mean duration of increased perfusion of about 8 minutes. One consequence of this is that the warm-up session must finish relatively close to the start of the subsequent event. If the delay between warm-up and competition is too great the benefit of the warm-up will be lost.

In sports such as football and rugby, groups of players can be observed to warm-up together. This may have advantages in terms of team cohesion but it is almost certainly inappropriate given the different natures of the physical demands of their individual positions. It would be interesting to know if defenders and strikers would benefit from more specific warm-up routines.

The influence of age on the occurrence of hamstring injury has not been studied specifically in this project. The age of participants in the present study ranged

between 15 and 47 years. Increasing age is one of the risk factors for sports injuries and the incidence of Australian football injuries was found to increase with increasing age. The hamstring injury was associated with older players age >23 years (Orchard, 2001). This study did not report the classification of age groups. Woods et al. (2004) studied the frequency of hamstring strains in English professional footballers. They identified a higher risk of hamstrings injury players aged between 17 and 23, years, when they are exposed to high-intensity training. The need of preventative strategies still requires more research.

The influence of age on muscle O_2 supply/utilisation balance and energy metabolism during hand grip and cycle ergometer exercises is similar between young (27 years) and older (62 years) volunteers. However, haemoglobin re-oxygenation is slower in older volunteers. The recovery of HbO_2 and HHb are slower in older volunteers than in younger ones caused by the process of increasing age (Kutsuzawa, Shioya, Kurita, Haida and Yamabaashi, 2001; Costes, Denis, Roche, Prieur, Enjolras and Barthélémy, 1999). It can be said that changing the muscle group and type of exercise would not influence muscle oxygenation in young and old individuals. This suggests that poor muscle oxygenation or low perfusion are unlikely to be important risk factors for muscle injuries.

7.4 Warm-Up of Athletes after Recovering from a Previous Injury

In the author's experience of observing his personal response to hamstring injury and the behaviour of fellow athletes with similar injuries, many athletes have concerns about the intensity of their warm-up when they return to training or competition after recovering from an injury. They may not prefer to perform a longer or more intense warm up at the start of each session. The most obvious change is that they spend more time in stretching. Their greatest anxieties are concerned with recurrence of their injury. This may lead to a loss of self-confidence and ultimately to poor performances.

A clear understanding of the causes of hamstring strains is still lacking. Orchard, (2001) states that the true value of warm-up in prevention of muscle strain injury is not known. He also stated that active warm-up is more likely to be of value than passive warm-up. In the author's point of view, it is important to perform at least light dynamic exercise and light static stretches before strenuous exercises followed by a rehearsal of the required sport event on the nature of the sport skill specific movements. The active warm-up can be performed through 5 minutes of jogging or swimming at intensity of 30% MVC. Then depending on the sports event, specific warm-up of the body parts involved in the activity can be performed. Stretching for not more than 10 minutes may be beneficial in injury prevention. Then 5 minutes of fast reactions such as sprinting during acceleration exercises provide a slight rehearsal of complex skills.

Special attention for environmental conditions is recommended especially during cold conditions. These procedures give the athlete more confident and prepare the athlete physically and psychologically. If this has done properly, it helps the athlete to perform better and may prevent him having an injury.

7.5 Recommendations for Future Work

The results show that muscle activity increased the muscle blood flow in the hamstrings after 30 and 40% MVC. It would be reasonable to investigate the effect of specific warm-up after 20% MVC. It would be also interesting to investigate the role of mental rehearsal in warm-up hyperaemias. If these work, it offers the change of warm-up without the risk of injury.

The associated risk factors and the mechanisms of hamstring strains were evaluated among healthy and injured athletes. The high rate of recurrence injuries causes problems to both coaches and athletes. With respect to many trials designed to decrease the incidence of hamstring injuries, no specific cause was considered and the problem remains not clear. Most of medical treatments did not prevent the recurrence of the injury. Different methods might be used in assessing risk of hamstring injuries considering personal and different sports events. It would be beneficial if an experiment could be done at the time of injury. Video analysis, NIRS and EMG can be used to look at inside and outside the body at the time of injury occurrence. Otherwise, predicting hamstring strains in healthy people could be evaluated by the use of EMG.

Chapter Eight

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Chapter Nine

Appendices

Appendix (9.1): Anthropometrics of first experiment

No.	Age	Height (cm)	Weight (Kg)	MVC						Sport
				Left			Right			
				50°	70°	90°	50°	70°	90°	
1	29	165	80	306	266	197	396	374	235	Sedentary
2	35	170	65	294	201	157	392	267	205	Recreational
3	21	169	65	262	217	168	290	255	205	Football
4	23	178	83	450	398	330	523	432	304	Football
5	36	174	105	420	338	224	468	422	324	Detrained
6	27	165	80	230	210	163	301	308	248	Sedentary
7	27	173	61	317	242	196	403	328	229	Football
8	23	174	75	531	462	361	538	487	367	Sprinter
9	20	176	87	448	352	211	462	425	326	Swimming
10	40	172	72	339	317	255	381	315	266	Sedentary
11	42	176	74	338	275	229	343	250	192	Football
12	23	166	69	413	347	257	374	380	281	Football
13	21	182	84	500	433	304	439	412	267	Rugby
14	18	180	60	303	252	134	343	326	290	Recreational
Mean	**27.5**	**173**	**76**	**368**	**308**	**228**	**404**	**356**	**267**	

Appendix (9.2): Anthropometrics of second experiment

No.	Age	MVC (Nm) at 60°	Height (cm)	Weight (Kg)	Sport
1	30	317	172	64	Sedentary
2	21	269	178	60	Triple jump
3	24	426	198	99	Basketball
4	21	376	173	66	Sedentary
5	21	421	170	87	Swimming
6	23	314	183	71	Recreational
7	22	307	189	75	Recreational
8	22	252	187	77	Rugby
9	21	298	168	68	Karate
10	23	450	174	75	Sprint events
11	20	306	172	75	Sedentary
12	41	229	172	72	Detrained
13	22	416	182	84	Rugby
14	26	493	183.5	85	Weightlifting
Mean	**24**	**348**	**179**	**76**	

Appendix (9.3): Anthropometrics of third experiment

No.	Age	Height (cm)	Weight (Kg)	MVC (Nm) at 60°	Sport
1	23	187	77	285	Rugby
2	20	171	75	295	Sedentary
3	23	180	90	330	Football
4	21	166	65	418	Detrained
5	21	171	63	379	Detrained
6	23	178	85	426	Rugby
7	23	170	65	297	Recreational
8	18	174	68	343	Recreational
9	20	172	72	396	Footballer
10	22	184	85	341	Hockey
11	29	175	96	388	Cycling
12	19	174	83	417	Weightlifting
Mean	**22**	**175**	**77**	**360**	

University of Glasgow
Institute of Biomedical and Life Sciences

Subject Questionnaire and Assent Form For Exercise Testing

If you feel unwell on the day of a proposed test, or have been feeling poorly within the last two weeks, you are excluded from taking part in an exercise test. The considerations that follow apply to people who have been feeling well for the preceding two weeks.

Name .....

Sex: M/F **Age**:.....(yrs) **Height**:.....(m) **Weight**:.....(kg)

Exercise Lifestyle:

What kind(s) of exercise do you regularly participate in (20minutes or more per session), and how often? (Please circle the number of times per average week)

Walking	1	2	3	4	5
Running	1	2	3	4	5
Cycling	1	2	3	4	5
Skiing	1	2	3	4	5
Rowing	1	2	3	4	5
Gymnastics	1	2	3	4	5
Martial arts	1	2	3	4	5
Sweat Session	1	2	3	4	5
Weight Training	1	2	3	4	5
Field Athletics	1	2	3	4	5
Racket Sports	1	2	3	4	5
Rugby/Football/Hockey etc.	1	2	3	4	5
Others*	1	2	3	4	5

*(please specify).....

How long have you been exercising at least 3 times per week for at least 20 minutes a session? .....yrs

Symptoms:

Have you ever suffered had to consult a physician relating to any of the following?

Breathlessness	**N/Y**
Chest Pain	**N/Y**
Dizzy Fits/fainting	**N/Y**
Heart murmurs	**N/Y**
Palpitations	**N/Y**
Tightness in chest, jaw or arm	**N/Y**

Other* **N/Y*** (Please specify).....

If yes for any, was it when at rest or during exercise?.....

Medication: Are you currently on any medication? **N/Y***
*(Please specify what and what for?).....

Family history of sudden death:
Is there a history of sudden death in people under 40 years of age in your family? **N/Y**

Muscle or joint injury:
Do you have/or have you had any muscle or joint injury (particularly knee or hamstring injury) which could affect your safety in performing the exercises that will be performed in this test? **N/Y***
*(Please specify).....

Can you think of any other reason why you shouldn't take part in our tests? **N/Y***

*(Please specify).....

The following exclusion criteria will apply to this study:

Exclusion criteria:

(a) Asthma*, diabetes*, epilepsy*, heart disease, a family history of sudden death at a young age, fainting bouts, high blood pressure, anaemia and muscle or joint injury.
(b) If you are taking any medication that may adversely affect your performance or health during any tests in this study.
(c) If you have ingested alcoholic drinks in the previous 48 hours.
(d) If you take recreational drugs.
(e) If you do not exercise at a moderate intensity for at least 20 minutes per session at least 3 times per week.
(f) If you are significantly fatigued or sore from exertions undertaken in previous 48 hours

* not relevant if condition is well controlled and you are confident that the tests involved will not trigger any complications related to these conditions

If you meet any of the above criteria you are excluded from any further participation in this study, thanks for your time and cooperation.

Signature..... **Date**.....

Appendix (9.5): Consent Form

Consent Form

You are invited to participate in a PhD study which aims to investigate muscle blood perfusion.

I (name) .....have read and understood the patient information sheet about the study.

The nature and purpose of the study has also been explained to me any quires I had on the study were answer by:

Abdul-Majeed Al-Mousawi

I have completed the questionnaire and I am eligible to participate as the guidelines within dictate.

I understand that I can withdraw from this study at any time and that all information collected will be held in strict confidence.

I am willing to participate as a subject in this study.

Signed .....Date.....

Appendix (9.6): Subject questionnaire and assent form for hamstrings muscle testing

University of Glasgow

Institute of Biomedical and Life Science (IBLS)

Subject questionnaire and assent form for hamstrings muscle testing

Injury definition: Any pain in the posterior thigh muscles (the hamstrings) as a result of participation in sports activities affected your performance or limited you from training for a period of one day or more with a need for medical advice or treatment.

If you feel unwell, you have the right to not taking part in this experiment or withdraw at anytime during the test.

NB: Please circle option(s) as appropriate:

1. Date of injury: / /

2. Warm-up before training/competition:

1-	Running (minutes)	≤ 5	10 - 15	20 ≥
2-	Stretching (minutes)	≤ 5	10 - 15	20 ≥

3. During which sport have you been injured? (i.e. Football –Other activity.....)

4. Injury occurred during: (i.e. Training – Competition – Other activity.....)

5. Who made the diagnosis? (i.e. GP – Doctor – Physio – Trainer – Other specify.....)

6. Was there any noticeable swelling? .....**Yes ( ) No ( )**

7. Pain during first 48 hrs: as **0** (no pain) and **10** (most sever pain) ..... ( )

8. Pain toddy: as **0** (no pain) and **10** (most sever pain) ..... ( )

9. Where were you treated? (i.e. Hospital – GP – Sport clinic – Other specify.....)

10. What treatment did you receive? (i.e. R.I.C.E. – Physiotherapy – Splint – Other...)

R.I.C.E ----------→ **R** = rest, **I** = ice, **C** = compression, **E** = elevation

11. Who guided the rehabilitation? (i.e. Dr. – Physio – Trainer - Other specify.....)

12. Did you take enough time to recover from the injury? Yes ( )No ( )

13. Did you complete the treatment course?..... Yes ( ) No ( )

14. Was this a recurrence?.....Yes ( )No ( )

15. How was the injury defined?

Region	Side	**Mild** Strain ≤ **4** weeks	**Moderate** Strain **4 - 12** weeks	**Sever** Strain (tear) **12** ≥ weeks
Hamstrings (back thigh)	Right			
	Left			

16. Jogging commenced after:

1 week	2 wks	3 wks	4 wks	2 mths	3 mths	6 mths	≥ 10 mths	Other

Appendix (9.7): Laboratory assessment

Laboratory Assessment

1. **The laboratory assessment was after ..... Of the injury**:

1 week	2 wks	3 wks	4 wks	2 mths	3 mths	4 mths	≥ 6 mths	Other

2. **Active knee extension (hip** at **90°** and **knee** starts from **0°):**

Injured .....° Non-injured .....°.

3. **Passive knee extension (hip** at **90°):**

Injured .....° Non-injured .....°.

4. **Full knee flexion from prone position (0° being straight knee):**

Injured .....°. Non-injured .....°.

5. **Measurement of muscle strength (kin-Com):**

Injured .....Nm. Non-injured .....Nm.