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Isokinetic force ratios, muscle function and anaerobic performance of the knee extensors and flexors

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Isokinetic Force Ratios, Muscle Function and Anaerobic Performance of the Knee Extensors and Flexors

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SUMMARY OF THESIS

This thesis is presented as a series of four empirical studies. The studies measured and examined the isokinetic force ratios of the knee extensors and flexors and investigated the effects of strength training on force production, ratios and subsequent power output during maximal activity in men and women.

The initial study gathered preliminary data regarding isokinetic force values and strength ratios of the knee extensors and flexors in rugby league players. Values for rugby league players were within previously reported ranges but the usefulness of the ratios obtained was questioned.

The second study therefore investigated the dynamic control ratio. The dynamic control ratio was compared with the traditional hamstrings/quadriceps strength ratio in rugby league players at three velocities. The dynamic control ratio was higher than the conventional ratio, and the difference increased as the velocity of measurement increased. The dynamic control ratio more closely represented normal functioning and highlighted the role played by the eccentrically acting flexors in controlling the opposing knee extensors.

The third investigation examined the influence of strength training on force production and the subsequent production of peak and mean power. After 12 weeks of strength training men and women had significantly increased isokinetic force production. This was mirrored by an increase in peak power output. There were also increases in work done during a maximal isokinetic test suggesting that strength training improves the ability to perform anaerobic activity and may positively enhance anaerobic capacity.

Finally, strength training was analysed for its effect on muscle quality using simple ratio or power function ratio measures. Improvements in muscle quality will be potentially masked if simple ratios are used. If leg volume is raised to the power 0.67 then muscle quality in men and women is similar. This is the case for isokinetic force and anaerobic performance.

CHAPTER 1

INTRODUCTION

1.1 Summary

This thesis is presented as a series of four empirical studies. The studies investigate the isokinetic force values of the knee extensors and flexors and the related hamstring/quadriceps strength ratios. They also examine the influence of strength training with regard to the function of the knee extensors and flexors and the effects of strength training on anaerobic performance during maximal cycling in men and women. The thesis also examined the effects of training on muscle quality when normalised for body size.

1.2 Knee Extensors and Flexors

Muscles of the thigh can be classified on functional grounds as flexors and extensors (Banister *et al.*, 1995). Grays Anatomy (Banister *et al.,* 1995) describes how the muscles are organised into anterior and posterior groupings. The anterior thigh consists of the tensor fascia latae, sartorius, rectus femoris - all of which operate across both the hip and the knee- and the vastus medialis, vastus lateralis and the vastus intermedius. The latter three only operate across the knee joint. The rectus femoris and the vastus muscles share a common tendon and are commonly referred to as the 'quadriceps femoris'. The quadriceps femoris is the great extensor muscle.

The posterior group consists of the biceps femoris, the semitendinosus, and the semimembranosus. These are commonly referred to as the 'hamstring' group and all muscles in the group act across both the hip and the knee and they usually contract as a whole. These muscles are largely responsible for the flexion of the knee, aided by the sartorius, popliteus and gastrocnemius (Sinclair, 1961).

Summary of movements at the knee:

Flexion = hamstring group; gastrocnemius; popliteus; sartorius.

Extension = quadriceps femoris.

Lateral rotation of femur on tibia = popliteus; semimembranosus; semitendinosus.

Medial rotation of femur on tibia = biceps femoris; sartorius; iliotibial tract.

(Sinclair, 1961)

1.3 Muscle Strength

The assessment of muscle function and strength testing has been extensively employed in sport, physical education and clinical practice (Jaric, 2002). The knee extensors and flexors have been commonly assessed because leg power is a critical element of sports performance (Potteiger *et al.,* 1999) and improvements in performance in strength-based activity require regular strength assessment (Schmidt, 1999). Additionally the quadriceps and hamstring muscle groups are two of the most commonly injured muscle groups in multiple sprint sports (Brady *et al.*, 1993). Absolute strength values have been used to compare differing population groups for a variety of differing sports and between men and women (Holloway and Baechle, 1990). For more accurate comparisons of differing populations, studies have employed ratios where strength is divided by a particular body dimension, such as cross-sectional area or mass in order to remove the influence of size (Maughan 1983; Ivey *et al.,* 2000). However, these ratios rarely remove the influence of size, rather they distort it (Winter, 1992). The use of more appropriate statistical procedures has demonstrated that the quality of male and female muscle, rather than being the same, is in fact different, with male muscle being stronger and more powerful than that of the female (Winter and Maughan, 1991; Winter *et al.*, 1991; Eston *et al.*, 1997). Much of the knowledge that exists about strength and performance is based on simple ratios as most studies have reported data in this way, e.g. (Tracy *et al.,* 1999; Ivey *et al.*, 2000). In view of this further investigations into strength and muscle performance are required.

Additionally when the study commenced, the area of training for strength was identified as an expansive and relevant area for future research (Jakeman *et al.*, 1992). This was despite extensive research in this area and the application of strength training techniques that have been in existence since the Greek Olympic era (Behm and Sale, 1993). Limitations in previous research have included lack of uniformity in experimental design (Hakkinen, 1989), poorly conducted studies and inappropriate duration of training periods (Brooks and Fahey, 1985).

1.4 Isokinetic Dynamometry

When investigating strength, muscle function and the effects of strength training, isokinetic dynamometry is a key factor. At the commencement of the study, 'isokinetics' was still a relatively new method of resistive exercise that was introduced in the late 1960's (Hislop and Perrine 1967; Thistle *et al.,* 1967). Dynamometers with eccentric capability became available more recently (Baltzopoulos, 1997). Isokinetic dynamometers not only aid the quantification of strength, but also allow for greater understanding of muscle function. Again, investigations regarding the knee joint have been extensively undertaken, but due to the nature of the available dynamometers, much of the work has focused only on the concentric action of the knee extensors and flexors. As a consequence, the much reported hamstring/quadriceps strength ratio has been predominantly analysed using only concentric values. Such ratios do not reflect the normal functioning of muscle during most sporting activity. Thus, whilst isokinetic dynamometry remains an artificial situation, an investigation of isokinetic force ratios using both concentric and eccentric force values may prove to be more functional and have a greater degree of application.

1.5 Anaerobic Performance

In comparison with research involving strength, investigations into the anaerobic system are in their relative infancy although considerable effort has been placed in evaluating the system since the early 1980's (Tharp *et al.*, 1984; Jakeman *et al.*, 1992; Nevill, 1992). This has coincided with a desire to further understand the physiological demands of sprinting and multiple sprint sports (Jakeman *et al.*, 1992) in which the reproducibility of maximal effort is a key aspect if performance is to be successful. Strength training is commonly prescribed in these sports; therefore the strength/performance relationship requires further investigation (Jakeman *et al.*, 1992) in order to optimise both preparation and performance. Whilst the relationship between anaerobic power and strength has been explored and is generally accepted, the relationship between strength and anaerobic capacity is less well understood.

1.6 Purpose

Therefore the purpose of these studies was to measure and examine the isokinetic force ratios of the knee extensors and flexors and to investigate the effects of strength training on force production and ratios, subsequent power output during maximal activity and to compare male and female responses.

1.7 Structure and Overview

The sequence of the four studies represents a developmental process. The development is reflected in links between the studies with regard to muscle function and strength and in the experimental design and ultimate statistical analysis.

1.7.1 Study 1

The initial study was undertaken to gather preliminary data regarding isokinetic force values and to identify the hamstring/quadriceps strength ratio in specific population groups involved in high intensity, multiple sprint sports. This included professional rugby league players and sport studies students. Rugby league is unique in the demands that are placed upon players, particularly since the advent of the 'Super League' competition. Strength is an essential component of the game, but without continual monitoring in relation to performance, training methodologies cannot be assessed and revised. As much interest has focused upon the multiple sprint sports, it was decided to study a sport where the demands with regard to strength and high intensity activity are particularly great. Additionally, it was clear that in some of the professional rugby league clubs there was a lack of understanding with regard to strength training and its potential benefits. Little published material exists with regard to the sport. A review paper looking at the physiology of rugby league (Brewer and Davis, 1995) listed only 18 references. A need exists to further investigate the physical, strength and performance characteristics associated with the game. This study was therefore designed to provide initial population-specific data, and to enable initial evaluation of the strength characteristics of rugby league players in relation to the game and to compare with another physically active group. The study compared the force values between the two groups and related the force values to the anthropometric characteristics of the subjects. Analysis produced findings that were similar to those previously reported, but highlighted issues relating to the appropriateness of the force values and the hamstring/quadriceps strength ratios commonly used.

1.7.2 Study 2

As a consequence, the second study focused on a relatively underused hamstring/quadriceps strength ratio. This ratio was calculated by dividing the eccentric force of the hamstrings with the concentric force of the quadriceps, previously reported as the 'dynamic control ratio' (DCR). The ratio was again calculated in professional rugby league players. Previous studies have investigated the effect of velocity on concentric and eccentric force production. Because the different actions respond differently to changes in velocity, this should also influence the DCR. This study therefore employed different velocities in order to analyse their effect on the DCR. Again the study was also designed to provide information regarding the specific population studied and to suggest clarification with regard to the most appropriate way of reporting knee extensor and flexor strength ratios.

1.7.3 Study 3

The third investigation examined the influence of strength training on isokinetic force production and the subsequent production of power, both peak and mean, as measured during maximal cycling. Although the strength-power relationship is well known and widely reported, the influence of strength training on mean power, a reflection of anaerobic capacity, is less well understood. This is of clear importance in multiple sprint sports such as rugby league. The study also analysed the effects of strength training on the total work performed during 30 s of continuous isokinetic extension and flexion. The strength ratios were analysed to see if training had altered them and to establish whether the training had been balanced with regard to its effects on both the knee extensors and flexors and the concentric and eccentric modes. This study represented a relatively unique training intervention study that examined both males and females and made use of a control group.

1.7.4 Study 4

The fourth study examined the influence of strength training on muscle quality in males and females. In studies where normalisation has been undertaken utilising simple ratios, the results have shown that the quality of male and female muscle is equal. In studies where other scaling procedures such as power function ratios have been used, the results have demonstrated that men have greater muscle quality than women. This study compared muscle quality between men and women and then examined the effects of training, enabling evaluation of trained and untrained men against trained and untrained women. Few studies have reported the effects of strength training on muscle quality when appropriate scaling procedures have been adopted.

It is hoped that the findings from these studies will provide clear directions for the future with regard to both further studies and the use of appropriate measures and terminology.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

As the product of force and velocity is power, maximal muscular power should be enhanced with improvements in both strength (force) and /or speed (velocity) (Sleivert *et al.*, 1995). However, accurate comparisons of previous strength training studies are difficult to make due to a lack of uniformity in experimental design (Hakkinen, 1989). Analysis is further complicated because many earlier studies have been poorly conducted and undertaken over too short a period of time (Brooks and Fahey, 1985). Results from human studies investigating strength gain and morphological change are equivocal and further investigation is required (McCall *et al.*, 1996). Indeed, the exact content of an ideal or appropriate strength training programme is not precisely known because of the many differing phases of activity which occur in sports (Delecluse *et al.*, 1995). Additionally strength gains may not lead to power improvements, particularly if the gains are very specific, or involve only a single joint when the actual movement pattern of the activity from which power is measured involves complex multi-joint action (Sleivert *et al.*, 1995). Despite such limitations, strength training is frequently and commonly employed in sports requiring maximal efforts (Delecluse *et al.*, 1995). Because of this and the limitations that exist, strength training remains a viable and relevant area for future research (Jakeman *et al.*, 1992).

One method of measuring strength involves the use of isokinetic dynamometry, a procedure that was first introduced in the late 1960's (Thistle *et al.*, 1967) and has become an accepted procedure for the evaluation of muscle status (Holm *et al.*, 1994). Isokinetic force or torque values have been reported in a number of sports, particularly those involving multiple sprint activity such as football (Brady *et al.*, 1993; Gur *et al.*, 1999). Force values are subsequently used to derive ratios, the most common being the ratio between concentric knee flexion and concentric knee extension (Baltzopoulos and Brodie, 1989), although ratios for other joints are also reported. Additionally the ratios between concentric and eccentric actions of individual muscle groups have been measured, mainly for the knee extensors and knee flexors (Colliander and Tesch, 1989). As the technology continues to become more sophisticated and capable of measuring a greater range of parameters the application of isokinetics is becoming more widespread. Normative strength values and ratios are reported for specific populations (Merlini *et al.*, 1995; Calmels *et al.*, 1997) across a variety of sports (Hakkinen, 1991; Kovaleski *et al.*, 1994).

Inter- and intra- muscle group ratios are also utilised in rehabilitation (Li *et al.*, 1996; Oni *et al.*, 1996) and used as a method of screening for normal functioning. The use of isokinetic dynamometry is now vital in the assessment and evaluation of knee extensor and flexor activity.

As with isokinetic dynamometry, investigations into the anaerobic system of energy production are in their infancy when compared with research on the development of strength, although there have been a considerable number of studies which have evaluated the system since the early 1980s (Tharp *et al.*, 1984; Jakeman *et al.*, 1992; Nevill, 1992). This has coincided with a desire to further understand the physiological demands of sprinting and multiple sprint sports (Jakeman *et al.*, 1992) in which the reproducibility of maximal effort is a key aspect if performance is to be successful. As strength training is commonly prescribed in these sports, the strength / performance relationship requires further investigation to further understand the specific physiological demands and to optimise performance (Jakeman *et al.,* 1992).

It is well documented that strength training, and increases in strength, can lead to improvements in high intensity activity in man (Lesmes *et al.*, 1985; Bell *et al.*, 1989; Mannion *et al.*, 1994; Delecluse *et al.*, 1995) and in animals (Westra *et al.,* 1985). Likewise, performance improvements in maximal exercise have been found following high intensity sprint and interval training (Nevill, 1989; Jenkins *et al.*, 1994). The mechanisms by which training affects maximal performance require clarification, particularly considering the wide variety of training methodologies employed. Muscular adaptations due to strength training are widely reported (Costill *et al.*, 1979; Jones and Rutherford, 1987; Booth and Thomason, 1991), yet the relationship between such changes and the ability to produce and reproduce maximal effort remains under explored.

This review will explore the use of isokinetic dynamometry and its role within the analysis of muscle function. It will identify adaptations resulting from heavy strength and interval training and examine possible causes of improvement in maximal performance.

2.2 Isokinetic Dynamometry.

2.2.1 History/Definition

'Isokinetics' refers to the conditioning or measurement of muscle strength under conditions of constant angular velocity (Dvir, 1991). It is a relatively new method of resistance exercise, introduced in the late 1960's (Thistle *et al.*, 1967). However the method is now extensively used within the fields of physiotherapy and exercise physiology where considerable research is undertaken to examine *'in-vivo'* characteristics of human muscle (Dvir, 1991; Kannus, 1992; Gleeson and Mercer 1996; Baltzopoulos and Gleeson, 2001).

Isokinetic actions are undertaken using special dynamometers which contain a rotating mechanical lever to accommodate the force generated by the acting musculature such that the limb moves at a constant angular velocity, controlled by either electrical or hydraulic mechanisms (Dvir, 1991). These systems allow for maximum muscular force and maximum resistance throughout the entire range of movement, something that is not possible with either isometric or isotonic actions (Baltzopoulos and Brodie, 1989). Dynamometers measure either torque or force at a number of differing velocities and angular positions. The majority are interfaced with a computer and rapid quantification of a number of muscle function parameters is possible (Kannus, 1992). Originally dynamometers only worked in concentric modes but it is now also possible to assess muscle function during eccentric activations (Kellis and Baltzopoulos, 1995). The developments in this method of dynamometry have meant that it is possible to achieve a greater degree of reliability and objectivity than in other forms of muscle testing (Abernethy *et al.*, 1995). In addition, isokinetic testing provides a range of other benefits including the ability to test differing physiological traits of muscle e.g. endurance, strength (Baltzopoulos *et al.*, 1988; Hakkinen, 1991), the availability of visual feedback to motivate subjects (Kimura *et al.*, 1997), and the safety afforded to subjects due to the prescribed velocity settings (Baltzopoulos, 1997).

Isokinetic dynamometry is most commonly used for strength testing, rehabilitation, research, diagnosis of injury (Bennett and Stauber, 1986; Ellenbecker and Roetert 1995; Orchard *et al.*, 1997) and for medico-legal uses (Dvir 1996).

2.2.2 Isokinetic Parameters.

2.2.2.1 Torque/Force

In both scientific and clinical settings the most commonly reported isokinetic measurement is peak torque (Morrissey, 1987; Kannus, 1992; Tis and Perrin, 1994; Dvir and David, 1995). It refers to the highest value recorded from muscular action as the limb moves through the range of motion (Kannus, 1992). It has been shown to be a valid and reproducible measure (Gleeson and Mercer, 1992), and is accepted as a gold standard reference point in isokinetic measurement (Kannus and Beynnon, 1993). As dynamometers have developed it is now also possible to directly measure force as well as torque. Whether a dynamometer measures force or torque directly, depends on the location of the load cell. For example, the Kinetic Communicator (Kin Com; Chattecx Corp. Chatanooga) has the load cell located at the distal pad attachment and not at the axis of rotation, thus force is measured from the point of application (Tis and Perrin, 1994). The software used with dynamometers has the capability to report data as force or torque subsequent to collection. Tis and Perrin (1994) undertook correlational analysis of torque and force values and found that strong relationships existed between them, thus supporting interchangeable use.

Another torque parameter that is less often reported is average torque, which is equal to the arithmetic average of the sampled points that constitute the isokinetic curve (Dvir and David, 1995). As with the force-torque relationships, high correlations have been found between peak and average values (Dvir *et al.,* 1989; Tis and Perrin 1994) which again suggests that the values can be used interchangeably. However Dvir and David (1995) have recommended caution, pointing out that high correlations alone do not automatically justify interchangeable use. It is possible that two highly correlated parameters in relation to individual conditions may manifest different proportions in each of the conditions. Tis and Perrin (1994) also recommend caution, highlighting the extra sensitivity of average torque measures. Dvir and David (1995) concluded by recommending the use of peak values for the creation of normative strength data, but when muscle function is being assessed by the use of inter-muscle or intra-muscle strength ratios, they suggested the use of the average torque values.

Other parameters including work, (Morrissey, 1987; Kannus, 1992) and peak power (Kannus, 1992) have also been measured. Peak work and peak power were closely related to peak torque and have been subsequently recommended for clinical use (Kannus, 1992).

When analysing the peak or average torque values obtained from isokinetic dynamometry, it is important to recognise that the torque values obtained are not exact reflections of the torque values produced in the muscles (Gulch, 1994). The equality between the muscles and reported values is compromised by the influence of gravity and the length of the dynamometer arm (Gulch, 1994), although gravity correction is now a common feature of isokinetic assessment. If gravity correction is not undertaken then the validity if the isokinetic procedure will be compromised.

Gravity is not the only factor that can affect the validity of isokinetic dynamometry. Baltzopoulos and Gleeson (2001) referred to a "myriad of features" that influence the torque or force reported for a joint system during isokinetic evaluation. Other factors include those directly associated with the dynamometer such as the velocity of the test movement, inertial forces and calibration (Sapega, 1990). Others associated with the testing generally such as individual circadian rhythm and time of day, limb dominance, personal motivation and level of verbal encouragement can also impact on the result of the test (Kannus, 1994).

The former factors are dynamometer specific and are inherent within the limitations of the machinery, which are in–turn regulated by factors such as design and manufacturing cost (Gleeson and Mercer, 1996). For this reason comparison of values obtained from different dynamometers, even of the same make and model, should be undertaken with caution (Francis and Hoobler, 1987). A further issue is that isokinetic movement rarely occurs during human movement or sports performance (Kannus, 1994) and the velocity of measurement is considerably slower than the velocities experienced during sport and physical activity (Sale, 1991, cited in Baltzopoulos and Gleeson, 2001). At higher testing velocities the portion of the movement that is isokinetic reduces, hence care has to be taken when choosing the protocol and the speed at which testing is to be conducted. Slower velocities contain a larger isokinetic component but are even less representative of normal human performance than higher velocities. These are illustrative of the competing demands within protocol design that may effect the evaluation and interpretation of isokinetic strength values (Baltzopoulos and Gleeson, 2001). However, despite such limitations isokinetic dynamometers have greatly increased the opportunities for examining dynamic muscle activity and have proven usefulness in analysing muscle function (Kannus, 1994). Isokinetic dynamometry is a powerful tool that provides objective data regarding muscle kinetic parameters and its development has represented a significant advance over the semi-quantitative methods that were previously used (Dvir, 1991).

To maximise the validity, it is necessary to ensure consistency in the application of protocols and to ensure that the researcher is experienced, well informed and aware of the factors that may interfere with the testing protocol (Kannus, 1994). The researcher can reduce the possible adverse effects of a test protocol by appropriate design and implementation. A protocol should preferably contain a series of trials from which a mean score is derived (Gleeson and Mercer, 1996) and if possible employ inter-day trials (Baltzopoulos and Gleeson, 2001). Additionally the protocols should standardise the test environment, the time of day that testing occurs, the visual and oral encouragement and the recovery period between each trial (Kannus, 1994; Gleeson and Mercer, 1996; Baltzopoulos and Gleeson, 2001). It is clear that protocol design will depend on logistical, financial and subject availability issues (Baltzopoulos and Gleeson, 2001) as well as the rationale underpinning the testing. The sensitivity required from a protocol will differ depending on the nature of the investigation, for example a case study as opposed to analysis of the effects of training on an elite squad of sports participants (Baltzopoulos and Gleeson, 2001).

Further important considerations relating to the analysis of obtained torque values concern the dependence of the developed torque on the joint position (Kannus and Beynnon, 1993; Gulch, 1994). Kannus and Beynnon (1993) reported that peak torque occurs later in the range of movement as velocity increases. At high angular velocities, therefore, it is possible that the joint can often pass the optimal position before the muscle attains maximum tension. This could lead to erroneous conclusions relating to muscle function (Baltzopoulos and Brodie, 1989; Kannus and Beynnon, 1993; Gulch, 1994). If the nature of the protocol compromises the utility and validity of the measurement then the value of isokinetic dynamometry must be questioned, whereas if the protocol accounts for the limitations known to exist then there can be a degree of confidence in the results obtained (Gleeson and Mercer, 1996). In summary, there are a considerable number of known limitations with regard to the application of isokinetic dynamometry. However these can be controlled, and if done so sufficiently, isokinetic dynamometry provides a powerful, quantitative tool from which to analyse muscle function.

2.2.2.2 Muscle Group Ratios

a) Intra-Muscle Group Ratios

The eccentric/concentric ratio of an individual muscle or muscle group is an important parameter in the assessment of muscle function. Eccentric actions have been shown to develop greater muscle tension than concentric actions (Colliander and Tesch, 1989). Anderson *et al.* (1991) reported concentric force values to be generally 90 % of force values resulting from eccentric action. Because the ratio is calculated by dividing the eccentric peak torque by the concentric peak torque, a normal value should be in excess of 1.0. These results have proven stability within both healthy subjects and in patients with anterior cruciate ligament deficiency (Dvir 1989). If the ratio is less than 1.0, then it is potentially indicative of eccentric torque deficiency, which in turn can indicate errors in control of muscle function (Bennett and Stauber, 1986; Kovalski *et al.*, 1994). Such errors in control were suspected by Bennett and Stauber (1986) to cause varying degrees of soft tissue trauma and anterior knee pain. As a consequence, they prescribed resistance training to patients who displayed a 15 % deficit in eccentric torque production of the symptomatic knee. On completion of the training, the patients had altered eccentric torque production such that it was equal to, or exceeded, the concentric values and this was accompanied by a reduction in, or loss of anterior knee pain. These findings support the importance of the intra-muscular ratio with regard to assessment of normal functioning and as a measure to be used in rehabilitation. Its efficacy however, goes beyond clinical applications. Strength assessment in sporting populations should account for eccentric/concentric ratios to ensure training is appropriate and to maintain a ratio that will not increase the risk of injury. However, more analysis is required as the findings relating to the eccentric/concentric ratios of different muscles are limited and conflicting (Kellis and Baltzopoulos, 1995) and the mechanisms by which eccentric strengthening can reduce pain have not been adequately explained (Dvir, 1991).

b) Reciprocal Muscle Group Ratios

The reciprocal muscle group ratio refers to the strength relationship that exists between opposing muscle groups that operate around a particular joint. For example, a commonly reported reciprocal ratio is the hamstrings/ quadriceps (H/Q) ratio (Kellis and Baltzopoulos, 1995), which is considered important because of the size and complexity of the knee joint. Baltzopoulos and Brodie (1989) reported the work of Campbell and Glen (1982) who suggested that the H/Q ratio is more important in the assessment of muscle function than peak torque values. Such importance is attributed to the H/Q ratio in the belief that it can be used as an indicator of susceptibility to injury (Grace *et al.*; 1984, Knapik, 1992), and as a goal for injury rehabilitation (Li *et* *al.*, 1996). The H/Q ratio has been considered to be important in relation to injuries of the knee joint itself (Grace *et al.*, 1984) as well as muscular injury, particularly those affecting the hamstring group (Yamomoto, 1988; Bennell *et al.*, 1998).

The H/Q ratio is considered to be of importance with regard to knee function because the co-activation of the hamstrings and quadriceps is related to knee stability and influences the loading of the cruciate ligaments (Kellis, 1998). Ligaments and the other passive structures of the knee joint are at risk if instability exists because either the quadriceps or hamstrings are excessively strong in comparison with each other (Baratta *et al.*, 1988).

Hamstrings are considered to be at risk of injury if extensor/flexor imbalance exists with the quadriceps being excessively strong in relation to the hamstrings (Orchard, 1997). As a consequence normal values have been reported for the H/Q ratio (Kannus, 1994; Bennell *et al.*, 1998; Clanton and Coupe, 1998) below which the risk of hamstring strain is suggested to increase. Clanton and Coupe (1998), reported that athletes were ready to return to competition following injury if the H/Q ratio was between 50-60 %. However Bennell *et al.* (1998) had found no relationship between hamstring strain and H/Q ratios of less than 60 %.

Orchard *et al.* (1997) found a significant association between hamstring muscle weakness and hamstring muscle strain injury. The best predictor of injury came from ratios derived from tests undertaken at 60° s^{-1}. This speed does not represent the speeds of sprint activity but Orchard *et al.* (1997) stated that concentric ratios are lower at slower speeds and these appear to more accurately show ratio deficits. They concluded that the risk of hamstring muscle strain was increased when the concentric H/Q ratio (at $60° s^{-1}$) was less than 0.61.

There would therefore appear to be ambiguity with regard to results relating hamstring muscle strain to the concentric H/Q ratio. This could be due to the nature of the ratio and the fact that it reflects the strength of the quadriceps and hamstrings in the same contraction mode. No functional relationship exists between the concentrically acting hamstrings and the concentrically acting quadriceps. Orchard *et al.* (1997) recognised this limitation in their study and suggested that the role of eccentric action in predicting muscle injury requires further investigation. A more functional H/Q ratio has recently been suggested (Aagaard *et al.,* 1995; Baldwin *et al.,* 1997; Aagaard *et al.,* 1998) which is calculated by dividing the force output from the eccentrically acting hamstrings by the force output from the concentrically acting quadriceps. This ratio was briefly discussed some years earlier and was labelled as the dynamic control ratio (DCR) (Dvir, 1989). It is considered to be a more functional index because it refers to the capacity of the eccentrically acting hamstrings to control the concentric quadriceps extension of the knee (Dvir, 1989). Studies by Aagaard *et al.* (1997, 1998) demonstrated significant capacity of the eccentric hamstrings for providing muscular stability about the knee joint, thus supporting the more functional nature and ecological validity of this ratio. They concluded that isokinetic evaluation of the knee joint should involve analysis of both conventional and functional (DCR) H/Q ratios.

In summary, isokinetic evaluation of the knee extensors and flexors and the establishment of the various intra- and inter- muscle ratios may help with the prescription of training and the estimation of the risk of injury. It can identify muscle imbalance that can reduce antagonist co-activation and lead to excessive loading of the passive structures of a joint such as the ligaments (Baratta *et al.*, 1988). Additionally, it may be able to estimate the risk of hamstring injury by comparing the strength of hamstrings and quadriceps (Orchard *et al.*, 1997), particularly by comparing the eccentrically acting hamstrings with the concentrically acting quadriceps (Dvir, 1989, Aagaard *et al.*, 1998).

2.3 Skeletal muscle adaptation to resistance exercise

Reviews analysing muscular adaptations to exercise (Booth and Thomason, 1991) and more specifically strength-training induced muscular changes (Jones *et al.*, 1989; Abernethy *et al.,* 1994), are available and provide a detailed account of how muscle adapts under the influence of a training stimulus. The adaptations to strength training can be classified into two main categories, a) myogenic and b) neurogenic. Myogenic adaptation concerns the ratio of force per motor unit. Neurogenic adaptation involves the number of motor units activated (Lamb, 1984).

2.3.1 Myogenic adaptations

Heavy resistance exercise enhances single-repetition strength (Hickson *et al.,* 1994). This is attributable to both neuromuscular adaptations as well as increases in the size of individual muscle fibres (Luthi *et al.*, 1986) referred to as hypertrophy. Hypertrophy is the term used to describe the enlargement of the cell and therefore exercise-induced hypertrophy is enlargement beyond that brought about by normal growth (Edgerton, 1973).

2.3.1.1 Hypertrophy

An increase in the cross-sectional area of muscle brought about by an increase in the number of myofibrils enables the production of increased force (Goldspink, 1983). Longitudinal splitting of the myofibrils occurs when they reach a certain size, reportedly because of a mismatch in the spacing of the thick and thin filament lattices. A more detailed account of how this occurs is provided by Goldspink (1983).

When resistance training results in hypertrophy of muscle it is specific, and differs from the morphological changes occurring via other modes of activity such as long-term endurance training that may result in different patterns of protein expression. For example, heavy resistance training increases the cross-sectional area of Type II fibres, but this diminishes with endurance training. Likewise, the two modes of training have differing effects on the mitochondrial volume (Dons *et al.,* 1979; Booth and Thomason, 1991). Booth and Thomason (1991) reported a number of studies showing increases in cross-sectional area and circumferences of selected muscle groups and body parts as a result of resistance training using low-frequency repetitions with loads of between 67-75 % of maximal voluntary contraction.

Protein turnover is cyclical, with protein synthesis opposing protein degradation and any imbalance between the two will cause an alteration in the size of the tissue protein pool (Sugden and Fuller, 1991). Resistance training possibly modifies the protein cycle by stimulating protein synthesis which results from an increase in messenger RNA (mRNA) synthesis (Kadi *et al.,* 1999). It appears likely that the overcompensation in protein synthesis comes from training that involves eccentric as well as concentric action. Antonio and Gonyea (1993) described how eccentric action leads to hypertrophy through a process of myofibre injury followed by repair or regeneration, resulting in an anabolic effect due to the increased protein synthesis. The damage to the muscle may cause an increase in the number of satellite cells leading to the fusion of myotubes to existing fibres causing hypertrophy. However, it has been difficult to establish exact mechanisms relating to exercise and protein turnover because of a number of methodological difficulties and because other changes occur simultaneously which leads to complications regarding interpretation (Goldspink, 1983; Sugden and Fuller, 1991).

Changes in the morphological characteristics of the muscle, induced from resistance exercise as described above, is a slow process which occurs at a rate of approximately 0.1 % per day in man and at a similar value of 0.07 % in animals (Booth and Thomason, 1991). The animal models were designed to reflect training undertaken by humans and involved mice, hamsters and cats obtaining food by moving or lifting weights. The slow rate of change makes protein turnover difficult to detect (Sugden and Fuller, 1991). However specific examples of hypertrophy have been reported in animals and man in response to a variety of training modes. One study examined the muscles of exercising rats and found a 24 - 34 % increase in the average diameter of 50 muscle fibres (Goldberg, 1975). Similarly, selective hypertrophy was also observed following 8 weeks of maximal isokinetic training (Thorstensson, 1977; Costill *et al.*, 1979,). It would appear therefore that hypertrophy is selective and dependent upon both the type of exercise and the location of the muscle, with fast twitch glycolytic fibres usually developing more than fast twitch oxidative or slow-twitch fibres (Goldspink, 1983). Abernethy *et al.* (1994) reported that hypertrophy of fast twitch muscle predominated in studies lasting between 6-10 weeks and that data from studies lasting 12 weeks was equivocal. Hypertrophy has been found in type I and type II fibres following a strength training programme in older men accompanied by an increase in actin- myosin turnover (Frontera *et al.*, 1988). Similarly, hypertrophy has been found in type II, but not type I fibres in older women (Charette *et al.* 1991). It has been suggested that hypertrophy in older individuals compensates for a loss of motor units (Aniansson *et al.*, 1992).

The best way to generate muscle hypertrophy is to undertake heavy resistance training (Antonio and Gonyea, 1993), involving high resistance and low-frequency repetitions. Such activity has been shown to increase protein synthesis by approximately 50 % and 109 % at 4 and 24 hours post-exercise respectively (MacDougall *et al.,* 1992; Chesley *et al.,* 1992). The training needs to include eccentric as well as concentric action and potential for the greatest magnitude of change lies within the type II fibres (McCall *et al.,* 1996).

2.3.1.2 Hyperplasia

Enlargement in skeletal muscle cells remains a controversial area. The controversy surrounds the fact that the changes in fibre cross-sectional area brought about by training may not account for all observed increases in muscle mass (Mikesey *et al.*, 1991; Antonio and Gonyea, 1993; McCall *et al.,* 1996). It would appear then that other mechanisms may contribute to muscle mass change, and an increase in the number of cells has been suggested as an alternative possibility. Evidence for the existence of hyperplasia largely comes from work with animals and has been derived both through exercise and stretch (Antonio and Gonyea, 1994). Gonyea *et al.* (1977) observed a 20 % increase in the number of fibres found in the skeletal muscle of cats following a strength-training programme. The exact cause of hyperplasia through training remains unknown although it is speculated that hyperplasia occurs in two ways, either through proliferation of satellite cells or through longitudinal muscle fibre splitting (Antonio and Gonyea, 1994). Muscle fibre damage may release a mitogenic substance that stimulates satellite cells. White and Esser (1989) explained how activating satellite cells can lead to the addition of new myonuclei to fibres and if the stimulus is intense enough can lead to muscle fibre hyperplasia. Newly innervated fibres could become functional and respond to further training. White and Esser (1989) stated clearly that skeletal muscle possesses the appropriate mechanisms for both hypertrophy and hyperplasia.

Alternatively, internal stress could cause fibre-splitting resulting in the creation of daughter fibres (Mikesey *et al.,* 1991), although this suggestion is not as well supported as the contribution of satellite cell proliferation (Antonio and Gonyea, 1994). The speculation is that muscle fibres enlarge to the point where they become mechanically or metabolically compromised. When this point arises the fibre splits into smaller fibres that are thus more efficient. Fibre-splitting was examined by Antonio and Gonyea (1994) by using progressive stretch overload on the anterior lattisimus dorsi of the Quail. After 28 days of stretch overload, the Quail demonstrated a 30 % increase in fibre number with 5.3 % of fibres exhibiting split profiles. These results differed from those obtained by the use of chronic stretch, which was reported to have induced fibre hyperplasia prior to hypertrophy. Progressive stretching appears to have separated hypertrophy and hyperplasia, with splitting occurring after enough time has passed to allow the fibres to reach a critical size. Fibre splitting was less evident after 16 days suggesting that both stimulus and time influence longitudinal fibre splitting.

Overcoming mechanical or metabolic limitations would fit with earlier studies that suggested that hyperplasia may be associated with activities requiring fast movements. It was therefore proposed that it occurred to prevent muscles becoming too bulky which could result in a loss of speed of movement (Gonyea *et al.,* 1978). As a consequence, hyperplasia is unlikely to occur following isometric exercise because rapid movement is not required (Gonyea *et al.*, 1986). Whether this is a contributor to muscle enlargement in humans continues to be widely debated and the evidence appears to be limited (McCall *et al.*, 1996). Evidence in humans has been derived from studies where the mean fibre area in biopsies of elite bodybuilders is no greater than normally trained individuals, despite significantly greater girth of the limb (Mikesey *et al.*, 1991). However it should be noted that this could be a result of genetic endowment as well as being a training development.

Saltin and Gollnick (1983) further outlined a number of arguments against the efficacy of creating additional fibres. They believed it could interfere with the architecture of the muscle, affecting the insertions and origins that are essential if the fibres are to be effective. Additionally, problems would exist in relation to incorporation into motor units and ultimately the capacity for neuro-muscular co-ordination. Abernethy *et al.* (1994) concluded their review of hyperplasia by stating that hyperplasia may occur under certain, non-specified conditions, but its effect on muscle cross-sectional area appears to be small. A study by McCall *et al.* (1996) investigated the effects of intensive resistance training on fibre hypertrophy and hyperplasia in twelve recreationally trained men. Like the studies reported earlier, they found little correlation between the magnitude of fibre hypertrophy and the overall muscle cross-sectional area. They concluded that this could be due to methodological and procedural limitations but cautioned against ruling out the possibility of hyperplasia, particularly because of the lack of correlation which existed between mean fibre area and muscle cross-sectional area. The research also highlighted individual differences in response to the training stimulus with regard to the magnitude of type II fibre hypertrophy. A lack of hypertrophy in such fibres in some individuals may suggest hyperplasia as an additional determinant of the overall enlargement in the muscle.

2.3.2 Neurogenic adaptation

Not all strength gain is brought about by gross structural changes in muscles. Significant improvements can occur by virtue of nervous system adaptations (Moritani, 1980). The increase in muscle size that accompanies regular strength training is not proportionately as great as the increase in the ability to produce force (Dons *et al.*, 1979). It has been found that isokinetic force production of the knee extensors increased by 17.6 % in the first half of a training period, yet it was only in the second half of the training period when the cross-sectional area of the muscle was found to have increased (Luthi *et al.*, 1986). One reason why strength increases occur in greater proportion than muscle growth is the neurogenic adaptation whereby a learning affect occurs and previously dormant fibres become activated. Within an act of strength, activation of the involved muscle mass is of great importance and so too is the activation of the synergists and the inhibition of antagonist (Sale, 1987). Sale (1987) has described how co-ordination of the synergists and antagonists is developed through training along with the activation of the motor units in the prime mover. Additionally, the period during which full activation can be maintained can increase. Cross-training effects have also been noted where strength increases in an untrained limb, following training of the contra-lateral limb. This is said to further emphasise the contribution made from an increase in neural activation leading to central adaptation (Sale, 1987). Concentric isokinetic training was recently shown to increase strength in the trained leg by 17.7 % with an accompanying increase in strength in the untrained leg of 9.3 % (Housh *et al.*, 1996). Jones and Rutherford (1989) report that a number of contradictory studies exist in relation to cross-over studies and that care must be taken to note the activity of the untrained leg during training. The untrained leg may be unknowingly contracted and subjected to a training stimulus.

Neural activation is an essential element in maximal force production (Hakkinen and Komi, 1986). The complex inter-relationship between the nervous and muscular system provides an explanation for the importance of specificity (Katch and McArdle, 1983) and illustrates the need for very careful training programme design, with some activities benefiting from specific training in the initial weeks and more general heavy resistance work latterly to develop hypertrophy (Sale, 1987). The significance of neurogenic adaptation in the early weeks of training suggest that much of the strength training literature is biased (Sale, 1987) because of the short duration of most programmes used and the use of previously untrained subjects.

2.4 Maximal Intensity Exercise

Maximal intensity exercise occurring at or above the maximal oxygen uptake ($\dot{V}O_2$ max) requires an immediate and rapid supply of energy (Troup *et al.*, 1986). This energy is supplied almost entirely from high-energy phosphates, adenosine triphosphate (ATP) and phosphocreatine (PCr) (McArdle *et al.*, 1996) and anaerobic glycolysis.

The limited concentration of ATP in the muscle requires continual resynthesis from adenosine diphosphate (ADP) and inorganic phosphate (Pi). The regeneration can occur when the phosphate from PCr is transferred to ADP via the enzyme creatine kinase (Thorstennson, 1976; Sjodin, 1992) or when two moles of ADP are converted to one mole of ATP and one mole of adenosine monophosphate (AMP) via adenylate kinase (Westing *et al.,* 1988; Sjodin, 1992). The latter occurs during very intense exercise such as maximal sprinting and requires the continual removal of AMP via deamination and breakdown to inosine monophosphate (IMP) and ammonia (Terjung *et al.*, 1986; Urhousen and Kindermann, 1992). The deamination of AMP to IMP occurs in both fibre types in human muscle, although fast twitch fibres have higher IMP values at fatigue (Sahlin and Broberg, 1990) and are known to have higher AMP deaminase activity than slow twitch fibres (Dudley *et al.*, 1983; Broberg and Sahlin, 1989).

PCr is a valuable buffer for ATP regeneration (Sjodin, 1992), but for high intensity exercise lasting longer than 5-10 seconds the energy to phosphorylate ADP must come from anaerobic glycolysis. The sum of the alactic and lactic capacities provides the anaerobic capacity, the maximum amount of ATP resynthesised via anaerobic metabolism during maximal activity (Green and Dawson, 1993). The lactic and alactic constituents are difficult to separate when measuring anaerobic capacity because glycolysis occurs within exercise lasting less than 10 seconds (Boobis *et al.*, 1983; Hultman and Sjoholm, 1986;Vandewalle *et al.,* 1987) and the two constituents act simultaneously a few seconds after exercise has commenced (Margaria, 1966).

Examinations of maximal intensity exercise have explored the effects of high intensity activity such as sprint exercise on skeletal muscle responses (Westra *et al.,* 1985; Tabata *et al.*, 1990; Voight and Klausen, 1990) as well as the specific effects of strength training on muscular performance in high intensity activity (Hickson *et al.*, 1980; Bell *et al.*, 1989; Mannion *et al.*, 1992; and Delecluse *et al.*, 1995).

2.4.1.Peak Power

High intensity training should complement endurance training. This is because peak power improvements require faster muscle contraction speeds to fully recruit fibres and to improve motor recruitment (Tabata *et al.,* 1990). High intensity training has been shown to improve performance in maximal anaerobic activity in animals, with a 24 % increase in sprint speed after 6 weeks of such conditioning (Westra *et al.*, 1985), and an increase in glycolytic capacity of type I and II fibres as well as the oxidative capacity of all fibre types in rats (Troup *et al.,* 1990). Proposed factors influencing such improvement include ability to mobilise a greater proportion of maximal anaerobic power and a greater contribution of aerobic power to total energy production (Westra *et al.,* 1985). Likewise in human subjects, performance following high intensity training has been shown to improve due to alterations in the substrate, metabolic and phosphagen profile of skeletal muscle (Abernethy *et al.*, 1990). It would appear that the training improvements are specific and the training regime needs to be carefully designed to be specific to the performance required.

Peak power is dependent upon force and velocity, therefore an increase in force and/or velocity should lead to an increase in peak power. A positive relationship between knee and hip torque outputs and peak power has been shown in male physical education students (Smith, 1987). Isokinetic training lasting 16 weeks has also been shown to significantly improve both peak power output and peak pedal velocity during cycling (Mannion *et al.,* 1992). The latter occurred despite no significant change in maximal voluntary contraction, possibly because the training load was not at a high enough percentage of the maximum to increase the MVC. The authors hypothesised that such improvements demonstrated that performance benefits could be achieved in other tasks if the trained muscle is employed at similar work intensities. A previous study had shown peak isokinetic torque improvements following seven weeks training due to enhanced neurological control of muscle fibre recruitment (Lesmes *et al.,* 1978). This study reported that significant adaptations occurred which increased the ability to generate power during short-term work. These studies were conducted at a low percentage of MVC and for a short duration respectively.

Delecluse *et al.* (1995) involved a group in strength training for nine weeks employing a 15, 10 or 6-repetition maximum (RM) depending upon the exercise and the period of training. In some exercises the RM reduced further to 5, 4 and 3 as the training progressed. This training resulted in significant improvements in the 10 RM values of 5 selected exercises and in selected activities such as the vertical jump and broad jump. The subjects were also tested for changes in sprint running speed but changes were limited and no gains in performance were achieved. They concluded that sprinting is a complex skill and that the results did not exclude the fact that a heavy weights programme could improve sprint performance. However, other studies have also reported no change in power output following a strength-training programme. Mannion *et al.* (1992) reported a study (Rutherford *et al.,* 1989) that showed no significant change in power output recorded on a cycle ergometer following 12 weeks of isotonic strength training.

2.4.2 Mean power

A high level of anaerobic capacity is essential to delay the onset of fatigue that occurs when biochemical and metabolic changes limit the contraction and relaxation of the working muscle. Considerable effort has been placed in evaluating the anaerobic system in humans (Green and Dawson, 1992) although it is less prevalent when compared with studies of aerobic capacity which dominated prior to 1984 (Tharp *et al.,* 1984; Jakeman *et al.,* 1992). Greater understanding is required (Nevill, 1992) despite significant advances which have enabled research to develop. These have included the introduction of isokinetic dynamometry, the non-motorised treadmill and the use of the Wingate maximal cycle ergometer test, as well as tests of optimal power output and the needle biopsy technique. Many of the tests used to evaluate anaerobic capacity use *mean power*, the average power sustained during the test, as an indicator of anaerobic capacity.

Few studies have been conducted exploring a relationship between mean power output, strength and strength training. However studies have analysed the effects of sprint training on anaerobic capacity. One study (Nevill *et al.,*1989) had recreationally active subjects undertake an 8 week training programme of sprint work. The programme resulted in improvements in peak power output of 12 % and in mean power output of 6 %. Analysis of muscle biopsy samples showed an increased contribution from anaerobic glycolysis from 51.7 % - 56.4 % pre- and post- training. Despite this increase in contribution and an increase in muscle lactate values, there was very little change in muscle pH. The conclusion was therefore, that sprint training led to increased anaerobic glycolysis and was accompanied by an increased buffering capacity. One hypothesis could be that an increase in strength could likewise lead to an enhanced buffering capacity.

This particular hypothesis was examined when the effects of isokinetic training of the knee extensors was investigated for its effect on skeletal muscle buffering (Mannion *et al.,* 1994). Subjects followed a 16-week training programme consisting of three sessions per week. Following the training, experimental subjects were able to perform significantly more total work during the high intensity cycling, but no change occurred in muscle buffer value. The study concluded that isokinetic training led to more work during high intensity cycling, but the adaptations were unlikely to include an increase in buffering. The precise adaptations remain unknown. Similarly, the effect of strength training on force production and subsequent power output, particularly mean power remains equivocal. A need for further research exists to better understand how force production, muscle group ratios and strength changes affect anaerobic power output.

2.5 Gender Comparisons

Gender comparisons of strength performance have been examined in considerable detail (Kraemer *et al.*, 2001). Similarly, research into performance in maximal activity, female responses and comparisons with men is on-going and has developed along with the introduction of new equipment and protocols (Winter *et al.*, 1991). However, despite the performance comparisons and the widespread use of strength training, researchers have only recently focused attention on women with regard to their acute and chronic responses to such training (Holloway and Baechle, 1990). As a consequence, understanding regarding responses and adaptations to strength training in women is still developing. Likewise, few studies have compared different styles of resistance training programmes to determine male and female adaptational differences (Kraemer *et al.*, 2001)

2.5.1 Strength Comparisons

Women on average have smaller bodies, less absolute muscle mass, smaller individual muscle fibres and display approximately two-thirds of the absolute overall strength and power when compared with men (Holloway and Baechle, 1990). The differences in strength and power are a reflection of the difference in physical size and body composition (O'Brien 1985; Holloway and Baechle, 1990; Castro *et al.*, 1995), the hormonal milieu (Shephard, 2000) and socio-cultural influences (Wilmore, 1975; Winter *et al.*, 1991; Shephard 2000). It is generally accepted that the strength of a muscle is directly related to its cross-sectional area (Blade *et al.,* 1992), consequently physical size and body composition will influence force production. Likewise anabolic hormonal differences may limit training increases in muscle size, and socio-cultural influences may affect initial fitness, which in turn may influence training tolerance and the scope for muscle adaptation. Gender differences in strength have been found to be more marked in the upper body (O'Brien, 1985), values of 55 % and 72 % of male strength being reported for upper-body and lower-body respectively (Kraemer *et al.*, 2001). This has been hypothesised to be due to dissimilarity of use or due to females having a smaller proportion of total lean body mass in the upper extremity (Castro *et al.*, 1995).

Recent studies investigating strength training adaptations and comparing responses in men and women have predominantly been concerned with the effects of age (Ivey *et al.*, 2000; Ivey *et al.*, 2000b; Lemmer *et al.*, 2000; Roth *et al.*, 2001) as well as analysing the effect of detraining, (Lemmer *et al.*, 2000) muscle volume responses (Roth *et al.*, 2001), hypertrophic response (Ivey *et al.*, 2000) and muscle quality (Ivey *et al.*, 2000b). In all studies there was a significant increase in strength in both men and women with no significant differences between gender. Differences between genders were however, found in muscle volume response (Ivey *et al.*, 2000), with men displaying a greater absolute volume increase than women following a 9- week training intervention. A later study (Roth *et al.*, 2001) employed a six-month intervention and found that males and females both increased thigh muscle volume with no significant difference between sexes. It suggested that muscle volume was preferable to cross-sectional area for examining muscle mass responses to strength training. Muscle volume is a better representative measure of muscle hypertrophy because the cross-sectional area represents a single-slice and is therefore not representative of other changes that may occur through the length of the muscle (Tracy *et al.*, 1999). The time-course for muscle adaptations of the lower extremity in men and women had previously been investigated in an 8-week training programme (Staron *et al.*, 1994). It was found that adaptations occurred gradually and that they were similar for males and females. Other investigations by Staron *et al.* (1990; 1991) have shown females to respond similarly to males with regard to muscle fibre hypertrophy and that adaptations occur rapidly in both previously trained and untrained females.

With average absolute strength differences between males and females being unequivocally accepted, and with studies showing similar proportional adaptations to training, recent attention has focused on analysis of muscle quality. Muscle quality has been defined as the force production per unit of muscle mass (Tracy *et al.*, 1999; Ivey *et al.*, 2000). Prior to this, a number of studies had analysed muscle performance in relation to strength per unit cross-sectional area (Maughan *et al.*, 1983; Alway *et al.*, 1990; Castro *et al.*, 1995), which indeed has been one of the main ways of analysing gender differences (McArdle *et al.*, 1996). In a study by Maughan *et al.* (1983) the ratio of knee extensor strength to cross-sectional area was greater in the males than the females, but not significantly so. In both male and female groups, a significant positive correlation existed between muscle strength and lean body mass. Similar results were observed with analysis of the elbow flexors, with no gender differences found in strength per-unit cross-sectional area in physically active subjects (Alway *et al.*, 1990). Castro *et al.* (1995) reported a number of studies that compared the effect of training status on the strength to muscle cross-sectional area. The majority of investigations found no difference in strength per unit cross-sectional area, although some studies found a difference between elite athletes, who had undertaken a long and intensive resistance training programme over several years, when compared with untrained subjects. The equivocal nature of these studies led Castro *et al.* (1995) to examine isometric torque per-unit cross-sectional area between trained and untrained men and women. This allowed for analysis of training status and gender difference. The results demonstrated a significant difference between the trained and untrained individuals, thus whether a difference exists or not continues to be debated. Castro *et al.* (1995) speculated that the results may be due to neuromuscular adaptations, but also correctly highlight the fact that the results of this and other studies could reflect a self-selective process of those with superior strength per unit cross-sectional area into physical activity and sport. This demonstrates a need for training intervention studies that do not simply rely on a comparison of previously trained and untrained subjects. The study of Castro and colleagues also reported no significant difference between men and women suggesting that strength per-unit cross-sectional area is not gender dependent. This therefore suggests that the absolute strength differences that exist between men and women are predominantly due to size. When strength is divided per-unit of cross-sectional area, gender differences are removed. It was therefore proposed that muscle quality is equal between men and women (Castro *et al.* 1995).

Other studies that have investigated strength per unit of muscle volume rather than cross-sectional area have concurred with this observation. Tracy *et al.* (1999) compared muscle quality in older men and women. Both groups increased strength and muscle volume. The percentage changes were similar across the groups and there was no significant difference between genders for muscle quality expressed as 1-RM per unit of muscle volume. A later study by the same group (Ivey *et al.*, 2000b) compared the influence of age and gender on the muscle quality response to strength training. Strength in the form of one repetition maximum (RM), muscle volume and muscle quality all increased with training but the muscle quality was significantly greater in young women when compared to older women and young and older men, respectively. In both these studies the muscle quality increased, reflecting a greater proportional increase in strength than muscle volume. The studies proposed that factors other than muscle mass contribute to strength gains, the latter study concluding that these factors may account for a higher portion of the strength gains in young women.

2.5.2 Power Comparisons

Much like the strength comparisons, gender differences have been reported for absolute power output (Maud and Shultz, 1989; Winter *et al.*, 1991; Mayhew *et al.*, 2001). These differences have again been considered to be as a result of body size and dynamic strength (Mayhew *et al.*, 2001), or attributed to mechanical or physiological factors and socio-cultural influences (Winter *et al.*, 1991). Again as with strength, it has been common to compare the quality of the muscle power output between men and women by expressing performance as a ratio to a body dimension such as body mass (Vandewalle *et al.,* 1985;) or leg volume (Winter *et al.*, 1991). When this has been done the differences in power output have been removed (Maud and Shultz, 1989) suggesting that the quality of male and female muscle is the same and that the absolute power output differences are ultimately attributable to size.

2.5.3 Normalisation for body size

To compare male and female performances in strength and power tasks it has been common to evaluate muscle quality (Tracy *et al.*, 1999; Ivey *et al.*2000), by dividing the force or power produced, by an appropriate body size variable. By doing so it has been assumed that differences in strength or power that are due to the individual's size will have been removed (Nevill *et al.*, 1992; Winter, 1992). This however, is often not the case and the problems underlying such an assumption have been documented in great detail in recent years (Nevill *et al.*, 1992; Winter, 1992; Rogers *et al.*, 1995; Winter and Nevill, 2001). The ratio-scale has the potential to distort data unless the data conforms such that the coefficient of variation of χ divided by the coefficient of variation of γ equals Pearsons's product moment correlation coefficient i.e. $\upsilon\chi/\upsilon\gamma = r_{xy}$ (Winter, 1992). As an example Winter (1992) highlighted his earlier study (Winter *et* *al.*, 1991) that examined the power output measured on a cycle ergometer and lean leg volume in both men and women. Absolute power output (W) was greater in the men, but when this was adjusted for muscle quality by dividing power by lean leg volume, the gender difference was removed. Further analysis of the regression lines suggested that the men and women were in fact different and that the use of a simple ratio scale was wrong and could lead to potentially incorrect conclusions. Further analysis of those results demonstrated that differences in maximal exercise performance exist in males and females and they are independent of size. Similar results were observed by Eston *et al.* (1997). Despite these findings and the widespread reporting of the problems associated with ratio scales, many studies continue to apply inappropriate scaling methods. For example, Tracy *et al*, (1999) and Ivey *et al.* (2000) both used simple ratio scales. As a consequence, male and female performance may not be being compared appropriately and analysis of the effects of a strength-training programme may lead to spurious conclusions. A recent review of strength testing papers (Jaric, 2002) reported that the majority of papers presented either non-normalised data or data normalised using inappropriate methods. Jaric (2002) called for standardisation in the use of scaling to allow for accurate comparison of results. Further studies of strength training are required using appropriate and accurate techniques to ensure that we fully understand the responses and adaptations to training in both males and females. When assessing strength recorded as force, Jaric (2002) recommended the use of the allometric model with the body size parameter raised to the power 0.67.

2.5.4 Summary

The results from the studies reviewed above are somewhat equivocal. The results are on occasion contradictory and based on data that has been potentially inappropriately normalised or analysed. As a consequence, further investigations into the effects of strength training on strength and muscle volume are required. It is also clear that when analysing and comparing muscle quality between males and females and the effects of a period of training, there are a number of factors that need to be considered. These factors include: the previous training status of the subjects, the nature of the training programme, the use of appropriate control groups, and comparisons of muscle quality using appropriate normalisation techniques.

CHAPTER 3

ISOKINETIC KNEE EXTENSOR AND FLEXOR STRENGTH, INTRA AND INTER MUSCLE GROUP RATIOS AND LEG VOLUME IN RUGBY LEAGUE PLAYERS AND RESISTANCE TRAINED SPORT STUDENTS.*

*Content from this chapter was presented in a paper by Baldwin, G., Barrow, N. and Cox, D. (1995) Intra and inter muscular strength ratios of quadriceps and hamstrings in professional rugby league, at the International Congress, Images of Sport in the World, German Sport University, Cologne. Nov.1-5th.

3.1 Abstract

Objectives

The purpose of this study was to document and describe data relating to the knee extensors and flexors, focusing in particular on professional rugby league players. A further consideration was to compare professional rugby league players with resistance trained sports students.

Methods

Twenty male professional rugby league players age 24.2 ± 5.9 years (mean ± SD), stature 180.2 ± 7.4cm and mass 90.6 ± 16 .32 kg were assessed for force production and muscle balance during knee extension and flexion in both concentric and eccentric mode. Ten strength trained sport students age 21.3 ± 1.4 years, stature 179.21 ± 5.4 cm and mass 79.2 ± 6.0 kg were analysed for comparative purposes. Subjects were tested using an isokinetic dynamometer (KIN-Com 125E Plus Chattanooga, Tennessee, USA) Anthropometric determination of leg volume was undertaken according to the methodology of Jones and Pearson (1969).

Results

Rugby league players showed no significant bilateral deviation ($P > 0.05$) for either force values or ratios. Significant differences were found between rugby league players and sport students for right leg peak concentric extension ($F_{2, 28} = 9.73$, $P = 0.01$), peak concentric flexion ($F_{2, 28} = 27.813$, $P = 0.00$) and peak eccentric flexion ($F_{2, 28} = 13.124$, $P = 0.00$). Difference in mean values also existed for concentric flexion ($F_{2, 28} = 13.251$, $P = 0.00$) and eccentric flexion ($F_{2, 28} = 16.524$, $P = 0.00$). Thus the sport students were significantly stronger in the right leg than the rugby league players. There were no significant differences in intra muscle eccentric/concentric ratios ($P >$

0.05) between rugby league players and sports students but there was a difference in the mean H/Q ratio ($F_{2, 28} = 6.224$, $P = 0.01$). Force values and H/Q ratios were considered in relation to anthropometric characteristics of the knee extensors and flexors. Rugby league players had a total leg volume for the right leg of 11.99 ± 1.96 l and a lean thigh volume of 6.08 ± 1.32 l. Sport students recorded values of 11.94 ± 2.02 l and 5.48 ± 1.31 l for leg volume and lean thigh volume respectively. No significant difference existed between the groups ($P > 0.05$). Moderate to high correlations were found between leg volume and mean concentric and eccentric flexion (r =0.62 and $r = 0.85$; $P < 0.05$), thigh volume and mean concentric and eccentric flexion ($r = 0.64$ and $r = 0.86$; $P < 0.05$) and between lean thigh volume and mean concentric and eccentric flexion ($r = 0.55$ and $r = 0.59$; $P < 0.05$). Moderate to high correlations were found between leg volume, thigh volume and lean thigh volume and all H/Q Strength ratios. Leg volume correlated with Peak H/Q ratio and mean H/Q ratio with values of $r = 0.56$ and $r = 0.77$ ($P < 0.05$) respectively. Thigh volume correlated with values of $r = 0.57$ and $r = 0.79$ ($P < 0.05$) and lean thigh correlated with mean H/Q ratio of $r = 0.68$ ($P < 0.05$).

Conclusion

The demands of rugby league require monitoring of muscle function and the establishment of norms to prescribe conditioning and to monitor injury. Rugby league players demonstrated H/Q ratios and E/C ratios within previously reported normal ranges. Both peak and mean values are important with regard to analysis of muscle function. Moderate to high correlations existed between isokinetic force and lean leg volume and H/Q strength ratios and lean leg volume. Studies in the future should further investigate the use of leg volume as a means of adjusting strength values for comparison between groups. Similarly muscle group ratios need further analysis to identify efficacy and application.

3.2 INTRODUCTION

Investigations into anaerobic energy production are in their relative infancy, although a considerable number of studies have evaluated the role of anaerobic pathways on performance since the early 1980s (Thorp *et al.*, 1984; Jakeman *et al.*, 1992; Nevill *et al.*, 1992). This has coincided with a desire to further understand the physiological demands of sprinting and multiple sprint sports (Jakeman *et al.*, 1992) in which anaerobic energy production and the reproducibility of maximal effort is essential for successful performance. The sports of Association Football, Rugby League and Rugby Union place great emphasis on anaerobic metabolism (Yamanaka *et al.*, 1988; McLean, 1992; Brewer and Davis, 1995). Although low intensity activity predominates, often in excess of 84 % of the game, the nature of the high-intensity efforts is such that the overall intensity of the games is high (Brewer and Davis, 1995). In rugby for example, the high intensity efforts include sprinting, high force generation and a high degree of physical contact (McLean, 1992; Brewer and Davis, 1995). As a result, training revolves around anaerobic activity with great emphasis also placed upon strength and power conditioning. Much of this emphasis focuses on the legs, specifically the extensors and flexors that are involved in sprint activity, rapid execution of typical movements (Kollath *et al.,* 1993) and lower body impacts. Indeed quadriceps and hamstring muscle groups are two of the most commonly injured muscle groups in multiple sprint sports (Brady *et al.*, 1993)

Assessment of lower extremity strength includes reporting force values of individual muscles or muscle groups and more specifically the hamstrings/quadriceps (H/Q) strength ratio. Such evaluation has been undertaken in a range of sports including tennis (Ellenbecker and Roetert, 1995), ice hockey (Posch *et al.*, 1989) and sailing

(Aagaard *et al.*, 1997) as well as various codes of football such as Australian Rules (Orchard *et al.*, 1997; Bennell *et al.*, 1998) American Football (Grace *et al.*, 1984) and Association Football (Brady *et al.,* 1993; Gur *et al.*, 1999). Studies have aimed to provide population-specific characteristics (Ellenbecker and Roetert, 1995), to establish a link with injury (Grace *et al.*, 1984; Posch *et al.*, 1989; Bennell *et al.,* 1998;) and to explore relationships with other performance variables (Anderson *et al.*, 1991).

The H/Q strength ratio is affected by age, sex and type of physical activity (Baltzopoulos and Brodie, 1989). Consequently, although an optimal ratio of between 50-80 % has been suggested (Kannus, 1994), a wide range of values have been reported from differing sub-populations. For example, association footballers have ratios in the range of 0.60-0.63 and 0.75-0.77 at 30^{o} s^{-1} and 60^{o} s^{-1} respectively (Oberg *et al.*, 1986; Brady *et al.*, 1993). These compare with values for untrained males of 0.44 and 0.56 at 30^{o} s^{-1} and 60^{o} s^{-1} respectively (Goslin *et al.*, 1979). This suggests that the nature of association football may lead to the development of differing H/Q strength ratios when compared with an untrained male population.

Such differences are important and H/Q strength ratios should be monitored in multiple sprint sports. One reason for this is because if either the quadriceps or hamstrings are too strong in relation to one another, then the passive structures of the knee such as the meniscus and intra-articular ligaments may be abnormally loaded and stressed (Chan and Maffuli, 1996).

It is not only the H/Q strength ratio that can be assessed and used for the identification of normal functioning within the extensors and flexors. The eccentric/concentric (E/C) ratio of a specific muscle group i.e. an intra-muscle ratio has also been used (Trudelle-Jackson *et al.*, 1989; Fairbanks, 1994). The E/C ratio can be used as an indicator of an individual's susceptibility to anterior knee pain (Bennett and Stauber, 1996). For example, a deficit in eccentric force production might arise from a lack of motor control. Therefore, an identified imbalance can be quickly treated to overcome deficiencies in force production (Bennett and Stauber, 1986).

Ratios based upon peak force values are the most commonly used, although ratios derived from average force values have been reported (Dvir and David, 1995). Because these share a high correlation it has been suggested that the use of either is appropriate (Dvir *et al.*, 1989; Tis and Perrin, 1994). However, Dvir and David (1995) have indicated the importance of presenting data in a uniform manner as well as highlighting the fact that two highly correlated parameters may differ proportionately in differing conditions. They concluded that normative strength data should be presented using peak force values, but that inter or intra-muscle performance may be better presented by average force values.

From the functional requirements of multiple sprint sports, and the involvement of the knee extensors and flexors in such sports, accurate assessment of muscle performance is necessary. This may ultimately help with the prescription of training and therefore the improvement or maintenance of performance as well as minimising the risk of injury. In multiple sprint sports the development and monitoring of normative strength data along with examination of inter and intra-muscle performance is required. As a consequence, both peak and mean forces need to be initially reported to establish population- specific characteristics and to optimise muscle performance assessment. Such values should also be related to anatomical and/or anthropometric characteristics of the involved muscle groups. Therefore the purpose of this study is to document and describe data relating to the knee extensors and flexors in professional rugby league players. A further consideration of the study is to compare these values with young trained male subjects.

3. 3 METHOD

3.3.1 Participants

Twenty male professional rugby league players, age 24.2 ± 5.9 years (mean ± SD), stature 180.2 ± 7.4cm, mass 90.6 ± 16.32 kg, were assessed for force production and muscle balance during knee extension and flexion in both concentric and eccentric mode. All subjects were full time professionals from two 'super league' clubs who were undergoing pre-season screening in a number of physiological parameters in the laboratory. Each player had completed and signed an informed consent form prior to participation in this study. All players assessed were free from injury and were involved in the resistance training programme prescribed by the clubs. Ten strength trained sports students age 21.3 ± 1.4 years, stature 179.5 ± 5.4 cm and mass 79.21 ± 6.0 kg were tested and analysed for comparative purposes. The sports students were all injury free and were experienced weight trainers.

3.3.2 Experimental Protocol

An isokinetic dynamometer (Kinetic Communicator 125E Plus, Chattanooga, Tennessee, USA) was used for testing. Peak and mean forces during maximal voluntary eccentric and concentric contraction were measured during flexion and extension of the right and left leg at an angular velocity of 30° s^{-1}. Subjects performed the tests in the seated position, with the seat angle horizontal (0°) and the backrest at an angle of 105°. The centre of rotation of the knee joint was aligned with the rotational axis of the dynamometer lever arm. The resistance pad was secured to the lower leg proximal to the ankle joint allowing for full dorsiflexion. Restraining velcro straps were placed around the chest, pelvis and the distal thigh of the tested leg. During the test the inactive leg remained untethered and arms were folded across the chest.

Gravity correction factors based on leg weight at full extension were calculated according to manufacturers guidelines prior to testing each leg. The acceleration/deceleration rate of the dynamometer was set to medium and the activation force for concentric and eccentric efforts was set to 50 N for all subjects. Muscle groups were tested through a joint arc of 10° to 90°, with knee flexion being 90° and full extension set at 0°. Testing order of the left and right leg and extensors and flexors were assigned randomly. A rest period of 10 - 15 s separated concentric from eccentric measurements of each muscle group. Each subject familiarised themselves with the action of the dynamometer and performed 3-5 reciprocal, sub-maximal warm ups. Six maximal voluntary contractions were then performed, from which three reproducible trials were averaged by the computer system to provide peak force values. Standardised verbal motivation was given to each subject to encourage maximal effort (McNair *et al.*, 1996). Values of force, in newtons, are reported, as the force transducers in the resistance pad make direct measurements of force exerted by the subject.

Calibration was performed regularly according to manufacturers instructions. Additionally, calibration was undertaken on a regular basis by the manufacturers engineers. Known weights were used to exert force on the lever arm and angular position and velocity of the lever arm were also calibrated. Biological control was also utilised with experienced users of the isokinetic dynamometer undergoing regular testing and assessment.

3.3.3 Anthropometric Determination of Leg Volume.

This was undertaken using the methodology of Jones and Pearson (1969). Subjects stood erect with feet slightly apart. Circumference measurements were taken using an anthropometric tape (Bodycare Products, Southam, England, UK) at seven sites on the leg. The seven sites were; the gluteal furrow, one third of the subischial height up from the tibial-femoral space, the minimum circumference above and below the knee, the maximum circumference around the knee, the maximum calf circumference and the minimum circumference of the ankle. The foot was measured for length. Additionally four skin-fold thickness were measured using Harpenden skin fold calipers (Bodycare Products, Southam, England, UK). These were measured at anterior and posterior thigh at the height of the one-third subischial height and at the medial and lateral calf at the height of maximum circumference. Values of total leg volume, lean leg volume and total and lean thigh volume were recorded.

3.3.4 Statistical Analysis

From the force values obtained, the H/Q concentric strength ratio was calculated. The E/C ratio for both the extensors and flexors was also calculated. Bilateral differences were analysed for the rugby league players for all force parameters and ratios by the use of independent *t*- tests. Differences between groups for all right leg variables were analysed by a one way analysis of variance (ANOVA). Although the focus was on rugby league players as a whole, for the purpose of analysing differences between force values and ratios, rugby league players were separated by club. Where a significant F ratio was achieved a *post hoc* Tukey test was used to ascertain where the difference occurred. Relationships between leg volume and force production were analysed using the Pearson Product Moment Correlation. Statistical analysis was undertaken using version 10 of the Statistical Package for Social Sciences

3.4 RESULTS

The means and standard deviations of the force values for knee extensors and flexors are presented in Table 1.

Table 1. Concentric and eccentric peak and mean force values for knee extensors and flexors. Values are in Newtons and are means (± SD)

		Concentric				Eccentric			
Group	Leg	Extensors		Flexors		Extensors		Flexors	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
PEAK									
rugby league 1	right	795.5	124.2	425.5	72.8	892.3	267.7	489.3	147.7
	left	775.4	131.7	492.5	118.5	875.5	183.3	533.3	122.9
rugby league 2	right	893.6	163.4	631.2	161.6	973.3	183.6	630.0	132.1
	left	862.6	165.5	616.4	128.7	934.75	187.9	623.5	147.7
sport students	right	1188.6	242.9	857.9	150.8	1284.0	370.6	848.1	197.4
MEAN									
rugby league 1	right	554.8	103.3	332.7	80.1	584.8	238.0	360.9	67.5
	left	519.6	116.5	361.4	63.9	610.6	146.6	423.7	86.1
rugby league 2	right	524.2	71.5	429.3	106.4	615.4	108.9	494.7	113.2
	left	571.9	105.9	453.1	96.5	618.3	136.8	509.6	119.0
sport students	right	619.6	114.2	577.6	34.2	840.0	204.5	674.0	174.8

As a group rugby league players showed no significant difference between right and left legs (*P* > *0.05*) for any of the values and no force value had a greater difference than 10 % between sides. A significant difference was demonstrated between force values for resistance trained sport students and rugby league players for right leg peak concentric extension. ($F_{2,28} = 9.73$, $P = 0.01$), peak concentric flexion ($F_{2,28} = 27.813$, $P = 0.00$) and peak eccentric flexion ($F_{2,28} = 13.124$, $P = 0.00$). Differences in right leg mean values were also found for concentric flexion ($F_{2,28} = 13.251$, $P = 0.00$) and eccentric flexion ($F_{2,28} = 16.542$, $P = 0.00$). Thus the strength trained students were significantly stronger in the right leg than the rugby league players. There was however, no significant difference ($P > 0.05$) between the players from the different clubs with the exception of right leg peak concentric flexion ($F_{2,28} = 27.813$, $P = 0.04$). Peak and mean force values correlated highly ($r = 0.8$-0.99, $P < 0.01$)

The mean and standard deviations for the peak and mean H/Q strength ratio and the E/C ratio for both extensors and flexors are presented in Table 2.

Table 2. Peak and Mean H/Q strength ratios and E/C ratios. Values are means (± SD)

Group	Leg	H/Q strength Ratio		E/C ratio			
				Extensors		Flexors	
		Mean	SD	Mean	SD	Mean	SD
PEAK							
Rugby League 1	Right	0.54	0.1	1.12	0.2	1.06	0.1
	Left	0.65	0.2	1.13	0.2	0.97	0.2
Rugby League 2	Right	0.74	0.3	1.10	0.2	1.10	0.2
	Left	0.73	0.2	1.10	0.2	1.02	0.2
Sport Students	Right	0.73	0.1	0.98	0.1	1.08	0.2
MEAN							
Rugby League 1	Right	0.61	0.2	1.03	0.3	1.10	0.1
	Left	0.73	0.2	1.17	0.1	1.17	0.1
Rugby League 2	Right	0.84	0.3	1.17	0.1	1.19	0.3
	Left	0.81	0.2	1.09	0.2	1.14	0.2
Sport Students	Right	0.95	0.2	1.18	0.2	1.36	0.2

As a group rugby league players showed no significant difference between right and left sides ($P > 0.05$) for any of the ratios with bilateral deviation less than 10 %. Peak and mean H/Q ratios were highly correlated in both groups ($r = 0.85$-0.94, $P < 0.01$). There were no significant differences in the peak H/Q strength ratio between all rugby league players and sport students ($P > 0.05$) but there was a significant difference in the mean H/Q ratio ($F_{2, 28} = 6.224$, $P = 0.006$). There were no significant differences in the E/C ratios ($P > 0.05$). Analysis of the two groups of rugby league players showed a difference in the peak H/Q strength ratio ($F_{2, 28} = 4.561$, $P = 0.03$).

Force values and H/Q ratios were considered in relation to anthropometric characteristics of the knee extensors and flexors in relation to leg volume (Jones and Pearson, 1969). Rugby league players had a total leg volume for the right leg of 11.99 ± 1.96 l and a lean thigh volume of 6.08 ± 1.32 l. Sport students recorded values of 11.94 ± 2.02 l and 5.48 ± 1.31 l for leg volume and lean thigh volume respectively. No significant difference existed between the groups ($P > 0.05$).

Low to moderate correlations were found between leg volume, thigh volume and lean thigh volume ($r = 0.04 - 0.55$; $P > 0.05$) and most of the force parameters. Moderate to high correlations were found between leg volume and mean concentric and eccentric flexion ($r =0.62$ and $r = 0.85$; $P < 0.05$), thigh volume and mean concentric and eccentric flexion ($r = 0.64$ and $r = 0.86$; $P > 0.05$) and between lean thigh volume and mean concentric and eccentric flexion ($r = 0.55$ and $r = 0.59$; $P < 0.05$).

Moderate to high correlations were found between leg volume, thigh volume and lean thigh volume and all H/Q Strength ratios. Leg volume correlated with Peak H/Q ratio and mean H/Q ratio with values of $r = 0.56$ and $r = 0.77$ ($P < 0.05$) respectively. Thigh volume correlated with values of $r = 0.57$ and $r = 0.79$ ($P < 0.05$) and lean thigh correlated with mean H/Q ratio of $r = 0.68$ ($P < 0.05$). The only ratio to have a lower correlation was the peak H/Q ratio with lean thigh ($r = 0.44$, $P < 0.05$).

3.5 DISCUSSION

Isokinetic dynamometry has been used extensively for the measurement of muscular strength of knee extensors and flexors and the generation of specific and reciprocal muscle group ratios (Colliander and Tesch 1989; Posch *et al.*, 1989; Fairbanks *et al.*, 1994; Ellenbecker and Roetert; 1995). Additionally, population-specific descriptive data have been provided in an attempt to profile characteristics of specific sporting populations such as tennis players (Ellenbecker and Roetert, 1995) and to assist in the design of conditioning programmes. Measurements obtained for specific groups may derive population-specific values and strength ratios which will allow for meaningful comparisons between groups.

The values obtained for the peak H/Q ratios for both groups tested fell within the 50-80 % range previously reported (Kannus, 1994). Ellenbecker and Roetert (1995) reported similar values for junior tennis players and these were lower than values reported previously by Davies (1987). The right leg value of 0.79 for the rugby league players is at the top of the reported range. Higher ratios may be important in multiple sprint sports to prevent stress being placed on the passive structures of the knee (Chan and Maffuli, 1996).

Care has to be taken when comparing these values with previously reported data. Kellis and Baltzopoulos (1995) described previous findings as limited and conflicting with differing ratios reported at differing angular velocities. The velocity for these tests was set at $30^{\circ}\ s^{-1}$ because the slower velocities allow for greater force production and one aim was to measure maximal dynamic strength. Another consideration was the differing response in the eccentric mode when compared with the concentric mode with increasing velocity. Because the tension in the eccentric mode increases with increasing velocity, it was felt that by choosing $30^{\circ}\ s^{-1}$ it helped equalise the eccentric and concentric conditions (Dvir, 1989).

Mean force values and the ratios derived from mean force correlated highly with peak values and ratios, thus strongly supporting findings from previous studies. However, the relationships between the peak and mean values have been shown to change as a function of the experimental set up and therefore careful selection of which condition to use is required (Dvir and David, 1995). These authors concluded that peak force should be used for normative strength values, but that ratios would be better represented by mean values. In this study both peak and mean force values were higher in the sport students than the rugby league players, but there was no difference in either the inter or intra muscle ratios. Mean value ratios were higher in both groups than their equivalent peaks. Although strength differences are likely across groups, these findings demonstrate that ratios allow for between group comparison in relation to muscle function and muscle quality. The sport students were significantly stronger than the rugby league players, reflecting their resistance training background and their own involvement in high intensity sport. Also, despite habituation of the rugby league players, the sports students were more familiar with working on the isokinetic dynamometer. However, despite the strength differences, as recorded on the isokinetic dynamometer, the ratios were similar with a similar pattern demonstrated between groups. With regard to muscle function the groups were similar despite the differences in absolute strength values. Thus, presentation of data including both peak and mean values can assist in the interpretation of isokinetic testing with regard to rehabilitation or screening of sport participants from within this population. Such interpretation often involves a bilateral comparison, particularly when rehabilitating an extensor or flexor injury. In the rugby league players there was no significant difference between force values or ratio for either side. Any difference that did exist was less than 10 %, a value considered to be normal (Sapega, 1990).

Beyond such comparisons, discussions as to the usefulness of the H/Q ratio are on-going (Dvir 1989; Aagaard *et al.,* 1998) because it is derived from forces measured in opposite contraction modes. Further investigations are required to examine a potentially more functional and useful ratio, derived from the eccentric force of the flexors and the concentric force of the extensors. In multiple-sprint activity the eccentric action of the hamstrings assists in the control of the concentrically acting quadriceps. Thus analysis of these parameters together may be even more useful in screening and analysing muscle function.

Care also has to be taken when considering the intra muscle group ratios because these have been reported as both eccentric/concentric (E/C) (Colliander and Tesch, 1989) and as concentric/eccentric (Fairbanks *et al.,* 1994). This data is reported as E/C, thus helping with analysis of individual muscle groups. Ratios should always be in excess of 1.0 to indicate normal functioning. The ratio for the right leg extensors in the sport students and for left leg flexors in the rugby league players were just below 1.0 (0.97 and 0.98 respectively) but all other ratios were in excess of 1.0. However, these ratios were lower for both quadriceps and hamstrings when compared previously reported data for healthy males (Colliander and Tesch, 1989). The differences could indicate that the strength conditioning undertaken by the participants in this study does not account sufficiently for the differing functions of the muscles involved. Indeed, the rugby league players became aware of a bias in the strength conditioning towards concentric activity and also considered there to be an imbalance between extension and flexion activities. Intra-muscle group ratios should alter with increasing velocity in line with the force-velocity relationship (Hill, 1938) and future monitoring of the ratios across differing speeds may provide an even better indicator of function within particular muscle groups.

Although a number of factors, such as fibre type, cross sectional area and enzyme activity are known to influence force production, aspects of body composition have been suggested to contribute to individual differences in strength (Nutter and Thorland, 1987). Because of the number of factors involved, correlations reported between strength and body composition have tended to be low to moderate. This study used leg volume, thigh volume and lean thigh volume as the anthropometric parameters. These were chosen because they are easy to measure and because of the focus on the knee extensors and flexors. The only moderate to high significant relationships were found with flexion and predominantly with mean values. This again supports the need to carefully select whether peak or mean values should be reported. If values are to be analysed in relation to anthropometric characteristics of the legs then mean values would appear to be the most useful.

Nutter and Thorland (1987) found significant moderate correlations between thigh volume and concentric extensor peak torque across three velocities. The highest correlation was found at the highest velocity. The speeds used were all in excess of that used in this study, which was chosen to establish maximal dynamic force.

Interestingly the highest correlations for each of the anthropometric parameters were with the H/Q strength ratio. Thigh volume obviously accounts for both the extensors and flexors and therefore correlates better with the ratios because these reflect force production in the flexors, in relation to force production in the extensors. Therefore the ratio accounts for force production in the whole thigh and not one muscle group. In all cases the mean H/Q strength ratio correlated most highly again suggesting that the reporting of mean values is important. Overall, the relationship between leg volume measurements and force parameters tended to be moderate. This is potentially due to the testing speed or the nature of the testing. Measurement difficulty with regard to leg volume could also account for the results. However, anthropometric measurement of leg volume is a relatively quick procedure that can easily be administered in the field. The results indicate that a relationship exists and suggest that studies in the future should further investigate the use of leg volume as a means of adjusting strength values for comparison between groups. The close relationship with muscle group ratios is interesting and suggests that these are useful in the overall analysis of muscle function and strength performance in specific-population groups.

CHAPTER 4

DYNAMIC CONTROL RATIO AND ISOKINETIC STRENGTH OF THE KNEE EXTENSORS AND FLEXORS IN PROFESSIONAL RUGBY LEAGUE PLAYERS: EFFECTS OF ANGULAR VELOCITY. *

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4.1 ABSTRACT

Objectives

The purpose of this study was to document and provide data relating to muscle balance in the quadriceps and hamstring muscle groups in professional rugby league players. The conventional concentric hamstrings/quadriceps muscle group ratio (H/Q) and the eccentric hamstrings/concentric quadriceps ratio, referred to as the dynamic control ratio, were compared at several angular velocities.

Methods

Eleven full time professional rugby league players were measured for mean and peak force for concentric and eccentric action of the extensors and flexors of the knee using an isokinetic dynamometer. Testing occurred across three different angular velocities; 30, 60 and 90° s^{-1}.

Results

Analysis showed an expected significant interaction of speed by mode of contraction on peak force values ($F_{1.2,\ 11.8\ GG} = 15.60$, $P < 0.01$) indicating that the type of muscle action moderates the effect of speed on force. Analysis also revealed a significant interaction of speed by ratio measurement technique on the actual derived ratio ($F_{1.3,\ 12.9\ GG,} = 7.1$, $P < 0.05$). The dynamic control ratio increased across speeds to a greater extent than the conventional H/Q ratio and was significantly higher ($P < 0.05$) at 60 and 90° s^{-1}.

Conclusion

The study demonstrated that the dynamic control ratio is higher than the conventional H/Q strength ratio. This was attributed to the greater eccentric force exerted during contractions. The difference between the two ratios also increased as the velocity increased, in line with the force-velocity relationship. We believe that the dynamic

control ratio more closely represents normal functioning and highlights the role played by the eccentrically acting flexors in controlling the opposing knee extensors during leg extension.

4.2 INTRODUCTION

It has been previously proposed that the conventional hamstrings/quadriceps (H/Q) strength ratio can be used as an indicator of susceptibility to injury (Grace *et al.,* 1984; Knapik *et al.*, 1991). If this is the case then it should also be possible for it to be used as a tool for injury prevention (Baltzopoulos and Brodie, 1989; Dvir, 1995) and as a goal for rehabilitation (Li *et al.*, 1996).

The rationale for these applications of the H/Q strength ratio can be illustrated by considering the performance of the knee joint. For example, in both healthy subjects and those undergoing rehabilitation, the H/Q ratio is of importance because the coactivation of hamstrings and quadriceps is related to knee joint stability and the loading of cruciate ligaments (Kellis, 1998). If either the quadriceps or hamstrings are excessively strong in comparison with the antagonistic muscle group, the passive structures of the knee such as the ligaments, which are responsible for joint stability, could be abnormally loaded. Indeed, antagonist co-activation is required to assist the ligaments in maintaining joint stability and to reduce the risk of ligamentous damage (Baratta *et al.*, 1988).

The significance of the H/Q strength ratio has also been related to the incidence of hamstring injuries. Some studies have reported a negative relationship between a low H/Q strength ratio and hamstring strains (Yamomoto, 1988; Orchard *et al.*, 1997). This however depends upon the definition of what constitutes a low value. A ratio of less than 0.60 was reported to show no relationship with hamstring muscle strain (Bennell *et al.,* 1998). However, ratios in respect of reducing the risk of hamstring injury have been reported to be between 0.5 to 0.8 (Kannus, 1994). It is generally accepted that large inter-individual and inter-population variations exist and therefore values need to be reported on an individual or population-specific basis. The nature of the population and the type of predominant activity will influence the nature of the ratio required to minimise the risk of hamstring injury. Therefore for those involved in high intensity sports which require explosive push-offs and place greater demands on the hamstring muscle group, such as rugby league, it has been argued that the conventional H/Q strength ratio should perhaps be nearer to one (Chan and Maffulli, 1996).

Differences and discrepancies in findings relating to H/Q ratios and their relationship with other factors like injury risk, are illustrative of the well documented controversy which surrounds H/Q ratios generally and particularly the suggestion that normal or optimal ratio values exist (Holm *et al.*, 1994). For example, studies have documented the positive alteration in the H/Q ratio, which occurs as angular velocities increase (Colliander and Tesch, 1989; Aagaard, 1995), whilst differing values have also been reported when knee flexion and extension measures are reported when corrected for gravity (Kannus, 1994). Further confusion arises from the common reporting of reciprocal ratios that use peak torque, and the less common reporting of ratios calculated from mean torque values.

Of potentially greater concern is the fact that H/Q ratios are normally calculated from torque values obtained via concentric actions of both the flexors and extensors, even though the coactivation of the hamstrings and quadriceps has opposite contraction modes. A ratio, calculated by dividing eccentric action of hamstrings by the concentric action of quadriceps, is perhaps of greater significance (Dvir, 1989; Perrin, 1993;

Aagaard *et al.*, 1998). Such a ratio has been titled the *'Dynamic Control Ratio'* (DCR) (Dvir, 1989) and described as both a new and a functional ratio (Aagaard *et al.,* 1998) because it relates to the ability of the eccentrically acting hamstrings to control the concentrically acting quadriceps during level running (Dvir, 1989). During running, the quadriceps act to extend the knee, and if the action is unrestrained, this may cause an anterior gliding movement of the tibia on the femur. Eccentric action of the hamstrings must counteract this movement in order to stabilise the knee and prevent excessive loading of the passive structures of the joint. This would appear to be of particular importance in a high-intensity sprint activity like rugby league, where the forces involved are high. Despite this apparent significance, current findings regarding the DCR are relatively limited and further research is needed to determine its use and efficacy in injury prevention and rehabilitation (Kellis and Baltzopoulos, 1995). A functional and reliable ratio is required to remove dependence on the conventional concentric/concentric H/Q strength ratios which have been described as idiosyncratic and from which recommendations relating to normal values should not be made (Kannus, 1994). Notwithstanding this, the majority of reciprocal H/Q ratios continue to be reported as concentric/concentric (Holm *et al.*, 1994; Dvir, 1995) with little attention paid to alternative H/Q ratios. Whilst the definitive measure for H/Q ratios remains undetermined, further evaluations of the knee joint should involve measures of maximal strength as well as both functional and conventional H/Q ratios (Aagaard *et al.*, 1998)

The functional requirements of the modern day rugby league player, which include high-force generation and sprint activity (Brewer and Davis, 1995) call for accurate assessment of muscle performance. This will help to ensure prescription of optimal and appropriate training and potentially reduce the risk of injury. The DCR as a functional ratio may be more significant in a sport of this nature, for the reasons stated above, but further research is required to establish its usefulness. Therefore the purpose of this study is to document and provide data relating to muscle balance between the quadriceps and hamstring muscle groups in professional rugby league players.

4.3 METHODS

4.3.1 Participants

Eleven full time professional rugby league players age 25 ± 5.7 years, stature 180.8 ± 7.2 cm, mass 92.13 ± 17.7 kg were measured for peak and mean force for concentric and eccentric action of the extensors and flexors of the knee. The participants, professionals from the same club, completed and signed informed consent forms prior to participation in this study. Players chosen were injury free and were experienced at working on an isokinetic dynamometer in both concentric and eccentric modes.

4.3.2 Experimental Protocol

A Kin-Com 125E plus (Chattanooga, Tennessee, USA) was used for testing peak and mean forces during maximal voluntary effort. Concentric and eccentric actions were measured during extension and flexion of the right and left legs at angular velocities of, $30° s^{-1}$, $60° s^{-1}$ and $90° s^{-1}$. The relatively narrow range of velocities was chosen for two reasons. Firstly, to ensure that the movement retained a significant Isokinetic component and secondly to be a sensitive measure of change. If the ratios respond differently over a narrow range of velocities then it can be expected that the differences will be more marked if the difference in velocity increases.

Subjects performed the tests in the seated position, with the seat angle horizontal (0 deg) and the backrest at an angle of 105 deg. Subjects were more familiar with operating in the seated position thus the use of this position aided the habituation process. The centre of rotation of the knee joint was aligned with the rotational axis of the dynamometer lever arm. The resistance pad was secured to the lower leg proximal to the ankle joint allowing for full dorsiflexion. Restraining velcro straps were placed around the chest, pelvis and the distal thigh of the tested leg. The inactive leg remained untethered and during the test subjects kept their arms folded across the chest.

Gravity correction factors based on leg weight at full extension were calculated according to manufacturers guidelines prior to testing each leg. The acceleration/deceleration rate of the dynamometer was set to medium and the activation force for concentric and eccentric efforts was set to 50N for all subjects. Muscle groups were tested through a joint arc of 90° to 10°, with knee flexion being 90° and knee extension 0°.Both mean and peak force parameters were recorded, Mean force referred to the arithmetic mean of the force values between 10° and 90°. Peak values for eccentric and concentric forces were the highest values attained throughout the range of motion for each contarcation cycle of the knee (Dvir, 1989). Testing order of the left and right leg and extensors and flexors were assigned randomly. A rest period of 10 - 15 s separated concentric from eccentric measurements of each muscle group. Each subject familiarised themselves with the action of the dynamometer and performed 3-5 reciprocal, submaximal warm ups. Six maximal voluntary contractions were then performed as the test, from which three reproducible trials were averaged by the computer system to provide peak force values. Standardised verbal motivation was given to each subject to encourage maximal effort (McNair *et al.*, 1996). Values of force, in newtons, are reported, as the force transducers in the resistance pad make direct measurements of force exerted by the subject. If required, values of torque in Nm can be calculated by the computer system utilising the length of the lever arm.

4.3.3 Statistical Analysis

Peak force and ratio values were averaged across the group for each velocity. A two-way repeated-measures analysis of variance (ANOVA) was used to determine the main effects and interactions between mode of action and speed. The 2 x 3 ANOVA measured the effects of mode of action (eccentric, concentric) and speed (30, 60, 90° s^{-1}) on peak force for leg extensors and flexors. A similar procedure was used to measure the effects and interactions between speed and ratio (H/Q Strength ratio and DCR). Greenhouse-Geissser corrections (indicated by $_{GG}$) were applied to significant *F*-ratios that did not meet Mauchly's assumption of sphericity. Calculations for observed power were performed. One-way repeated measures ANOVA (Speed) was applied to each ratio. ANOVA procedures were performed using version 10.0 of the Statistical Programme for Social Sciences (SPSS). Statistical significance was set at the 0.05 alpha level.

Graphical representation of the results utilised standard error of measurement (SEM). This was to ensure that sample size was also accounted for along with variability (Motulsky 2002). When SEM error bars overlap it indicates no significant difference. The converse is not true but despite this the SEM bars represented an easy and convenient tool from which provisional analysis could occur.

4.4 RESULTS

All players provided results for mean and peak force of the right and left knee extensors and flexors in both concentric and eccentric modes. Table 3 provides mean values for peak forces for the right leg at all three speeds and table 4 lists the ratios calculated from the force values.

Table 3. Peak concentric and eccentric force values for the right and left legs at 30, 60 and 90° s^{-1}. Values are means (± SD).

Peak Forces (N) **Speed (° s^{-1})**

	30° s^{-1} n = 11 mean ± s.d	60° s^{-1} n = 11 mean ± s.d	90° s^{-1} n = 11 mean ± s.d
Right			
Extensors, con	795.6 (± 124.2)	707.4 (± 109.9)	656.6 (± 90.9)
Extensors, ecc	892.3 (± 267.7)	957.6 (± 209.1)	948.3 (± 180.7)
Flexors, con	425.6 (± 72.8)	422.4 (± 77.7)	433.3 (± 73.3)
Flexors, ecc	489.3 (± 147.7)	529.3 (± 133.3)	551.7 (± 126.5)
Left			
Extensors, con	758.8 (± 174.3)	684 (± 134.7)	650.1 (± 142.7)
Extensors, ecc	871.9 (±174.3)	933.5 (± 195.5)	948.8 (± 151.1)
Flexors, con	490.9 (± 112.5)	460.7 (± 99.9)	482.6 (± 103.5)
Flexors, ecc	539.3 (± 118.3)	583.5 (± 131.8)	596.4 (± 142.2)

Table 4. Traditional H/Q strength ratios and DCR for right and left legs at 30, 60 and 90° s^{-1}. Values are means (± SD).

Ratios **Speed (° s^{-1})**

	30° s^{-1} n = 11	60° s^{-1} n = 11	90° s^{-1} n = 11
Right			
H/Q con/con	0.54	0.61	0.67
H/Q ecc/con	0.62	0.76	0.85
Left			
H/Q con/con	0.66	0.68	0.75
H/Q ecc/con	0.73	0.87	0.94

The analysis of peak force values via the repeated-measures ANOVA showed a significant interaction of speed by mode ($F_{1.2,\ 11.8\ GG} = 15.60$, $P < 0.01$) indicating that the type of muscle action moderates the effect of speed on force. Eccentric force values tended to increase with increasing velocity whilst concentrically produced force values decreased as velocity increased. This is illustrated in Figure1. A similar pattern was found for both flexion and extension and for both peak and mean values in both legs.

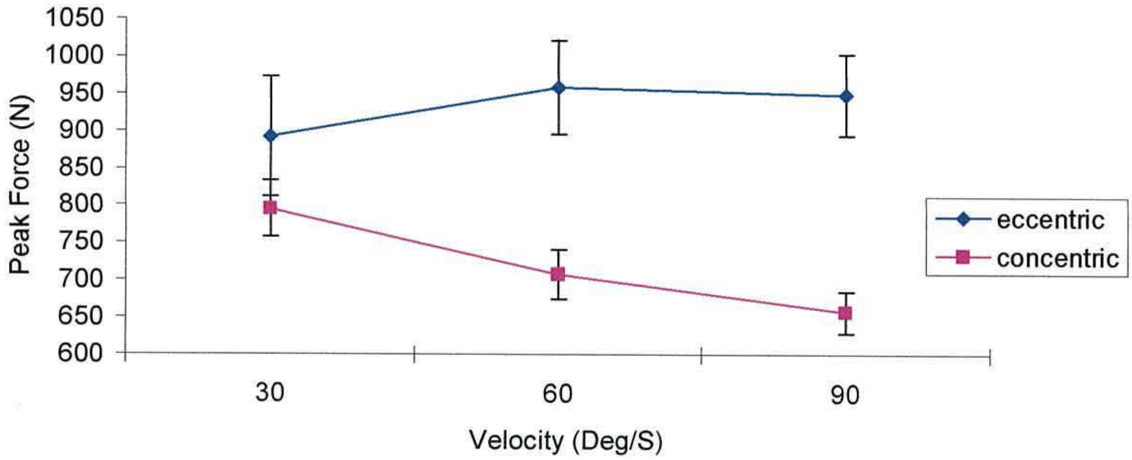

Figure 1. Effect of velocity on eccentric and concentric peak force values for the right leg extensors. All values are expressed as means (± SEM)

A significant interaction occurred between the different ratios across the differing speeds ($F_{1.3,\ 12.9\ GG,} = 7.1$, $P < 0.05$), with the DCR increasing across the speeds to a greater extent than the traditional H/Q strength ratio. This phenomenon is illustrated in Figure 2. Observed power was 0.760 or 77.64 %.Data for each leg was also analysed by a single factor ANOVA. This demonstrated no significant difference ($P > 0.05$) across speed in either leg for the conventional ratio. There was however, a significant effect of speed for the right (F= 3.8, df = 2, $P < 0.03$) and left (F=3.351, df = 2, $P < 0.05$) legs with the DCR increasing as speed increased.

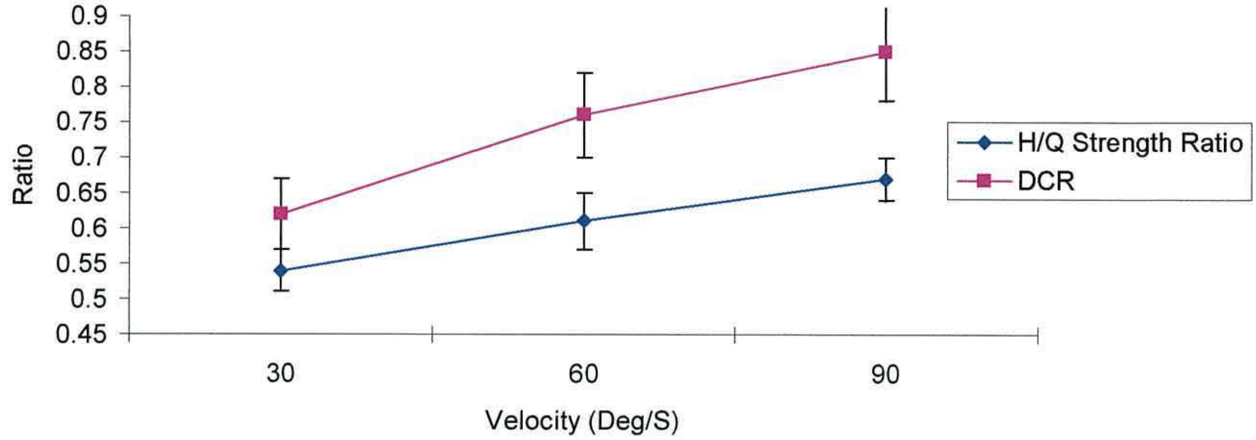

Figure 2. Effect of velocity on traditional H/Q strength ratio and DCR for right leg. All values are expressed as means (± SEM)

4.5 DISCUSSION

Isokinetic dynamometry has been used extensively in the measurement of muscular strength of the thigh and the generation of specific and reciprocal muscle group ratios (Colliander and Tesch, 1989; Posch *et al.*, 1989; Fairbanks *et al.*, 1994; Ellenbecker and Roetert, 1995). More recently, population-specific descriptive data has been provided in an attempt to profile specific characteristics (Ellenbecker and Roetert, 1995) and attempts have been made to measure ratios that are functional and reflect the actions involved in specific activity (Aagaard, 1998). The purpose of this study was to examine reciprocal ratios and to measure and compare the dynamic control ratio in professional rugby league players. The population-specific functional ratios derived may well represent more meaningful information than comparisons of idiosyncratic ratios with a normal database that is equipment, population and protocol specific. Absolute force values were lower than expected when compared with other groups tested in the laboratory or when compared with other values reported. Professional rugby league players could be expected to have higher values when compared with other groups due to the characteristics of the game. Furthermore, similar values for knee extension and flexion have previously been reported in junior tennis players (Ellenbecker and Roetert, 1995). However, values recorded on differing machines should only be compared with caution as differing machines, even of the same make, are not interchangeable (Francis and Hoobler, 1987). Nevertheless, the relatively low values recorded for the rugby players would suggest that an examination of conditioning methods should occur.

The conventional H/Q strength ratios have previously been reported to increase with increasing angular velocity (Colliander and Tesch, 1989) if gravity correction factors are not employed. In this study, as illustrated in Figure 2, the conventional ratio did not increase with increasing angular velocity ($P > 0.05$). With concentric force decreasing with increasing velocity for both extensors and flexors a change in the H/Q ratio should be relatively minimal. Concentric force decreased with increasing velocity for both extensors and flexors in line with the force-velocity relationship, as illustrated in Figure1. The reduction in concentric force production was greater in the extensors than the flexors and this discrepancy led to the non-significant increase in the conventional ratio across velocities.

The conventional H/Q strength ratios for both legs at all velocities fell in the previously reported optimal range of 50-80 % (Kannus, 1994). This lends support to the argument that ratios are better indicators of muscle function than strength per se because although the torque values might be considered to be relatively low for an elite group of this nature, the inter-muscle group ratios suggest normal functioning. Intervention should therefore focus on increasing strength proportionally in both extensors and flexors, whilst maintaining muscle balance.

It was noticeable that the DCR shows a significant increase ($P < 0.05$) in the ratio as the velocity increases. This is in line with the force-velocity characteristics of muscle with eccentric force production increasing and concentric force production decreasing with increasing velocity (Figure1). The change across velocities with the DCR is likely to demonstrate a more consistent pattern than any change in the conventional H/Q strength ratio. This could prove to be useful in determining normal functioning across velocities as a distinct and clear pattern of change is expected. If the pattern is not observed, irregular functioning can be assumed. Figure 2 demonstrates the noticeable and significant change occurring in the DCR as velocity increases. As eccentric force production increases and the concentric force production decreases, the ratio moves nearer to one. Such an expected change allows for optimal ratios to be identified at differing angular velocities. The ratios would be both specific and functional and allow for more accurate analysis of functioning. However, the comparison of response between the conventional H/Q ratio and DCR in this study has to undertaken with some caution because of the size of the sample investigated. The observed power was 77.64 %, lower than the 80 % value that is commonly applied in research of this nature (Thomas and Nelson, 2001). There is obviously a possibility of type II error and that the test was not powerful enough to detect changes in the conventional H/Q ratio. Although it would be desirable to study the phenomenon with larger numbers, the power is close to the normally adopted level and the ratios respond in line with the functioning of the muscle at differing velocities. These factors would therefore suggest that whilst considering the results cautiously, the two ratios have responded differently and that the DCR is sensitive to changes in the velocity of movement because of the underlying force-velocity relationship.

The DCR is an indicator of functional stability (Dvir *et al.,* 1989) and can be used to identify concentric or eccentric deficiency. Eccentric capacity is very important in sprint sports where much of the work is negative. Analysis has to be undertaken with care though, with significant increases in DCR potentially occurring due to reduction in concentric force of the quadriceps because of injury to the anterior cruciate ligament. However, this once again lends support to the usefulness of the DCR. Because a clear pattern of response is expected in the ratio, in line with the force-velocity relationship, it can act as a diagnostic tool both for the identification of injury as well as muscle function and the strength relationship between the extensors and flexors. With respect to the players examined in this study, although conventional ratios fell within the commonly described optimal range, the DCR could be a cause for concern when considering the nature of the game. A powerful hamstring group is required to control and restrict the anterior gliding movement of the tibia on the femur and therefore a ratio nearer to 1.0 may be required (Chan and Maffulli, 1996). However, the velocity at which the ratio is measured must be accounted for, as must the nature of the ratio. The ratio is not only influenced by whether peak or mean forces are used but also by the joint angle at which the measures are taken (Coombs *et al.*, 2002), with the DCR increasing with more extended knee joint positions (Aagaard *et al.*, 1998; Coombs *et al.*, 2002). Even with these factors accounted for, the players as a group still appear to be dominant in the quadriceps, a potential concern when considering the demands of the game.

In conclusion, this study demonstrated that due to greater eccentric force capability, the DCR is greater than the conventional H/Q strength ratio. Furthermore, the difference between the two becomes greater as the velocity increases, in line with the force-velocity relationship. Thus, the DCR more closely represents normal functioning and highlights the role played by the eccentrically acting flexors in controlling the opposing knee extensors during leg extension. This supports previous findings (Dvir *et al.*, 1989; Aagaard *et al.*, 1998; Coombs *et al.*, 2002) and suggests that the DCR could be a more appropriate tool than the conventional H/Q ratio for analysing muscle function. From analysis of the conventional ratio it would appear that the rugby league players in this study are within the previously reported optimal range, although their peak and mean force values appear to be relatively low and are a potential cause for concern. Analysis of the DCR would suggest that the players are dominant in the quadriceps. However, further examination of the demands of the game, the nature of the conditioning employed and the relationship of knee extensor and flexor strength and H/Q ratios to performance is required.

CHAPTER 5

THE EFFECTS OF WEIGHT TRAINING ON MAXIMAL ANAEROBIC PERFORMANCE IN MEN AND WOMEN

5.1 Abstract

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- **5.3.2 Experimental protocol**
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5.1 Abstract

Objectives

The purpose of this study was to evaluate the effects of strength training, using commonly available fixed weight training apparatus, on isokinetic force production, anaerobic performance and peak and mean power output in men and women. Isokinetic force ratios, peak and mean force values and anaerobic performance, measured during both 30 s continuous isokinetic extension and flexion and 30 s maximal cycling, were analysed before and after 12-weeks of strength training.

Methods

Nine women (age 24.1 ± 7.8 yr (mean ± SD), ht 169.5 ± 6.1 cm, mass 64.8 ± 7.2 kg) and eight men (age 21.6 ± 4.6 yr, ht 180.8 ± 6.6 cm, mass 79.8 ± 6.8 kg) participated as experimental subjects. A further six women (age 25.3 ± 5.2 yr, ht 167.6 cm, mass 66.4 ± 7.2 kg) and six men (age 26.0 ± 5.7 yr, ht 176.8 ± 7.0 cm, mass 78.0 ± 11.0 kg) participated as control subjects. Experimental subjects participated in a 12-week strength training programme using fixed weight apparatus. All groups were tested at the beginning and end of the programme for isokinetic force, anaerobic performance, measured during the Wingate 30 s test, and total work performed during a 30 s continuous test of isokinetic extension and flexion. Before and after values were analysed using a series of mixed-model, three factor analyses of variance.

Results

There were no significant interactions of time x group or time x gender for isokinetic force ratios. There were however significant interactions of time x group for peak concentric extension ($F_{1,25}$ = 17.25, P = 0.000), peak eccentric extension ($F_{1,25}$ = 8.41, P = 0.008), peak concentric flexion ($F_{1,25}$ = 9.18, P = 0.006) and peak eccentric flexion ($F_{1,25}$ = 10.245, P = 0.004) with experimental group subjects increasing

significantly with no change in control subjects. There was no interaction of time x gender for any of the peak force values. Similarly there were significant time x group interactions for mean concentric extension ($F_{1,25} = 24.408$, $P = 0.000$), mean eccentric extension ($F_{1,25} = 7.015$, $P = 0.01$), mean concentric flexion ($F_{1,25} = 4.136$, $P = 0.05$) and mean eccentric flexion ($F_{1,25} = 16.922$, $P = 0.000$), experimental subjects increasing in strength with no change in controls. There was no interaction of time x gender apart from mean concentric flexion ($F_{1,25} = 5.090$, $P = 0.033$). Peak power showed a significant interaction of time x group ($F_{1,25} = 4.428$, $P = 0.046$) by increasing in experimental subjects, but there were no interactions for mean power. Increases in total work performed during concentric extension ($F_{1,25} = 26.933$, $P = 0.000$) and concentric flexion ($F_{1,25} = 4.390$, $P = 0.046$) occurred for experimental group subjects. For concentric extension there were also significant interactions of time x gender and time x gender x group with experimental subjects increasing and male subjects increasing proportionally more than females.

Conclusion

The results supported the strength/power relationship and suggested that strength training can improve the ability to perform anaerobic activity and may positively enhance anaerobic capacity in males and females. The exact reasons for the improvement are not yet clear but the results highlight the importance of a balanced weight-training programme for those involved in activities that require a significant anaerobic contribution.

5.2 Introduction

The majority of coaches agree that resistance training is a key element in a training schedule for sprinters (Delecluse, 1995) and it is now widely used as a means of conditioning for those involved in multiple sprint sports (Baker and Nance, 1999). The relationship between strength and power has long been recognised (Coyle, 1981). This has been supported more recently through the use of plyometric intervention (Potteiger, 1999), measurement of isokinetic torque (Latin, 1992) and has been identified as an important relationship in specific sporting groups (Baker and Nance, 1999). Because power is the product of strength (force) and velocity, improvements in strength should enhance power (Sleivert, 1995). However, although strength and power are highly related, a large degree of variance still exists and remains unexplained (Baker and Nance, 1999).

The relationship between anaerobic power and isokinetic strength has been explored in a number of studies (Lesmes, 1978; Smith, 1987; Latin, 1992). Significant correlations have been found to exist between a variety of anaerobic power tests and isokinetic peak torque (Latin, 1992), as well as between anaerobic power, measured during 30 s maximal cycling, and isokinetic extension and flexion of the knee and hip (Smith, 1987).

Other studies have evaluated the effects of isokinetic training on peak torque and maximal power output (Lesmes, 1978). Lesmes prescribed training that included maximal extensions and flexions of the knee at a velocity of 180° s^{-1}. One leg was trained at an intensity, and for a duration that predominantly employed glycolytic mechanisms. The other was trained for shorter durations in an attempt to maximise utilisation of ATP-PC metabolism. Significant increases in peak torque occurred for both legs with no apparent relationship existing between torque increase and time of work. The strength increases were not accompanied by muscle hypertrophy but appeared to lead to a significant improvement in the ability to generate power during short-term activity. Such results not only support the link between strength and the production of power but also highlighted the potential to reduce fatigability and influence anaerobic capacity, particularly with high intensity training of 30 s duration. This finding has particular relevance for participation in multiple sprint sports where a requirement exists to reproduce maximal efforts throughout the period of play. Whilst strength and power are required, so too is a level of anaerobic capacity or the ability to resynthesise ATP via anaerobic metabolism (Green and Dawson, 1992).

An increase in high intensity exercise performance was further demonstrated following 16-weeks of isokinetic training that resulted in an increase in the amount of work achieved during a bout of maximal cycling (Mannion *et al.*, 1994). Previous work by the same authors had already demonstrated a link between isokinetic strength training and peak power output, again during maximal cycling (Mannion *et al.*, 1992). Beyond these studies, few have investigated the influence of strength training, or the influence of an increase in strength on the ability to perform prolonged anaerobic activity. Resistance training has been demonstrated to have the ability to improve performance in high-intensity activity, but only in a pilot study with few male subjects. Peak and mean power improved in men during 30 s of maximal cycling following 8 weeks of isotonic weight training using free weights and standard fixed weight apparatus (Baldwin, 1991).

Therefore, although the link between strength and power is well established, the relationship between strength and the ability to undertake prolonged, or to repeat bouts, of high intensity activity remains equivocal. Mannion *et al.* (1994) investigated muscle-buffering capacity, but observed no change following the period of isokinetic resistance training despite an increase in total work performed during high intensity exercise. Performance in maximal cycling has also been suggested to be related to muscle morphology in men (Froese and Houston, 1987) but studies have shown alteration in maximal performance following strength training with no change in muscle size (Lesmes *et al.* 1978). Indeed, muscle quality (strength per unit of muscle volume) has been shown to increase following strength training in both males and females (Tracy *et al.*, 1999; Ivey *et al.*, 2000).

With regard to gender comparisons in this type of activity, it is only relatively recently that studies using scaling techniques other than simple ratios have demonstrated strength and power differences between males and females that are not simply attributable to muscle size (Winter and Maughan, 1991; Winter *et al.*, 1991; Eston *et al.*, 1997). Other factors include hormonal differences (Shephard, 2000), socio-cultural influences (Wilmore, 1975; Winter *et al.*, 1991), dissimilarity of use (Castro, 1995) and mechanical issues (Winter *et al.*, 1991). Winter *et al.* explained how the amount and distribution of leg fat could have affected inertial and mechanical properties of the limb when comparing power output between males and females when measured on a cycle ergometer. Another issue to be considered when comparing power in males and females measured on a cycle ergometer is the resistance setting (Froese and Houston, 1987). If the resistance is too high for one of the groups, then power output will decline more rapidly and could influence comparisons between groups.

Thus, the exact reason for differences between males and females remains to be confirmed, but it appears that performance in strength and high intensity tasks is not only related to the size of the working muscle. A strength training intervention would assist in evaluating this by allowing comparisons between groups before and after training. As a consequence, improvements in performance that result from increases in strength can be examined and related to other factors such as changes in muscle size and morphology.

Although strength and power are related, and believed to be hierarchically linked to movement speed (Baker and Nance, 1999), the relationship and the influence of strength training remains only partly explained. This is even more so with regard to the relationship between strength training and more prolonged anaerobic activity, which has received relatively little attention. Many of the studies undertaken have concentrated on relationships, rather than examining the effects of a change in strength. Additionally male and female comparisons have suffered from inconsistent normalisation and from comparisons of subjects from differing backgrounds exposed to differing training stimuli. Therefore the purpose of this study was to evaluate the effects of strength training, using commonly available fixed weight apparatus, on isokinetic force production and peak and mean power output in men and women.

5.3 METHODS

5.3.1. Participants

Nine women (age 24.1 ± 7.8 yr (mean ± SD), ht 169.5 ± 6.1 cm, mass 64.8 ± 7.2 kg) and eight men (age 21.6 ± 4.6 yr, ht 180.8 ± 6.6 cm, mass 79.8 ± 6.8 kg) volunteered to participate as experimental group subjects. A further six women (age 25.3 ± 5.2 yr, ht 167.6 cm, mass 66.4 ± 7.2 kg) and six men (age 26.0 ± 5.7 yr, ht 176.8 ± 7.0 cm, mass 78.0 ± 11.0 kg) participated as control group subjects. All subjects were either sports participants or recreationally active but had not participated in a structured and systematic resistance training programme for six months prior to the study. All subjects were healthy and none suffered from any musculo-skeletal defects. All subjects received full explanations of the procedures to be used, were made familiar with the tests to be undertaken and provided written informed consent. Involvement in the study was ultimately dependant on successful completion of the pre-training tests.

5.3.2 Experimental Protocol

Subjects were allocated to an exercise or control group. The exercise groups undertook a series of tests in the laboratory before and after a twelve-week strength training programme. Control group subjects were required to be committed to the laboratory tests at the beginning and end of a twelve-week period.

5.3.3 Isokinetic Force Evaluation.

An isokinetic dynamometer (Kin-Com 125 E plus, Chatanooga, Tennessee, USA) was used for testing peak and mean forces during maximal voluntary effort. Concentric and eccentric actions were measured during extension and flexion of the dominant leg at an angular velocity of 30° s^{-1}. The protocol used was as described in Chapter 3. The force data collected was used to calculate the DCR and H/Q strength ratio.

5.3.4 Anaerobic Performance.

5.3.4.1 Wingate 30 s Test

This was measured on a cycle ergometer using the Wingate 30 s anaerobic test following the protocol of Lakomy (1986). The test was preceded by a warm up which consisted of cycling at a light load followed by a five-minute period for subjects to undertake a series of stretching exercises. Subjects began the test with an initial rolling start of 60-70 RPM with no resistive load. On the command go the pre-determined resistive load (0.075kg/kg of body weight) was applied and subjects pedalled as fast as possible for 30 seconds. The cycle ergometer was connected to a desktop computer from which three indices: *peak power*, *mean power* and *rate of fatigue* were calculated.

5.3.4.2 30 s Continuous Isokinetic Test

Subjects were seated and the limb positioned as in the isokinetic force evaluation test. The test consisted of maximal reciprocal contractions of the knee extensors and flexors of the dominant leg for a period of 30 s at a velocity of 240° s^{-1}. Subjects warmed up and undertook a 5-minute period of stretching prior to the start. Data was collected and analysed by desktop computer from which power output and total work performed were calculated.

5.3.5 Weight Training Programme

The weight-training programme for the experimental group began shortly after the completion of the laboratory assessments. Training sessions occurred three times a week and lasted for between one and one and a half hours. The programme consisted of seven exercises (dead lift, bench press, hack squat, leg extension, hamstring curl, lat pull downs and abdominal crunches) using standard fixed weight apparatus (Powersport, Bridgend, UK). Subjects completed 3 sets of 8 repetitions for each exercise, lifting a weight approximately equal to 75% of their maximum for that exercise. Exercises were designed to maximise strength gain for the legs, with other exercises being included to ensure a balanced muscular development and to replicate normal all-over strength training.

5.3.6 Statistical Analysis

The pre and post training data were analysed using a series of mixed-model, three factor (time x group; time x gender; time x group x gender) analyses of variance. Pearson product moment correlation coefficients were calculated to explore the relationship between isokinetic peak force and peak power and between mean power and total work. Analysis was undertaken using version 10 of the Statistical Package For Social Sciences (SPSS). Statistical significance was set at the 0.05 alpha-level.

5.4 RESULTS

5.4.1 Isokinetic force ratios.

5.4.1.1 Between subjects interactions

There was no significant interaction of time x group ($F_{1, 25} = 0.1$, $P > 0.05$), time x gender ($F_{1, 25} = 0.15$, $P > 0.05$) and time x group x gender ($F_{1, 25} = 0.18$, $P > 0.05$) on DCR, i.e. the pre and post scores were not influenced by gender or experimental group. The findings for the H/Q strength ratio were similar: time x group ($F_{1, 25} = 0.20$, $P > 0.05$), time x gender ($F_{1, 25} = 1.75$ $P > 0.05$), and time x group x gender ($F_{1, 25} = 1.67$, $P > 0.05$). Interactions were all non significant. In summary, strength training brought about no significant changes in the isokinetic force ratios of any of the groups.

5.4.1.2 Main effects for time.

There was no effect of time (pre and post training) on DCR, i.e., there was no significant difference between overall pre versus post training DCR measures ($F_{1, 25} = 0.893$, $P > 0.05$) irrespective of gender and group. Values were 0.66 ± 0.15 and 0.68 ± 0.14 (mean ± SD) pre and post, respectively. Similarly, the pre and post H/Q strength ratio values of 0.64 ± 0.13 and 0.64 ± 0.11 respectively, also showed no effects for time, irrespective of gender or group ($F_{1, 25} = 0$, $P > 0.05$).

5.4.2 Isokinetic Force

5.4.2.1 Peak Values

a. Between subjects interactions.

There was a significant interaction of time x group on peak concentric extension ($F_{1, 25} = 17.25$, $P = 0.000$), peak eccentric extension ($F_{1, 25} = 8.41$, $P = 0.008$), peak concentric flexion ($F_{1, 25} = 9.18$, $P = 0.006$) and peak eccentric flexion ($F_{1, 25} = 10.245$, $P = 0.004$). There was no significant effect of time x gender for any of the parameters, with males and females responding similarly to the training stimulus.

Values were as follows: peak concentric extension ($F_{1,25} = 0.37$, $P = 0.848$), peak eccentric extension ($F_{1,25} = 1.16$, $P = 0.292$), peak concentric flexion ($F_{1,25} = 1.19$, $P = 0.286$) and peak eccentric flexion ($F_{1,25} = 0.01$, $P = 0.292$). The significant interaction of time x group and the non interaction of time x gender are illustrated by using peak concentric extension values in Figures 3 and 4, respectively.

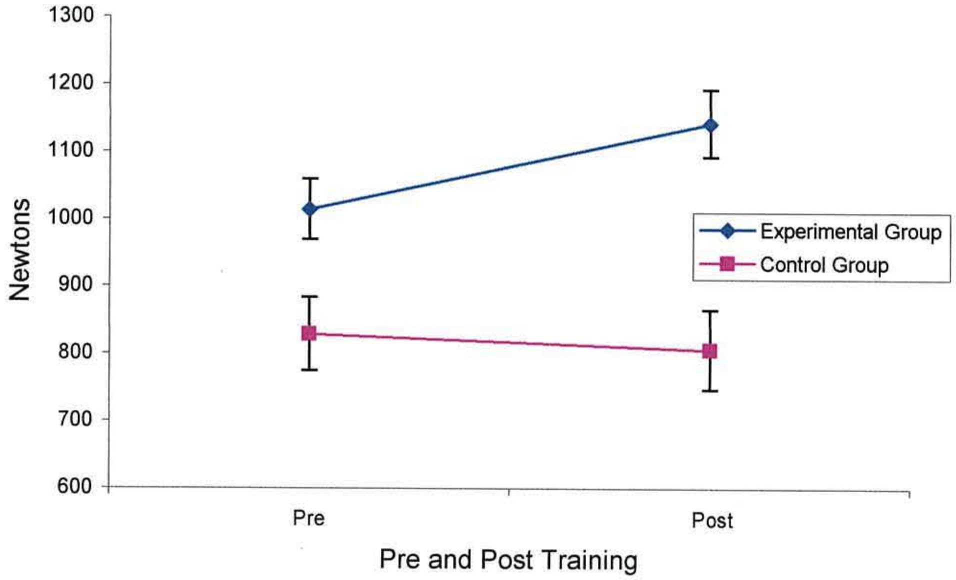

Figure 3: Illustration of the significant interaction of time x group for peak concentric extension ($F_{1,25} = 17.25$, $P = 0.000$). Values are means (± SEM).

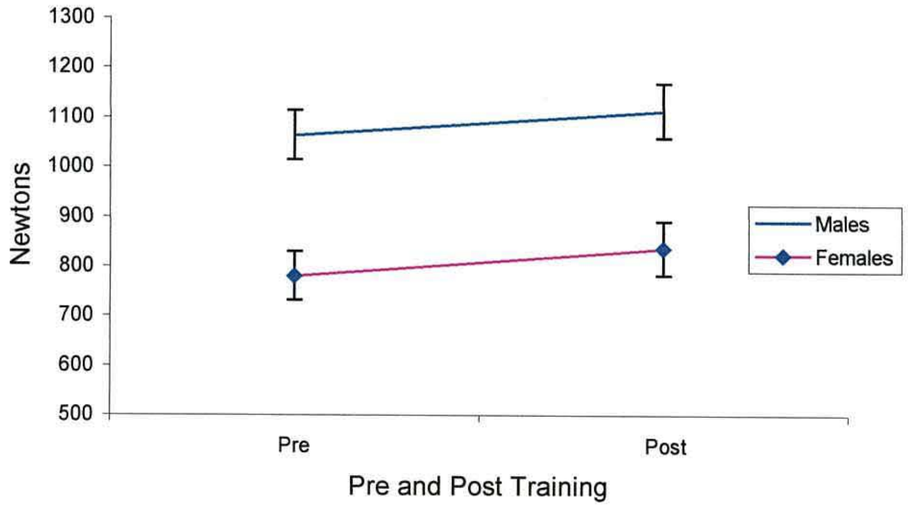

Figure 4: Illustration of the absence of interaction between time and gender for peak concentric extension ($F_{1,25} = 0.37$, $P = 0.848$). Values are means (± SEM).

Force in the male experimental group increased by 9.2 % from 1167 ± 66 N to 1285 ± 73 N (mean ± SEM) pre and post training for peak concentric extension. The response with the female experimental group was similar with an increase of 14 % from 860 ± 62 N to 1000 ± 68 N. Increases also occurred for peak eccentric extension, 1306 ± 83 N to 1404 ± 91 N and 885 ± 62 N to 1111.1 ± 86 N; for peak concentric flexion, 758 ± 50 N to 874 ± 49 N and 584 ± 47 N to 641± 46; and for peak eccentric flexion 797 ± 59 N to 894 ± 58 N and 495 ± 56 N to 587 ± 54 N for males and females respectively. The changes in male and female force production are illustrated in Figures 5 and 6, respectively.

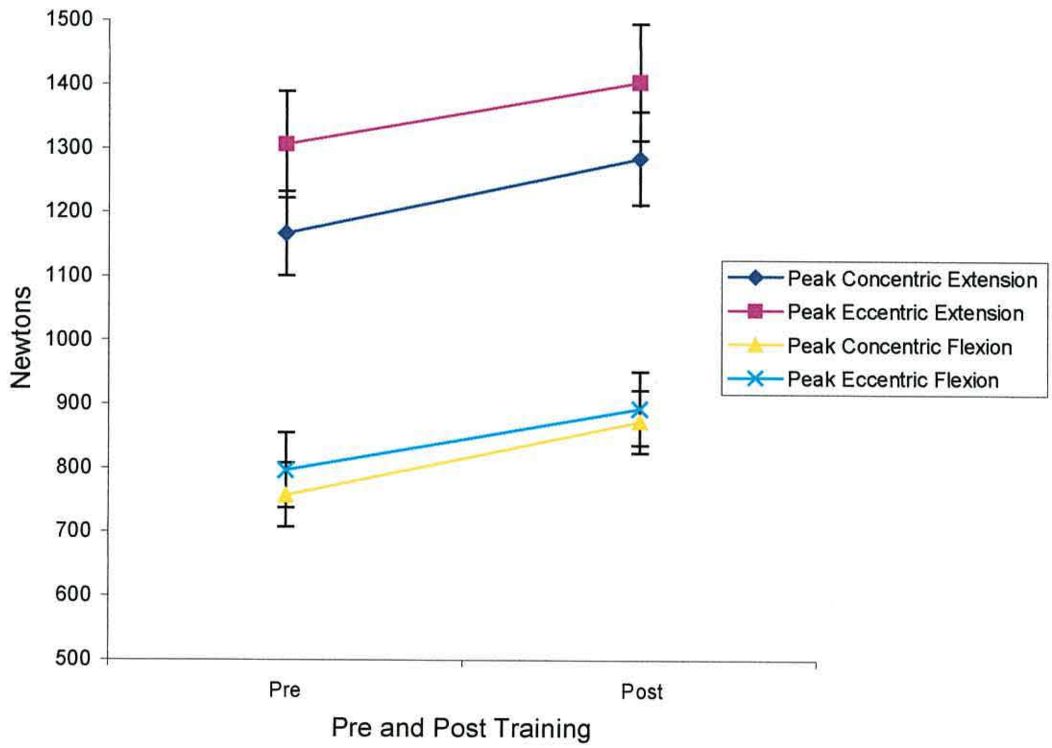

Figure 5: Changes in male experimental group peak isokinetic force values before and after strength training. Values are means (± SEM).

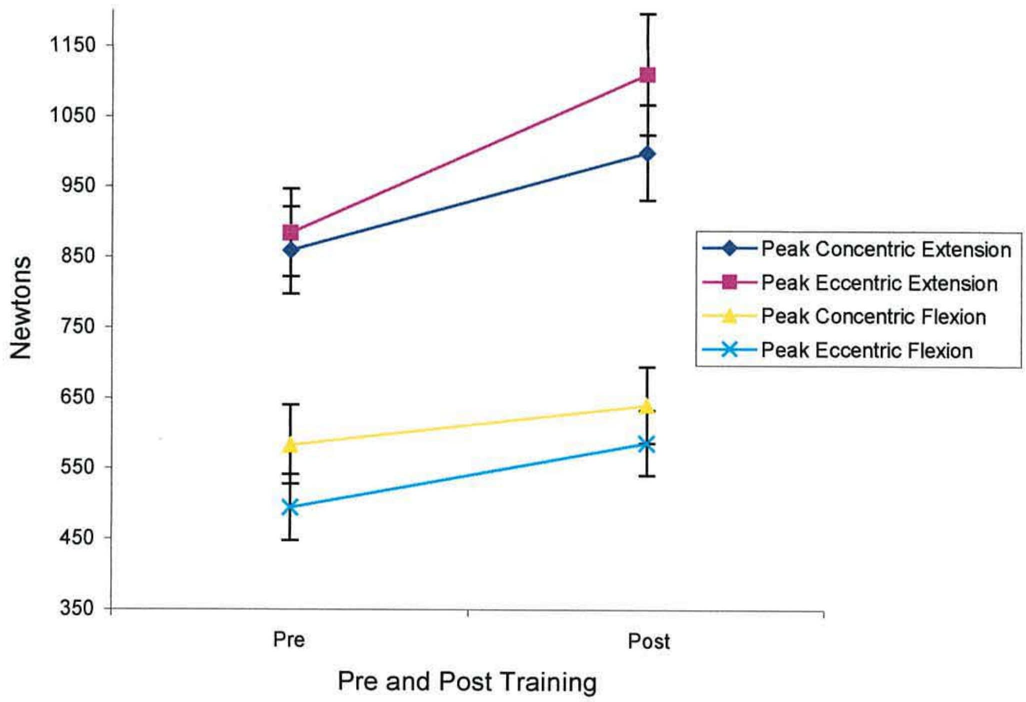

Figure 6: Changes in female experimental group peak isokinetic force values before and after strength training. Values are means (± SEM).

b. Main effects for time

Strength training had a positive effect on peak isokinetic force with post-training values being greater than pre-training values across all recorded modes. Pre and post mean (± SD) values for peak forces were 932 ± 246 N and 998 ± 292 N; 1021 ± 302 N and 1110 ± 330 N; 589 ± 179 N and 637 ± 213 N; 611 ± 202 N and 666 ± 213 N for peak concentric extension, eccentric extension, concentric flexion and eccentric flexion respectively.

There was also a significant main effect of time on peak concentric extension ($F_{1, 25}$ = 8.23 P = 0.008), peak eccentric extension ($F_{1, 25}$ = 4.98, P = 0.04), peak concentric flexion ($F_{1, 25}$ = 6.85, P = 0.015) and peak eccentric flexion ($F_{1, 25}$ = 9.86, P = 0.004). This effect is illustrated in Figure 7.

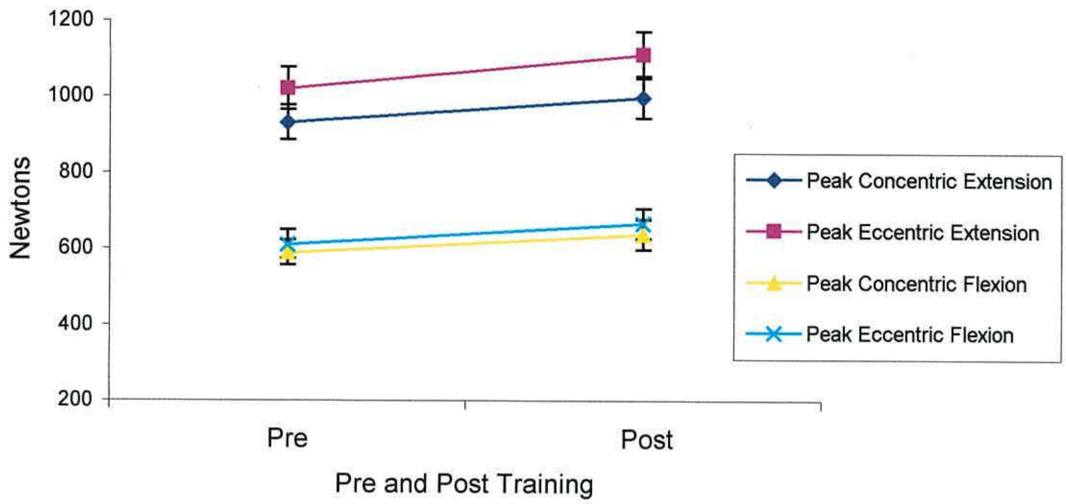

Figure 7: Changes in peak isokinetic force parameters before and after strength training. Force values are means for all subjects irrespective of gender or group. All values are expressed as means (± SEM) and were significantly different post-training ($P < 0.05$).

5.4.2.2 Mean Values

a. Between subjects interactions

There was a significant interaction effect of time x group on mean concentric extension ($F_{1,25} = 13.747$, $P = 0.01$), mean eccentric extension ($F_{1,25} = 4.446$, $P = 0.045$), mean concentric flexion ($F_{1,25} = 5.090$, $P = 0.033$) and mean eccentric flexion ($F_{1,25} = 5.913$, $P = 0.023$), i.e. the post-test scores were significantly affected by the experimental group. Those undertaking training experienced significant increases in strength whereas there was no significant difference in control group subjects. The significant interaction of time x group for each force parameter is shown in Figures 8 and 9.

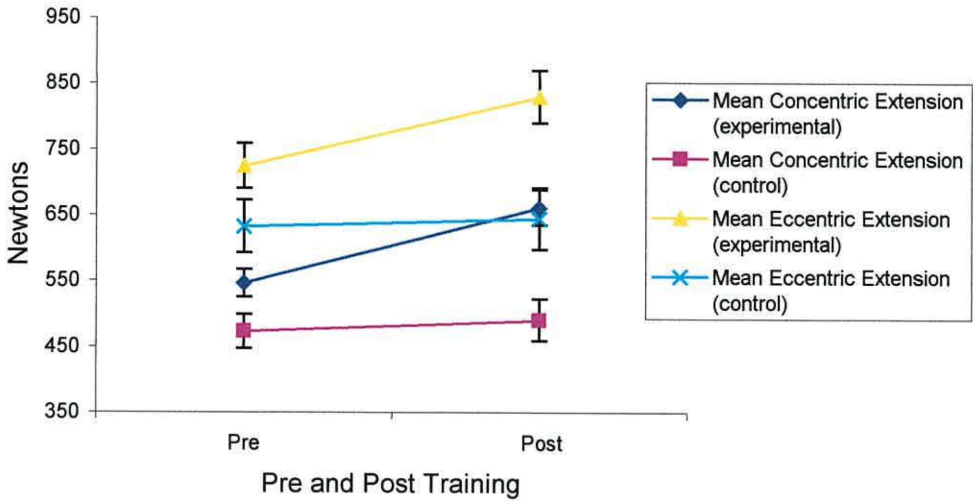

Figure 8: The significant interaction of time x group for mean isokinetic force values during leg extension. Values are mean (± SEM).

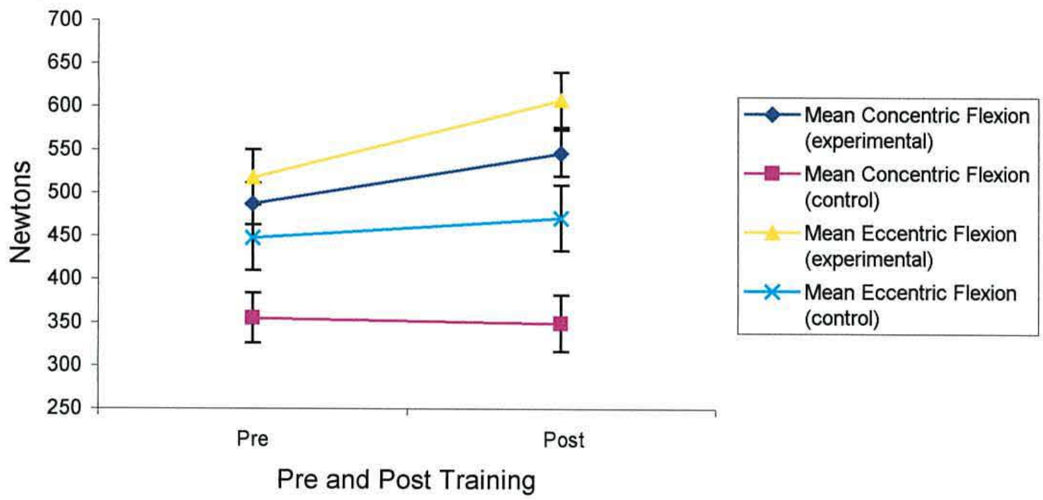

Figure 9: The significant interaction of time x group for mean isokinetic force values during leg flexion. Values are mean (± SEM).

There was no significant interaction of time x gender for mean concentric extension (($F_{1,25} = 0.826$, $P > 0.05$), mean eccentric extension ($F_{1,25} = 0.247$, $P > 0.05$) and mean eccentric flexion ($F_{1,25} = 0.033$, $P > 0.05$). There was, however, a significant interaction of time x gender for mean concentric flexion ($F_{1,25} = 5.090$, $P = 0.033$). The interaction of time x gender is illustrated in Figure 10.

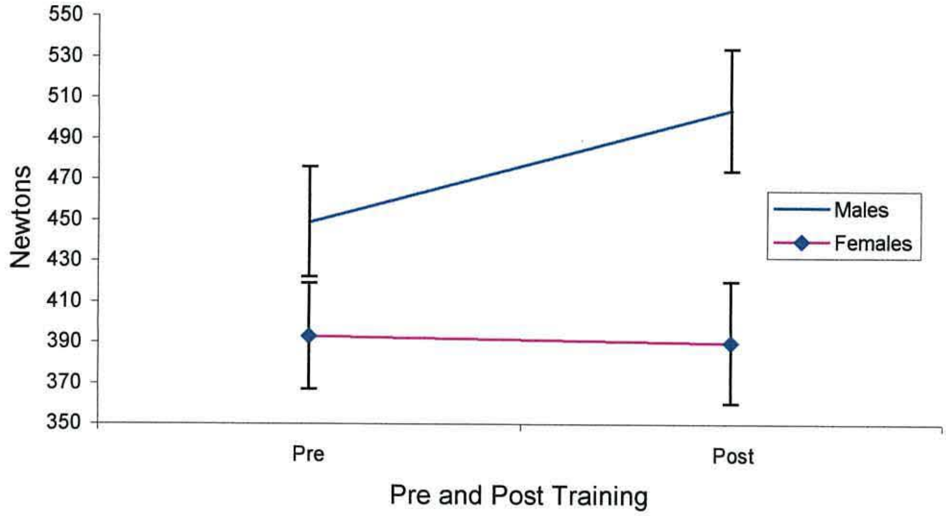

Figure 10: The significant interaction of time x gender ($F_{1,25} = 5.090$, $P = 0.033$) for mean concentric flexion. Values are means (± SEM).

b. Main effects for time

Mean isokinetic force responded to training in a similar way to peak forces. There was a significant main effect of time on all mean force parameters. Mean concentric extension increased from 514 ± 19 N to 587 ± 28 N (mean ± SEM) ($F_{1,25} = 24.408$. $P = 0.00$) whilst mean eccentric extension rose from 681 ± 32 N to 750 ± 37 N ($F_{1,25} = 7.015$, $P = 0.01$). Flexion values also increased with mean concentric flexion rising from 431 ± 23 N to 461 ± 30 N ($F_{1,25} = 4.136$, $P = 0.05$) and mean eccentric extension from 485 ± 29 N to 547 ± 30 N ($F_{1,25} = 16.922$, $P = 0.00$). The significant main effect of time is shown in Figure 11.

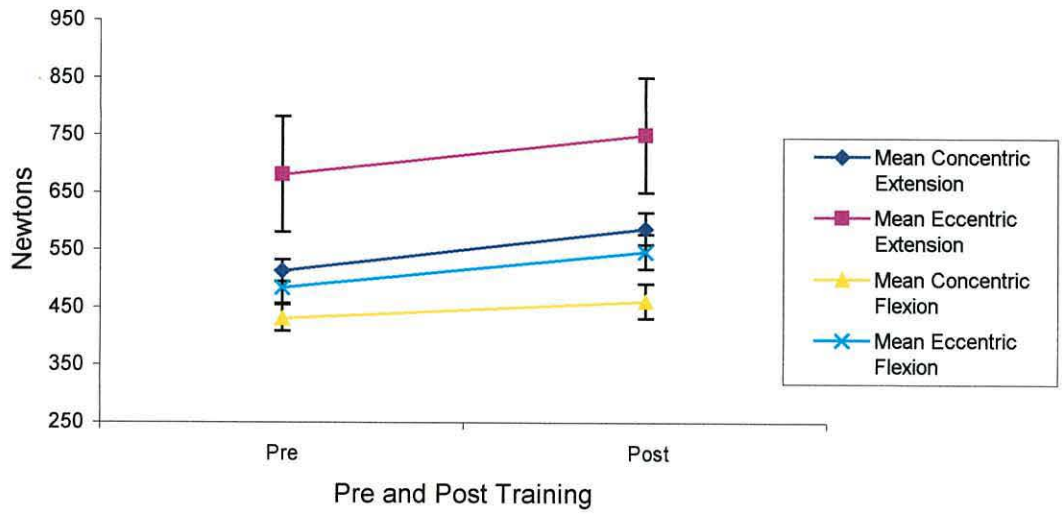

Figure 11: Changes in mean isokinetic force parameters before and after strength training. Force values are means for all subjects irrespective of gender or group. All values are expressed as means (± SEM) and were significantly different post-training ($P < 0.05$).

5.4.3 Power Output

5.4.3.1 Peak Power

a. Between subjects interactions

There was a significant interaction of time x group on peak power ($F_{1,25} = 4.428$, $P = 0.046$) with peak power increasing from 830 ± 35 W to 903 ± 38 W (mean ± SEM) for experimental subjects. The female experimental group improved from 622 ± 49 W to 673 ± 52 W before and after training and the male experimental group from 1038 ± 52 W to 1133 ± 55 W. There was no significant interaction of time x gender ($F_{1,25} = 0.591$, $P = 0.449$). The significant interaction of time x group is illustrated in Figure 12.

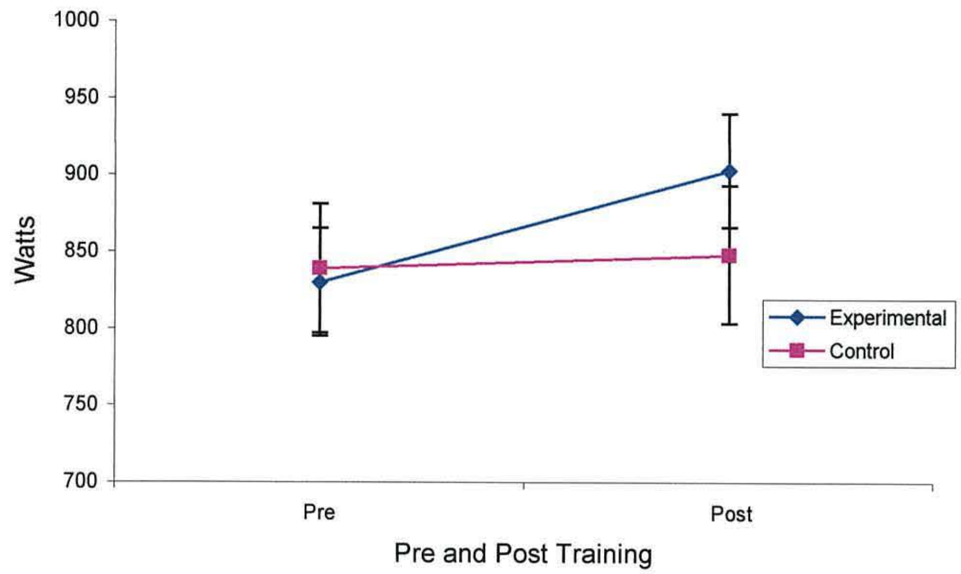

Figure 12: The significant interaction of time x group for peak power ($F_{1,25} = 4.428$, $P = 0.046$). Values are mean (± SEM).

b. Main effects for time

There was a significant main effect of time on peak power output, i.e. peak power output was significantly higher at post-test ($F_{1,25} = 7.080$, $P = 0.013$), irrespective of gender and group (pre 827 ± 232 W, post 873 ± 251 W) (Mean ± SD). The main effect of time on peak power is shown in Figure 13.

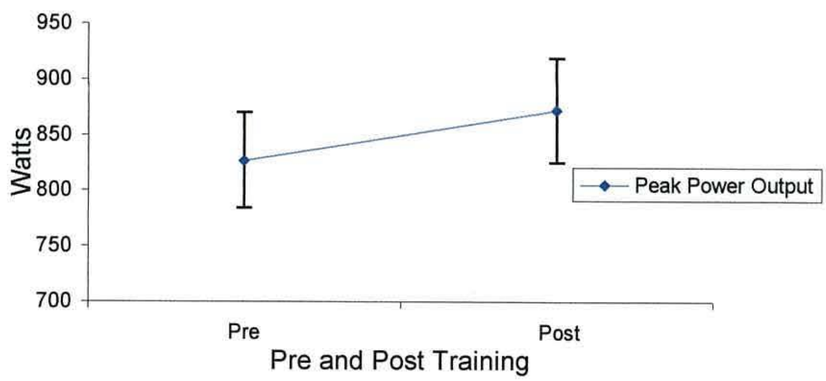

Figure 13: The main effect for time on peak power output for all subjects irrespective of gender or group. Power values are expressed in watts and as means (± SEM). Power output was significantly higher post-training ($F_{1,25} = 7.080$, $P = 0.013$).

5.4.3.2 Mean power

a. Between subjects interactions

There was no interaction of time x group ($F_{1, 25} = 2.358$, $P = 0.137$) or time x gender ($F_{1, 25} = 0.385$, $P = 0.540$) on mean power. The increase in mean power output for the experimental group from 538 ± 15 W to 558 ±17 W (mean ± SEM), with females increasing from 422 ± 21 W to 434 ± 23 W and males from 655 ± 23 W to 681 ± 25 W were therefore not significant.

b.Main effects for time

There was no main effect for time (pre v post) on mean power. There was no significant difference between the overall pre versus post-mean power measure ($F_{1, 25} = 2.813$, $P = 0.106$) irrespective of gender and group (pre 538 ± 144, post 549 ± 137 W) (mean ± SD).

5.4.4 **Total Work**

5.4.4.1 Between subjects interactions

a. Concentric extension

There was a significant interaction of time x group ($F_{1, 25} = 26.933$, $P = 0.000$), time x gender ($F_{1, 25} = 4.948$, $P = 0.035$) and time x gender x group ($F_{1, 25} = 5.140$, $P = 0.032$) on concentric extension values. Post-training values were affected both by group and by gender with the latter moderating the experimental effect. These interactions are shown in Figures 14-16.

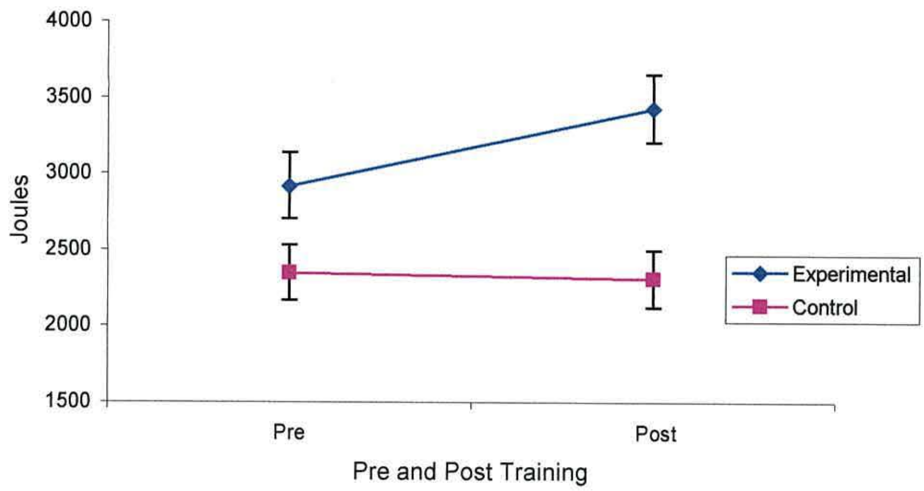

Figure 14 : The significant interaction of time x group on total work performed during 30 s of isokinetic concentric extension ($F_{1,25} = 26.933$, $P = 0.000$). Values are means (± SEM). Finding : experimental group increased whilst there was no change in control group.

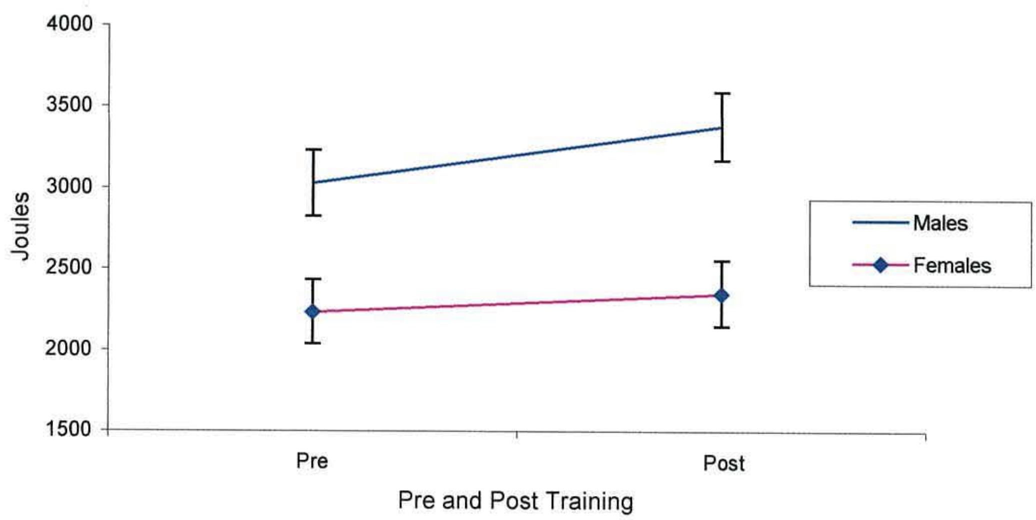

Figure 15: The significant interaction of time x gender for total work performed during 30 s of isokinetic concentric extension ($F_{1,25} = 4.948$, $P = 0.035$). Values are means (± SEM). Finding: Males increased to a greater extent than females.

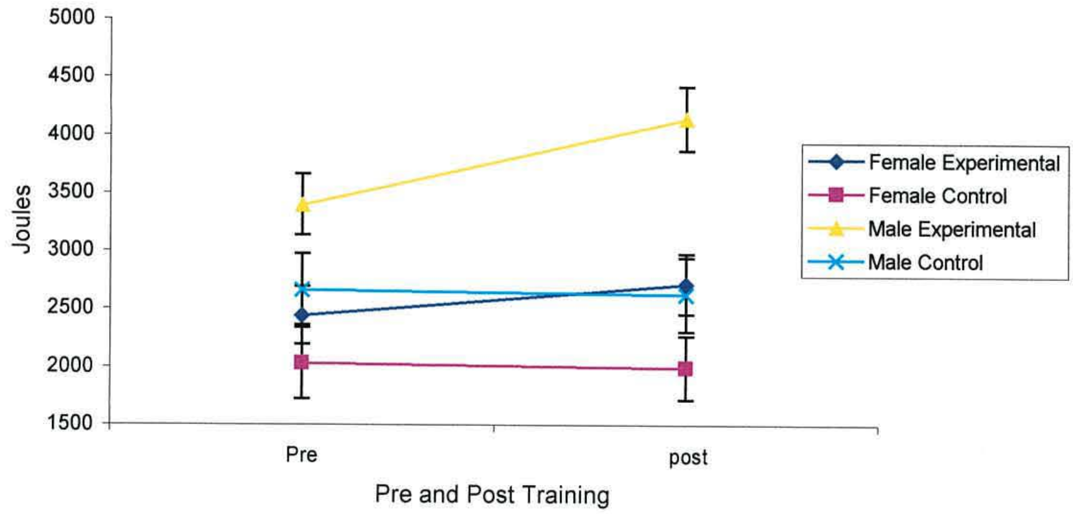

Figure 16: The significant interaction of time x gender x group for total work performed during 30 s of isokinetic concentric extension ($F_{1, 25} = 5.140$, $P = 0.032$). Values are means (± SEM). Finding : no change in male and female control groups, the change in male experimental group was greater than the change in the female experimental group.

b. Concentric Flexion

There was a significant interaction of time x group on concentric flexion ($F_{1, 25} = 4.390$, $P = 0.046$) but no interaction of time x gender ($F_{1, 25} = 2.230$, $P = 0.148$) or time x group x gender ($F_{1, 25} = 0.967$, $P = 0.335$) on concentric flexion i.e. the pre and post scores were affected by experimental group but not by gender. The interaction of time by group is shown in Figure 17.

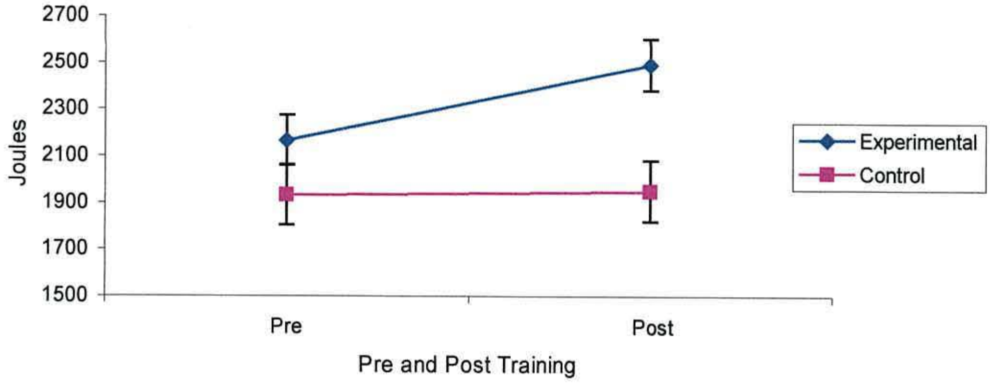

Figure 17: The significant interaction of time x group for total work performed during 30 s of isokinetic concentric flexion ($F_{1, 25}$= 4.390, P = 0.046). Values are means (± SEM).

5.4.4.2 Main effects for time

a. Concentric extension

There was a significant main effect of time (pre and post) on total work performed during concentric extension, irrespective of gender and group. Work done rose from 2665 ± 161 J (mean ± SEM) pre training to 2939 ± 202 J post training ($F_{1, 25}$ = 19.77, P = 0.000).

b. Concentric flexion

There was a significant main effect of time (pre and post) on total work performed during concentric flexion, irrespective of gender and group. Work done rose from 2054 ± 113 J pre training to 2245 ± 140 J post training ($F_{1, 25}$ = 5.430, P = 0.028). The main effect of time x total work is illustrated in Figure 18.

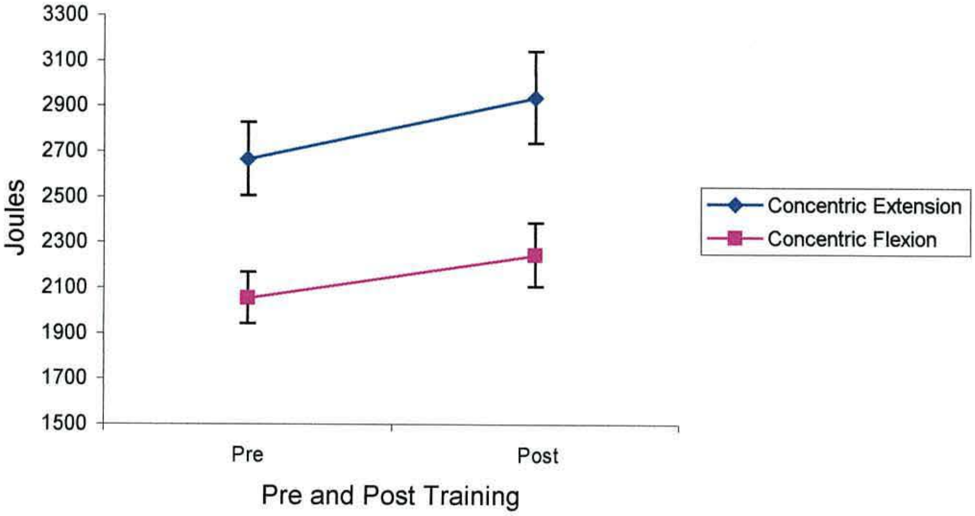

Figure 18: The main effect of time on total work performed during 30 s isokinetic extension and flexion. Values are in Joules and expressed as mean (± SEM).

5.4.5 Correlations

5.4.5.1 Peak concentric extension and peak power output

There was a significant relationship between isokinetic peak concentric extension and peak power output measured during 30 s maximal cycling both pre ($r = .688$, $P < 0.01$) and post-training ($r = .669$, $P < 0.01$). The relationship is shown in Figure 19.

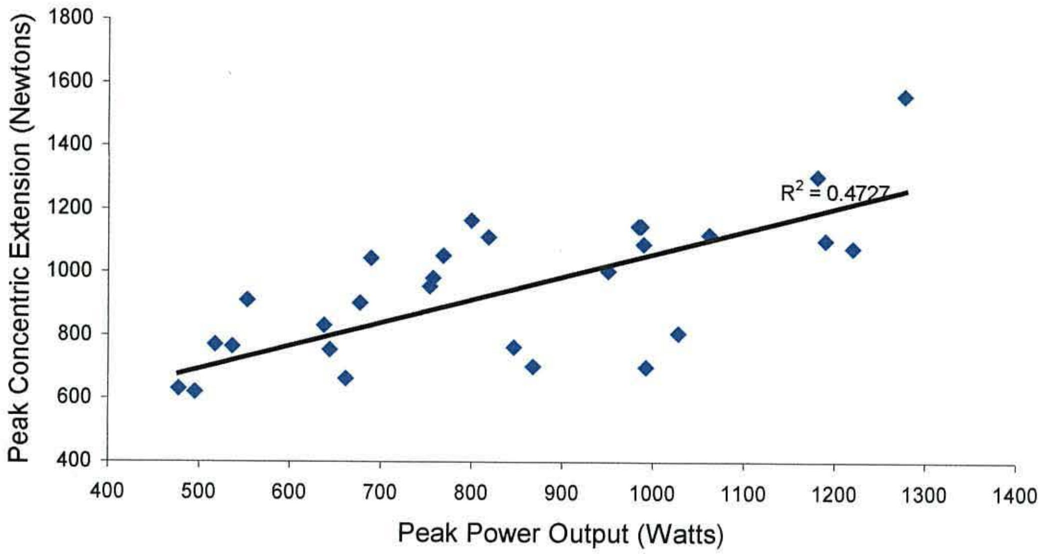

Figure 19: The significant relationship between pre-training isokinetic peak concentric extension and peak power output obtained during 30 s maximal cycling (r = .688, P < 0.01).

5.4.5.2 Mean power output and total work.

There was a significant relationship between mean power output and total work performed during concentric extension both pre (r = .627, P < 0.01), and post training (r = .607, P < 0.01). Results were similar for pre (r = .729, P < 0.01) and post-training (r = .734, P < 0.01) for mean power and total work performed during concentric flexion. The relationship between pre-training mean power and total work performed for concentric extension is shown in Figure 20.

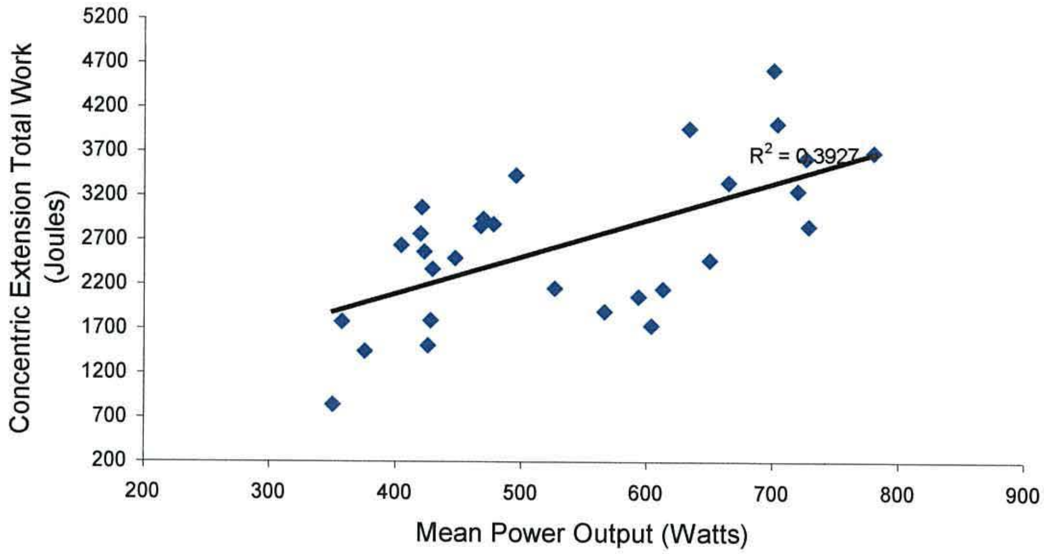

Figure 20: The significant relationship between mean power output and total work performed during 30 s of maximal isokinetic concentric extensions ($r = .627$, $P < 0.01$).

5.5 Discussion

5.5.1 Summary

There was a significant increase ($P < 0.05$) in force production across all variables for both experimental groups with no significant change in control groups ($P > 0.05$). Thus, the 12-week strength training intervention had successfully brought about an increase in strength as measured by isokinetic dynamometry. The experimental groups also experienced a significant increase in peak power ($P < 0.05$) with no significant change in control groups ($P > 0.05$). Strength training resulted in an increased ability to produce power during maximal cycling. However, mean power measured during 30 s maximal cycling demonstrated no significant change for either experimental or control groups ($P > 0.05$) although both experimental groups showed an increase, which suggested that strength training may have a positive impact on mean power or anaerobic capacity. Total work done increased in both modes in the experimental groups during the 30 s continuous isokinetic extension and flexion protocol ($P < 0.05$). This activity closely mirrored the movements that experienced increases in maximal force production, and would suggest that strength training and the increase in force production increased resistance to fatigability (Lesmes, 1978) and enabled a greater amount of maximal activity to be performed. The control groups displayed no significant change ($P > 0.05$), in either extension or flexion modes. Total work correlated highly with mean power output in both pre and post-training conditions ($P < 0.01$), further supporting the positive benefit of strength training on high intensity anaerobic activity. The generally accepted relationship between strength and maximal power was supported by the significant correlation between peak isokinetic concentric extension and peak power output measured during maximal cycling ($P < 0.01$). Both force and power output increased following training.

5.5.2 Design

The use of a weight training intervention and the accompanying use of control groups was an important feature of this study. Previous comparisons of male and female strength and power characteristics, or analysis of strength measures, have often used previously trained or untrained individuals, sometimes together, or with matched controls (Aagaard *et al.*, 1997). The results may often therefore be misleading due to the inherent disposition of subjects, resulting in natural self-selection for particular activities (Castro *et al.*, 1995).

The training intervention in this study allowed for a comparison of individuals who had been exposed to the same training stimulus. The pre and post testing helped remove performance differences that may have resulted from the situation described above, and other issues relating to methodology such as appropriate loadings during cycle ergometry (Froese and Houston, 1987). The design allowed for comparison of responses to a training stimulus, which is important in the evaluation of strength and its relationship with power and anaerobic capacity.

5.5.3 Isokinetic force ratios

There was no significant difference in either the H/Q strength ratio or the DCR. This finding helped to support the efficacy and quality of the training programme undertaken, suggesting that strength increased in a balanced way and that the strength of the quadriceps and hamstrings increased proportionately. The unchanged DCR would also suggest that the eccentric activity has been equal to the concentric activity and that the muscles were trained effectively in both modes. As discussed previously, ratios are important tools to analyse muscle function (Grace *et al.*, 1984; Knapik, *et al.*, 1992; Dvir 1995) and are equally important for monitoring the nature and effects of training intervention. In this study both ratios had similar values, but the DCR provided important information with regard to the eccentric phase of training. As stated in Chapter 3, rugby league players reported a biased approach to training with greater emphasis placed on concentric rather than eccentric action. This study supports the previous studies with regard to the usefulness of the knee flexor/extensor strength ratios and in particular supports the use of the DCR. Importantly, in relation to the aims of this study, the ratios demonstrated that the training had been balanced and led to strength improvements that had been similar in both males and females. There was no significant interaction between time x gender ($P > 0.05$) or time x group

($P > 0.05$) on isokinetic force ratios. Thus, experimental subjects experienced an increase in strength, with no change in ratios regardless of gender.

5.5.5 Isokinetic Force Values

Both experimental groups (men and women) significantly increased force ($P < 0.05$) following the strength training programme in comparison with no significant change in control group subjects ($P > 0.05$). Increases occurred for peak and mean values, concentric and eccentric actions and in extension and flexion modes. The strength training intervention was thus successful in bringing about improvements in strength and force production. It demonstrated that a simply designed training programme, using readily available fixed-weight training apparatus has a beneficial effect on strength.

The overall increase in strength across experimental subjects for peak forces ranged from 9.2 % to 13.3 % percent for men and from 8.9 % to 20.3 % for women. This was in line with a previous study that reported strength increases of 17.6 % for knee extension when measured by isokinetic dynamometry (Luthi *et al.*, 1986). Percentage changes tend to be less when measured by isokinetic dynamometry compared with improvements measured on the training apparatus. This is probably connected with the neurogenic adaptation (Sale, 1987) and the training effect associated with the training apparatus. A more recent study employed isokinetic training of one leg and found an increase in strength of 17.7 % (Housh *et al.*, 1996). It would therefore appear that the fixed-weight apparatus utilised in this study brought about strength changes similar to those achieved using other training apparatus including isokinetic dynamometry.

The pre and post measures were moderated by group, but not by gender. There were no interactions of time x gender for any of the force variables measured, apart from mean concentric flexion ($P = 0.033$). Men and women therefore increased similarly and responded equally to the training stimulus. In their review, Holloway and Baechle (1990) reported a number of studies comparing the training response between men and women undertaking the same training routine. Although the absolute changes had been greater for the men, the percentage change was similar across the sexes for both the upper and lower body. They also cited the work of Hakkinen *et al.* (1989) who found greater percentage changes in women than men in isometric leg extension force. The results of this study are in line with these previous findings and with more recent studies that have shown similar responses in men and women (Staron 1991) and that the time-course for changes is similar in both groups (Staron 1994).

In the light of the above findings, the significant interaction of time x gender for mean concentric flexion is hard to explain. The disproportional increase in force for mean concentric flexion compared with mean concentric extension resulted in a mean H/Q strength ratio that was less after training than before training. However both values were well within the previously reported optimal range (Kannus, 1994). Although absolute strength differences between males and females have been suggested to be due to size and body composition (Holloway and Baechle, 1990; Castro *et al.*, 1995), hormonal differences (Shephard, 2000) and socio-cultural differences (Wilmore, 1975; Winter *et al.*, 1991; Shephard, 2000), these will not necessarily account for the differences in responses between males and females. When comparing differences in response for mean concentric flexion in this study, the first factor can be discarded because of the nature of a training intervention study, and because the other parameters have changed in line with the males. Additionally, the theory that women adapt differently due to differing levels of hormones, particularly lower testosterone, can also be discounted because of the reaction of the other force variables and because men and women have been shown to respond in proportion to baseline levels of hormones (Holloway and Baechle, 1990). The consideration of these aspects is made easier because of the comparisons using a training intervention study and is further support for such an experimental design. As already discussed, studies have shown men and women to respond to strength training in the same way. Although this study has looked at the strength of the thigh by analysing differing muscle groups and modes of action, this unlikely to have influenced the results. Studies have shown that males and females respond similarly with regard to both eccentric and concentric improvements and that the improvements between the modes are similar (Colliander and Tesch, 1991). There would therefore appear to be no physiological explanation for this particular interaction.

A possible factor in the time x gender interaction is therefore, the influence of socio-cultural factors. The training programme employed the use of the hamstring curl, a notoriously uncomfortable and often difficult movement to perform. It was chosen because of its availability and its specificity. The differing response in the women may have been due to pre–training differences due to prior use or activity. This would not have been identified at pre-testing due to the different position used to test isokinetic concentric flexion compared with the training apparatus. Further to this, studies have shown that males and females respond similarly with regard to both eccentric and concentric improvements and that the improvements between modes are similar (Colliander and Tesch, 1991).

In summary men and women significantly improved force production after a period of strength training. With one exception, responses were not moderated by gender.

5.5.6 Maximal Anaerobic power.

5.5.5.1 Peak power

A link between strength and peak power has long been recognised (Coyle, 1981), and has been identified through the use of plyometric intervention (Potteiger, 1999), measurement of isokinetic torque (Latin, 1992) and has been identified in specific sporting groups (Baker and Nance, 1999). Improvements in strength should lead to improvements in power output because power is the product of strength (force) and velocity (Sleivert 1995). In this study, male and female experimental subjects experienced significant increases in force production ($P < 0.05$) and in peak power output following training, thus supporting previous findings. Analysis showed there to be a significant main effect for time ($P = 0.013$) and a significant interaction of time x group on peak power output ($P = 0.046$). Thus a strength training programme increased isokinetic force production, and consequently increased the ability to produce peak power during maximal cycling. Isokinetic forces and peak power output have previously been studied (Lesmes, 1978; Smith, 1987; Latin, 1992), with significant correlations found to exist between anaerobic power and isokinetic peak torque (Latin, 1992). In this study, peak power output showed a moderate to high correlation with peak concentric extension pre ($P < 0.01$) and post training ($P < 0.01$). Peak concentric extension was chosen to illustrate the relationship because cycling in non-elite subjects is likely to involve predominantly concentric extension activity. The highly significant correlation clearly demonstrates the relationship between strength and power.

There was no significant interaction of time x gender ($P = 0.449$), once again demonstrating that men and women have responded similarly to the training response. Men had higher absolute peak power outputs than women but both groups showed similar increases with male peak power increasing by 8.4 % and female peak power by 7.6 % post-training. Higher absolute power output values have previously been reported for males (Froese and Houston, 1987; Winter *et al.*; 1991, Hill and Smith, 1993) with physiological, mechanical and social factors cited as possible reasons for the difference (Winter *et al.*, 1991). None of the above studies made comparisons of training and responses to training. Rather they compared male and female subjects, the majority of whom were students of physical education or students who were moderately active. Although the absolute differences may exist, analysis of responses to a training intervention provides more detail and allows for a potentially greater understanding of the strength power/relationship. With no significant moderation by gender, and with the highly significant correlation between peak concentric extension and peak power output, this study supports the conclusions of Mayhew *et al.* (2001) that body size and strength appear to be the major factors explaining leg power differences. Such differences are not altered by strength training with men and women responding in a similar manner.

5.5.5.2 Mean Power Output.

The peak power attained in the first five seconds of the Wingate 30 s test is used as an index of anaerobic power, whereas the mean power attained over the full 30 s is used as an indication of anaerobic capacity. In other words, the peak power is assumed to reflect maximal power generation by the breakdown of phosphagens, whereas mean power represents energy production from combined phosphagen breakdown and glycogenolysis (Jacobs *et al.*, 1982, cited in Smith, 1987). This is a somewhat simplistic explanation and it is clear that glycogenolysis contributes from the beginning and that oxidative phosphorylation makes a significant contribution during the 30 s all-out effort (Hill and Smith, 1993). However, the mean power derived provides a useful indication of maximal exercise performance (Winter *et al.*, 1991; Hill and Smith, 1993) and the ability to sustain high-intensity effort over a 30 s period.

Peak power is more commonly quoted than mean power (e.g. Latin, 1992; Mayhew *et al.*, 2001) although mean power has previously been correlated with isokinetic torque (Smith, 1987), and been compared between males and females (Froese and Houston, 1987; Winter *et al.*, 1991). Smith (1987) found high and significant relationships between isokinetic peak torque (at $180^{\circ}s^{-1}$) and mean power. Values were largely mirrored in this study with significant correlations existing between peak concentric extension and mean power both before and after training ($P < 0.01$).

Few studies have investigated the effects of strength training on mean power specifically, and prolonged anaerobic performance generally. This study found no significant main effect for time ($P = 0.106$), no significant interaction for time x group

($P = 0.137$), or time x gender ($P = 0.540$) on mean power. These appear contrary to studies that have shown a significant reduction in fatigability (Lesmes, 1978), and an increase in total work performed during maximal cycling following a strength training intervention (Mannion *et al.*, 1994). However, these studies did not focus directly on mean power output and although this study produced non-significant results, both male and female experimental groups demonstrated increases in mean power output. Although the results are equivocal it would appear that there is a strong relationship between strength and mean power and that strength training can have a positive effect on mean power output. Certainly in activities that require prolonged anaerobic activity, there should be no concerns in prescribing a structured weight-training programme.

As with peak power, there were absolute differences between males and females, although the difference was greater for mean power (64 and 65 % of male power pre and post-training) than it was for peak power (75 % of male power pre and post-training). Such gender differences in anaerobic power and capacity have been previously reported (Evans and Quinney, 1981; Froese and Houston, 1987; Hill and Smith, 1993) but what is of interest in this study is again the similar response that occurred after strength training. Although the positive changes were non-significant, there was no gender interaction, demonstrating that men and women respond similarly to anaerobic performance following strength training.

5.5.6 Concentric Extension and Concentric Flexion Total Work

As well as examining the effects of strength training on power output during maximal cycling, this study also measured total work performed during 30 s of maximal concentric extension and flexion performed on an isokinetic dynamometer. Such isokinetic evaluations have previously been proven to be useful measures of anaerobic performance and to correlate significantly with values measured during a 30 s Wingate test (Baltzopoulos *et al.*, 1988). This study supported the previous findings, with significant correlations obtained between mean power output and both concentric extension and flexion total work ($P < 0.01$) in pre and post conditions. Such correlations helped support the appropriateness of the isokinetic tests as a measure of anaerobic capacity. The isokinetic evaluation consisted of 30 s continuous isokinetic extension and flexion and was the same action used to measure changes in peak force. It was consequently a specific test that was closely related both to the force measure and the nature of the intervention. However, the movements were different enough from the training such that neurogenic adaptations would not be entirely responsible for any post-training improvement.

The significant main effect for time on both extension and flexion would suggest that the strength training has led to a significant improvement in the ability to undertake maximal activity. Following strength training the subjects were able to perform a greater amount of total work. The significant interaction of time x group highlighted that the experimental groups increased their ability with no significant change in control subjects. The responses for extension and flexion were similar, with females increasing by 10 % and 7.8 %, respectively and the males by 18 % and 16.1 % respectively. The female responses were similar to those reported by Mannion *et al.* (1994) who found that a mixed group of males and females increased work by 8-9 % after training. However their study found that a similar level of work was maintained for a longer period of time, whereas the current study found an increase in work for a given period of time. This phenomenon occurred for both males and females, but to a greater extent in the males. Indeed, the male and female difference was significant for concentric extension with a significant interaction of time x group x gender ($P < 0.05$). The moderation of the experimental effect by gender is hard to explain. Men and women responded similarly with regard to strength increases and in production of power output on the cycle ergometer. The only gender interaction reported for force production was with mean concentric flexion; it is unlikely that this affected the total work performed during concentric extension. Although absolute differences have been reported, it is not clear why this particular parameter would respond differently to training, particularly with all other parameters responding similarly. It is also difficult to explain because few studies have previously studied the effects of strength training on performance of this type. Although similar, the Mannion study measured work using a cycle ergometer following isokinetic training, whereas this study used conventional strength training and measured work using an isokinetic dynamometer.

A greater number of studies have examined the effect of sprint training on anaerobic performance and have examined enzymatic influences and responses (Linossier *et al.*, 1997; Dawson, *et al.*, 1998; MacDougall, *et al.*, 1998,). These studies all concluded that sprint training increased peak power output, or short-term power, with improvements also recorded for total work over 30 s (MacDougall *et al.*, 1998) and repeated sprint performance (Dawson *et al.*, 1998). Performance increases were accompanied by changes in glycolytic enzyme activity, thus performance was suggested to have increased due to glycogenolytic and glycolytic adaptation. In this respect gender differences have been previously identified (Hill and Smith, 1993) because of the greater aerobic contribution made by females. It is therefore possible that changes in the glycolytic potential of the muscle may be brought about by strength training, but that these may be less significant in influencing anaerobic performance in women than in men. This is however extremely speculative as the training undertaken in this study was strength and not sprint focused and because no specific measurements of enzyme activity were made. Additionally, there was no interaction of time x gender on concentric flexion. The situation is further unclear because the sprint training studies cited all used relatively few subjects (n=8, n=9, n=12 respectively with no control) and in all cases the subjects were male. This is of course a potential limitation with the current study. The individual groups, i.e. male / female and experimental / control, contain relatively few subjects, therefore there is a potential for type II error to occur. The limited gender interaction discussed above may simply be due to the small sample size and subsequent lack of power leading to the null hypothesis being wrongly accepted. The analysis of gender interaction demonstrated a particularly low power, on occasion little over 50 % and much lower than the commonly accepted 80 % (Thomas and Nelson, 2001). Hence, the time x gender interaction for mean concentric flexion may be unusual simply due to type II error occurring for the other parameters. There is a need also to be cautious when considering the time x group interactions. Analysis of these yielded greater power, 70 %-84 %, but the risk of type II error still exists and it is possible that control group changes were masked by the lack of power. There is therefore a need for further studies examining enzymatic responses but using greater numbers, employing females as well as males and using a strength training intervention.

Overall however, there was a significant increase in total work performed during 30 s of concentric extension and flexion for both males and females. This suggests that strength training can significantly improve the ability to undertake prolonged anaerobic activity.

5.6 Conclusion

A twelve-week period of strength training brought about significant increases in isokinetic force production in both males and females. This in turn led to significant increases in peak power production measured during cycle ergometry. Mean power, also increased in both males and females and although the increase was not significant, the mean power values correlated significantly ($P < 0.01$) with total work performed during concentric extension and flexion measured during a 30 s continuous isokinetic test. These results support previous findings with regard to the strength/power relationship, but also suggest that strength training can improve the ability to perform anaerobic activity and may positively enhance anaerobic capacity in both males and females. The exact reasons for this improvement are not yet clear but the results highlight the importance of a balanced weight-training programme for those involved in activities that require a significant anaerobic contribution.

CHAPTER 6

STRENGTH TRAINING IN MALES AND FEMALES: EFFECTS ON MUSCLE QUALITY

6.4.10 Concentric Extension Total Work Expressed as a Power Function Ratio

6.5 Discussion

6.5.1 Summary

6.5.2 Isokinetic Force Values

6.5.3 Anaerobic Performance

6.5.4 Isokinetic Total Work

6.5.5 Conclusion

6.1 Abstract

Objectives

The purpose of this study was to compare muscle quality of the knee extensors and flexors in males and females, before and after a strength training programme using power function and simple ratios. Male and female subjects performed the same strength training programme, and were analysed for muscle quality with regard to maximal isokinetic force, power output during maximal cycling and 30 s continuous isokinetic activity.

Methods

Nine women (age 24.1 ± 7.8 yr (mean ± SD), ht 169.5 ± 6.1 cm, mass 64.8 ± 7.2 kg) and eight men (age 21.6 ± 4.6 yr, ht 180.8 ± 6.6 cm, mass 79.8 ± 6.8 kg) participated as experimental subjects. A further six women (age 25.3 ± 5.2 yr, ht 167.6 cm, mass 66.4 ± 7.2 kg) and six men (age 26.0 ± 5.7 yr, ht 176.8 ± 7.0 cm, mass 78.0 ± 11.0 kg) participated as control subjects. Experimental subjects participated in a 12-week strength training programme using fixed weight apparatus. All groups were tested at the beginning and end of the programme for isokinetic force, anaerobic performance, measured during the Wingate 30 s test, and total work performed during a 30 s continuous test of isokinetic extension and flexion. Additionally subjects were measured for leg volume using the anthropometric technique of Jones and Pearson (1969). Simple ratios were calculated by dividing the performance variable by lean thigh volume. Power function ratios were calculated by dividing the performance variable by lean thigh volume $^{-0.67}$. Before and after values were analysed using a series of mixed-model, three factor analyses of variance.

Results

There were no interactions for time x group or time x gender for lean thigh volume. There were no interactions for time x group or time x gender for muscle quality when expressed as a simple ratio but there was a significant interaction of time x group ($F_{1, 25} = 5.278$, $P = 0.03$) when expressed as a power function ratio. There was no significant change in either type of ratio, for either peak or mean power output ($P > 0.05$) following training, although the differing ratios demonstrated differences with regard to male and female muscle quality. Analysis of total work performed during isokinetic dynamometry showed a general increase in concentric extension total work on the second test occasion, but no significant interactions of time x group or time x gender when expressed as a simple ratio ($P > 0.05$). Using the power function ratio also indicated an increase in total work on the post-training occasion and also a significant interaction of time x group ($F_{1, 25} = 8.058$, $P = 0.01$).

Conclusion

Although correct normalisation procedures have been used for male and female comparisons they have not previously been used to compare the effects of training. This study shows that strength training improvements in muscle quality in both males and females will be potentially masked if a simple ratio is used. If leg volume is raised to the power 0.67, then muscle quality in males and females increases similarly. This is the case for both isokinetic force and anaerobic performance during continuous isokinetic activity.

6.2 Introduction

Despite the widespread use of strength training it is only recently that researchers have focused their attention on acute and chronic responses in women (Holloway and Baechle, 1990). As a consequence, understanding regarding strength training interventions and their effects on women is still developing. One way of exploring adaptations in females is to make comparisons with male subjects. Strength differences between males and females have been attributed to size and body composition (O'Brien 1985; Holloway and Baechle, 1990; Castro *et al.*, 1995), the hormonal milieu (Shephard 2000) and socio-cultural differences (Wilmore, 1975; Shephard 2000). Because size and body composition are a factor, and because muscle strength is directly related to its cross-sectional area (Blade *et al.*, 1992) it is common practice to make comparisons by dividing strength by cross-sectional area (Castro *et al.*, 1990) or by unit of muscle mass (Tracy *et al.*, 1999; Ivey *et al.*, 2000). The force production per unit of muscle mass has been referred to as 'Muscle Quality' (Tracy *et al.*, 1999; Ivey *et al.*, 2000).

Strength per unit cross-sectional area has been compared in males and females with no significant differences observed in either non-trained (Maughan *et al.*, 1983) or physically active subjects (Alway *et al.*, 1990). However Castro *et al.* (1995) reported that few studies have compared the training response with regard to such a ratio and that those that have are equivocal. These investigators examined isometric torque per-unit cross-sectional area between untrained men and women. They found a significant difference between trained and untrained individuals, but due to a lack of a control group these differences could simply have been due to a natural self-selection process. For example, those with greater strength may have entered into physical activity and training. The Castro *et al.* study also found no difference between males and females, proposing that muscle quality is equal between men and women.

More recently, studies have calculated ratios by dividing strength by unit of muscle volume. This is preferred in strength intervention studies because it better represents muscle hypertrophy through the length of the muscle (Tracy *et al.*, 1999). Recent strength training intervention studies have demonstrated significant increases in strength, with no significant differences across gender (Ivey *et al.*, 2000; Roth *et al.*, 2001), a response supported by the study reported in the previous chapter. Likewise it has been proposed that muscle quality responds similarly to training in both, males and females (Tracy *et al.*, 1999; Ivey *et al.*, 2000b), the response being an increase in muscle quality due to the greater proportional increase in strength than in muscle volume. The above studies have consequently concluded that muscle quality is the same in males and females and that muscle quality responds to strength training similarly across both sexes.

By using muscle quality and creating a ratio of strength per unit of muscle volume, it has been assumed that differences resulting from an individual's size have been removed (Nevill *et al.*, 1992; Winter 1992). However, this is not the case and the problems underlying such an assumption have been documented in great detail (Nevill *et al.*, 1992; Winter 1992; Rogers *et al.*, 1995; Winter and Nevill, 1996). Rather than removing the size difference, the ratio-scale distorts it and its use can lead to potentially incorrect conclusions. However despite this, studies continue to employ inappropriate scaling procedures (Jaric, 2002).

Few studies have compared muscle quality responses to a strength training intervention programme in men and women, and few have utilised the appropriate scaling procedures. There are therefore few data regarding the correct muscle quality in men and women and conflicting evidence exists regarding the muscle quality responses across gender following a period of strength training.

Muscle quality with regard to power output has also been studied by comparing male and female power outputs following 30 s maximal cycling (Winter *et al.*, 1991; Eston *et al.*, 1997). Simple ratio scales calculated by dividing power output by lean upper leg volume were compared with power function ratios that raised the leg volume to a logarithmic power. This used an appropriate scaling technique and demonstrated differences in the muscle quality, with males having higher muscle quality than females. However, no studies have examined normalised power output values in males and females following a period of strength training.

The purpose of this study is therefore to compare muscle quality in the knee extensors and flexors in males and females before and after a strength training programme using power function as opposed to simple ratios. To maximise understanding of the training effects, male and female subjects performed the same strength training programme and were compared with untrained control subjects. Subjects were analysed for muscle quality with regard to maximal isokinetic force, power output during maximal cycling and total work during 30 s continuous isokinetic activity.

6.3 METHODS

6.3.1 Participants

Nine women (age 24.1 ± 7.8 yr (mean ± SD), ht 169.5 ± 6.1 cm, mass 64.8 ± 7.2 kg) and eight men (age 21.6 ± 4.6 yr, ht 180.8 ± 6.6 cm, mass 79.8 ± 6.8 kg) volunteered to participate as experimental group subjects. A further six women (age 25.3 ± 5.2 yr, ht 167.6 cm, mass 66.4 ± 7.2 kg) and six men (age 26.0 ± 5.7 yr, ht 176.8 ± 7.0 cm, mass 78.0 ± 11.0 kg) participated as control group subjects. All subjects were either sports participants or recreationally active but had not participated in a structured and systematic resistance training programme for six months prior to the study. All subjects were healthy and none suffered from any musculo-skeletal defects. All subjects received full explanations of the procedures to be used, were made familiar with the tests to be undertaken and provided written informed consent.

6.3.2 Experimental Protocol

Subjects were allocated to an exercise or control group. The exercise groups undertook a series of tests in the laboratory before and after a twelve week strength training programme. Control group subjects were required to be committed to the laboratory tests at the beginning and end of a twelve-week period.

6.3.3 Isokinetic Force Evaluation.

An isokinetic dynamometer (Kin-Com 125E plus, Chattanooga, Tennessee, USA) was used for testing peak and mean forces during maximal voluntary effort. Concentric and eccentric actions were measured during extension and flexion of the dominant leg at an angular velocity of 30° s^{-1}. The protocol used was as described in chapter 3. The force data collected was used to calculate the DCR and H/Q strength ratio.

6.3.4 Anthropometric Determination of Leg Volume.

This was undertaken using the methodology of Jones and Pearson (1969). Subjects stood erect with feet slightly apart. Circumference measurements were taken using an anthropometric tape (Bodycare Products, England, UK) at seven sites on the leg. The seven sites were; the gluteal furrow, one third of the subischial height proximal to the tibial-femoral space, the minimum circumference above and below the knee, the maximum circumference around the knee, the maximum calf circumference and the minimum circumference of the ankle. The foot was measured for length. Additionally four skin-fold thickness were measured using Harpenden skin fold calipers (Bodycare Products, England, UK). These were measured at anterior and posterior thigh at the height of the one-third subischial height and at the medial and lateral calf at the height of maximum circumference. Raw values were computed using the formula of Jones and Pearson. Values of total leg volume lean leg volume and total and lean thigh volume were recorded.

6.3.5 30 s Continuous Isokinetic Test

Subjects were seated and the limb positioned as in the isokinetic force evaluation test. The test consisted of maximal reciprocal contractions of the knee extensors and flexors of the dominant leg for a period of 30 s at a velocity of 240° s^{-1}. Subjects warmed up and undertook a 5-minute period of stretching prior to the start. Data was collected and analysed by desktop computer from which power output and total work performed were calculated.

6.3.6 Wingate 30 s Test

This was measured on a cycle ergometer using the Wingate 30 s anaerobic test following the protocol of Lakomy (1986). The test was preceded by warm up cycling at a light load followed by a five-minute period for subjects to undertake a series of stretching exercises. Subjects began the test with an initial rolling start of 60-70 RPM with no resistive load. On the command 'go' the pre-determined resistive load (0.075kg/kg of body weight) was applied and subjects pedalled as fast as possible for 30 seconds. The cycle ergometer was connected to a desktop computer by which three indices: *peak power*, *mean power* and *rate of fatigue* were calculated.

6.3.7 Weight Training Programme

The weight-training programme for the experimental group began shortly after the completion of the laboratory assessments. Training sessions occurred three times a week and lasted for between one and one and a half hours. The programme consisted of seven exercises (dead lift, bench press, hack squat, leg extension, hamstring curl, lat pull downs and abdominal crunches) using standard fixed weight apparatus (Powersport, Bridgend, UK). Subjects completed 3 sets of 8 repetitions for each exercise, lifting a weight approximately equal to 75 % of their maximum for that exercise. Exercises were designed to maximise strength gain for the legs, with other exercises being included to ensure a balanced muscular development and to replicate normal all-over strength training.

6.3.8 Statistical Analysis

Simple ratios were calculated by dividing the performance variable by lean thigh volume. Power function ratios were calculated by dividing the performance variable by lean thigh volume$^{-0.67}$ as recommended by Jaric (2002). The power$^{-0.67}$ was chosen to allow comparisons to be made with other groups and because allometric parameters have been reported to be close to this figure, for the tested force of both leg and arm muscles (Jaric, 2002). The application of a common and externally derived exponent could allow for easy comparisons between groups and could provide a straightforward means by which appropriate normalisation can occur. This study will examine the effect of normalising in this way on the change in muscle quality following strength training.

The pre and post training data were analysed using a series of mixed-model, three factor (time x group; time x gender; time x group x gender) analyses of variance. Analysis was undertaken using version 10 of the Statistical Package For social Sciences. Statistical significance was set at the 0.05 alpha-level.

6.4 RESULTS

6.4.1 Isokinetic Force

Peak and mean force values increased post-training as discussed in the previous chapter (section 5.4.2).

6.4.2 Lean Thigh Volume

6.4.2.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25} = 0.002$, $P = 0.97$), time x gender ($F_{1, 25} = 0.094$, $P = 0.76$) and time x group x gender ($F_{1, 25} = 0.087$, $P = 0.94$), i.e. the pre and post lean thigh volumes were not affected by gender or experimental group.

6.4.2.2 Main effects

There was no main effect of time (pre versus post) on lean thigh volume, i.e., there was no significant difference between overall pre versus post-lean thigh measures ($F_{1, 25} = 0.035$, $P = 0.85$), irrespective of gender and group (pre 3.75 ± 1.40, post 3.73 ± 1.43 L) (mean ± SD).

6.4.3 Muscle Quality Expressed as a Simple Ratio – Peak concentric extension/ Lean thigh volume (SR)

6.4.3.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25} = 2.138$, $P = 0.16$), time x gender ($F_{1, 25} = 0.187$, $P = 0.67$) and time x group x gender ($F_{1, 25} = 0.006$, $P = 0.94$), i.e. the pre and post muscle quality values were not affected by gender or experimental group.

6.4.3.2 Main effects

There was no main effect of time (pre versus post) on the SR, i.e., there was no significant difference between overall pre versus post SR measures ($F_{1, 25} = 2.761$, $P = 0.11$), irrespective of gender and group (pre 268 ± 88, post 291 ± 115 N) (mean ±

SD). The results would however suggest an increase in muscle quality following the training intervention.

6.4.4 Muscle Quality expressed as a Power Function Ratio – Peak concentric extension/ Lean thigh volume$^{-0.67}$

6.4.4.1 Between subject interactions

There was a significant interaction effect of time x group on power function ($F_{1,25}$ = 5.278, P = 0.03), but no significant interaction of time x gender ($F_{1,25}$ = 0.150, P = 0.70) and time x group x gender ($F_{1,25}$ = 0.010, P = 0.92), i.e. the pre and post scores were affected by experimental group but not affected by gender. The significant interaction of time by group is shown in Figure 21.

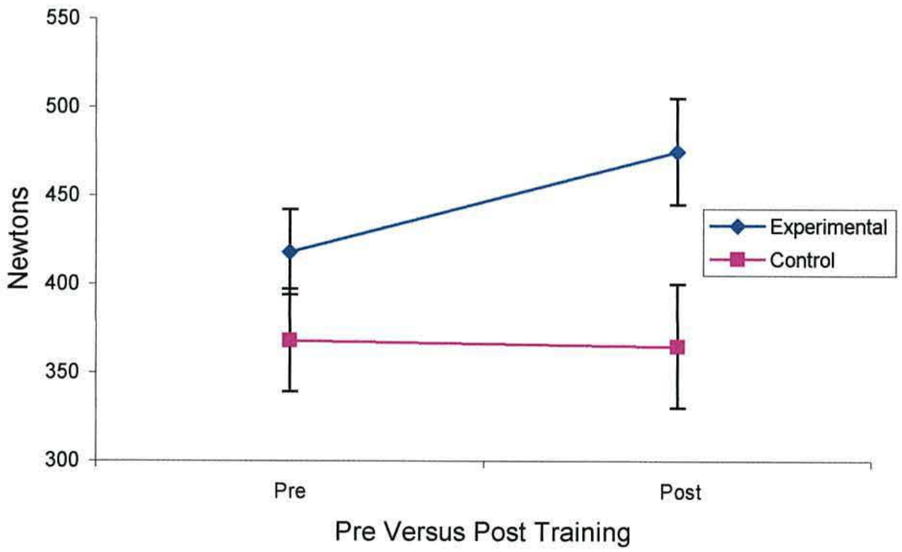

Figure 21: The significant interaction of time x group for PF ($F_{1,25}$ = 5.278, P = 0.03). Values are mean (± SEM).

6.4.4.2 Main effects for time.

There was a significant main effect for time (pre versus post training) on the power function ratio, i.e., there was a significant difference between overall pre versus post training power function measures ($F_{1, 25}$ = 4.280, P = 0.49), irrespective of gender and group (pre 398 ± 98, post 431 ± 131 N) (mean ± SD).

6.4.5 Peak power output expressed as a Simple Ratio – Peak power output/ Lean thigh volume (SRPPO)

6.4.5.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25}$ = 0.181, P = 0.67), time x gender ($F_{1, 25}$ = 0.007, P = 0.93) and time x group x gender ($F_{1, 25}$ = 0.630, P = 0.44), i.e., the pre and post training scores were not affected by gender or experimental group

6.4.5.2 Main effects for time.

There was no main effect of time (pre versus post training) on SRPPO, i.e., there was no significant difference between overall pre versus post training SRPPO ($F_{1, 25}$ = 2.558, P = 0.12), irrespective of gender and group (pre 235 ± 54, post 250 ± 73 W) (mean ± SD).

6.4.6 Peak power output expressed as a Power Function Ratio – Peak power output/ Lean thigh volume$^{-0.67}$ (PFPPO)

6.4.6.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25}$ = 0.874, P = 0.36), time x gender ($F_{1, 25}$ = 0.090, P = 0.77) and time x group x gender ($F_{1, 25}$ = 0.573, P = 0.46) on PFPPO, i.e., the pre and post scores were not affected by gender or experimental group.

6.4.6.2 Main effects for time.

The main effect of time (pre versus post training) on PFPPO was approaching significance ($F_{1, 25} = 3.870$, $P = 0.60$), irrespective of gender and group (pre 351 ± 77, post 372 ± 86 W) (mean ± SD).

6.4.7 Mean power output expressed as a Simple Ratio – mean power output/ Lean thigh volume (SRMPO)

6.4.7.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25} = 1.632$, $P = 0.94$), time x gender ($F_{1, 25} = 0.035$, $P = 0.85$) and time x group x gender ($F_{1, 25} = 0.673$, $P = 0.42$).

6.4.7.2 Main effects for time.

There was no main effect of time (pre versus post) on SRMPO ($F_{1, 25} = 0.850$, $P = 0.37$), irrespective of gender and group (pre 153 ± 36, post 157 ± 38 W) (mean ± SD).

6.4.8 Mean power output expressed as a Power Function Ratio – Mean power output/ Lean thigh volume$^{-0.67}$ (PFMPO)

6.4.8.1 Between subject interactions

There was no significant interaction of time x group ($F_{1, 25} = 0.250$, $P = 0.62$), time x gender ($F_{1, 25} = 0.153$, $P = 0.70$) and time x group x gender on PFMPO ($F_{1, 25} = 0.755$, $P = 0.39$).

6.4.8.2 Main effects for time.

There was no main effect of time (pre versus post training) on PFMPO ($F_{1, 25} = 1.531$, $P = 0.23$), irrespective of gender and group (pre 234 ± 39, post 229 ± 38 W) (mean ± SD).

6.4.9 Concentric Extension Total Work expressed as a Simple Ratio – Extension Total Work/ Lean thigh volume (SRTW)

6.4.9.1 Between subject interactions

There was no significant interaction of time x group, although it was approaching significance ($F_{1, 25} = 2.946$, $P = 0.10$), no significant interaction of time x gender ($F_{1, 25} = 0.160$, $P = 0.69$) and no significant interaction of time x group x gender ($F_{1, 25} = 0.961$, $P = 0.34$).

6.4.9.2 Main effects for time.

There was a significant main effect for time (pre versus post training) on SRTW ($F_{1, 25} = 4.694$, $P = 0.04$), irrespective of gender and group (pre 762 ± 270, post 849 ± 349 J) (mean ± SD). The significant main effect for time is illustrated in Figure 22.

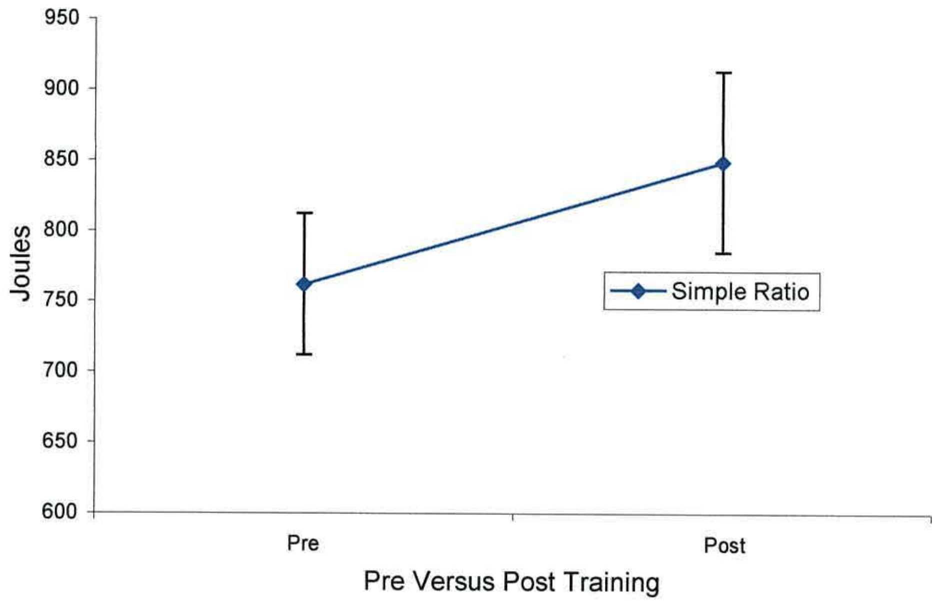

Figure 22: The main effect for time on SRTW for all subjects irrespective of group or gender. SRTW ratios are expressed in Joules (± SEM). SRTW was significantly different post training ($F_{1,25}$ = 4.694, P = 0.04).

6.4.10 Concentric Extension Total Work expressed as a Power Function Ratio – Extension Total Work/ Lean thigh volume$^{-0.67}$ (PFTW)

6.4.10.1 Between subject interactions

There was a significant interaction of time x group on PFTW ($F_{1,25}$ = 8.058, P = 0.01), which increased in the experimental subjects from 1200 ± 84 J (mean ± SEM) to 1411 ± 101 J after the strength training intervention. There was no significant change in control subjects who recorded values of 1041 ± 100 J and 1046 ± 120 for the first and second test occasions respectively. There was no significant interaction between time x gender ($F_{1,25}$ = 0.818, P =0. 37) or time x gender x group ($F_{1,25}$ = 1.766, P = 0.20). The significant interaction of time x group is illustrated in Figure 23.

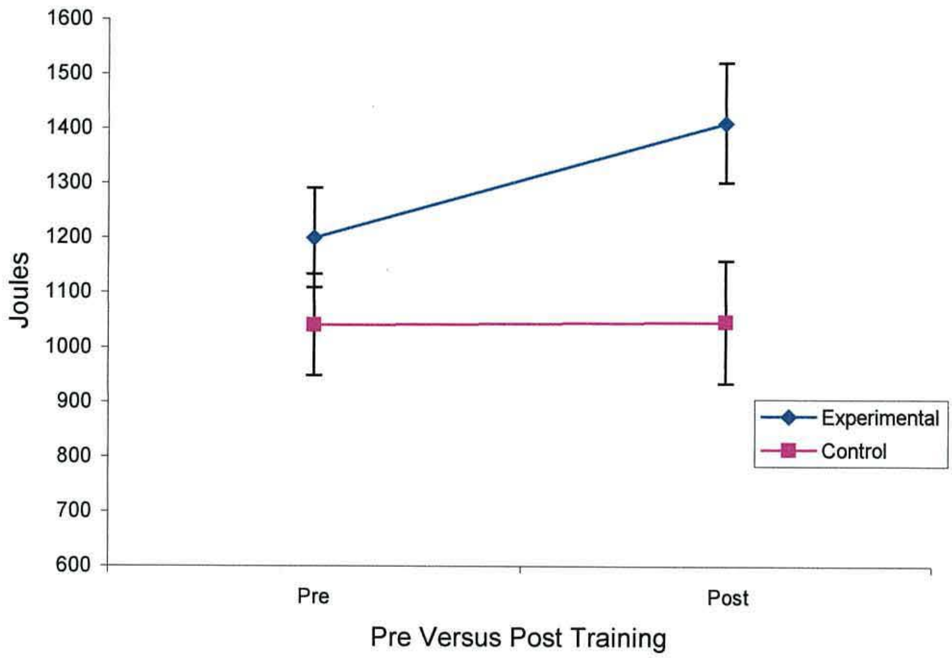

Figure 23: The significant interaction of time x group for PFTW ($F_{1, 25} = 8.058$, $P = 0.01$). Values are mean (± SEM).

6.4.10.2 Main effects for time.

There was a significant main effect for time (pre versus post) on PFTW ($F_{1, 25} = 8.825$, $P = 0.04$), irrespective of gender and group (pre 1136 ± 339, post 1259 ± 437 J) (mean ± SD).

6.5 DISCUSSION

6.5.1 Summary

The strength training intervention programme brought about significant increases in absolute force values ($P < 0.05$) in both male and female experimental groups as described in the previous study. The strength training also led to significant increases in peak power output and total work performed for the experimental groups ($P < 0.05$). The purpose of this study was to examine the effect of training on muscle quality, the strength per unit of lean thigh volume. Lean thigh volume showed no significant change ($P > 0.05$) in any group following training.

When muscle quality was expressed as force by a simple ratio there was no significant change after training in either male or female experimental groups. This suggested that muscle quality had not been affected by training. However, when muscle quality was expressed as a power function ratio there was a significant main effect for time and a significant interaction of time x group. Therefore muscle quality expressed as force/lean thigh volume $^{-0.67}$ had improved following a strength training intervention, with a similar response in both males and females.

When analysing muscle quality in the form of power output values, there was no significant change ($P > 0.05$) in either type of ratio for either peak or mean power, although the differing ratios did demonstrate differences with regard to male and female muscle quality. Female values were higher with simple ratios and male values higher with power function ratios.

When analysing total work performed during isokinetic dynamometry there was a general increase total work on the second test occasion with the simple ratio but no significant interactions between subjects ($P > 0.05$). Using the power function ratio, also indicated an increase and, perhaps more adequately indicated that the experimental group increased whilst the control group did not. Thus the power function ratio suggests a different response to training from that given by the simple ratio.

Strength training has brought about changes in force, power output and the ability to perform work in both male and female subjects. When analysing the muscle quality the use of differing ratios is clearly a factor as the interpretation of responses in muscle quality to training is dependant on the type of ratio used to analyse the data.

6.5.2 Isokinetic force values

As discussed in the previous study, absolute isokinetic force values significantly increased in both males and females following the strength training programme, with responses being similar in the male and female group. Although absolute strength differences had been previously reported (Holloway and Baechle, 1990) the use of a strength training intervention allowed for a comparison with regard to strength adaptations between men and women. The adaptations occurred similarly irrespective of the size of the muscle. However when comparing males and females it has been common to adjust for size, either by using a simple ratio scale (Castro *et al.*, 1995) or less frequently by using power function ratios (Jaric, 2002). The adjustment for size has been undertaken to provide a measure of muscle quality. This has been done to compare men and women (Maughan *et al.*, 1982; Castro *et al.*, 1995) using simple ratio scales.

Studies have recently investigated the effects of a strength training intervention on muscle quality (Ivey *et al.*, 2000b) but none have employed the use of power function ratios. In the present study both ratios were analysed in respect of the training intervention. The simple ratio showed no significant main effect for time ($P = 0.11$) and no significant interactions between group, time and gender.. According to the simple ratio, the women were stronger than the men relative to lean thigh ($P < 0.05$), and therefore had greater muscle quality. This is not supported by the majority of the literature, which reports male and female values to be similar (Winter and Maughan 1991; Castro *et al.*, 1995), although muscle quality has been reported to be higher in young females when ratio scales have been used (Ivey *et al.*, 2000b).

When force values in men and women were compared using the power function ratio it was indicated that there was a significant increase in strength from time one to time two ($P = 0.049$), and a significant interaction of time x group ($P = 0.03$). These indicated a greater increase in strength in the training intervention group. This clearly contrasted the results obtained from the simple ratio and demonstrated a significant improvement in muscle quality following training, an improvement that was non significant, and thus masked by the use of simple ratios. The power function ratios also removed the gender difference and equalised the muscle quality between males and females.

The differing results demonstrate the need to be clear regarding which method of normalisation should be used. Reporting of simple ratios would suggest that training does not alter muscle quality and that the muscle quality is greater in women than in men. Conversely, the use of power function ratios demonstrates that training enhances muscle quality and that there is no difference between genders. With the much publicised problems underlying the assumptions made with the use of the simple ratio (Nevill *et al.*, 1992, Winter, 1992; Rogers *et al.*, 1995; Winter and Nevill, 1996) it would be statistically more appropriate to use the power function ratios for comparisons of this type (Jaric, 2002). Hence this study would indicate that a 12-week strength training programme can lead to significant increases in muscle quality in both males and females with males and females responding similarly. This differs from the study of Ivey *et al.*, (2000b) which reported differences between young men and women in muscle quality responses to training. This study did not however use the power function ratio but rather the more traditional simple ratio. Consistency of use needs to be established for valid comparisons of the effects of training, and to ensure enhanced understanding of muscle responses to training.

6.5.3 Anaerobic Performance

Both mean power and peak power were compared before and after training using the simple and power function ratios. The changes in absolute power output values were discussed in the previous study. For mean power output there were no significant differences across time and no significant interactions of group x time x gender, when either the simple ratio or power function ratio were used. Female values were again greater than male values suggesting differences in muscle quality. Findings were similar for peak power output. Peak power expressed as a simple ratio showed no main effect for time and no interactions of time x gender, or time x group supporting the findings of Winter *et al.* (1991) and Eston *et al.* (1997). However, as with the isokinetic force values, the simple ratio and power function ratios differed, with power function ratios indicating that males had a greater muscle quality than females. The difference was not significant, but the trend of males having higher muscle quality when properly corrected for body size is supported in the literature (Winter *et al.*, 1991; Eston *et al.*, 1997). The results again highlight the problem of reporting values differently. If simple ratio scales are used then muscle quality is higher in females, both before and after training, but if power function ratios are used then males have greater muscle quality before and after training. If we are to fully understand the effects of training on the muscle quality and the different influences across genders it is essential to normalise appropriately.

6.5.4 Isokinetic total work

When expressed as a simple ratio, concentric extension total work increased from time one to time two ($P = 0.04$). Although it was approaching significance, there was no interaction of time x group ($P = 0.10$). When expressed as a power function ratio, concentric extension total work also increased from time one to time two ($P = 0.04$). The significant interaction of time x group ($P = 0.01$) indicated that there was a greater increase in total work performed in the experimental group. Again the results regarding the effect of training were different depending on the ratio adopted. Use of the simple ratio suggested that there was no significant difference between the experimental and control subjects, inferring that the training had no effect on muscle quality. The power function ratio provided a different interpretation of results. The significant interaction of time x group suggested that the experimental group adapted to the training intervention when compared with the control group, and that muscle quality in experimental subjects had improved. Hence the use of the power function ratio shows that the knee extensors are capable of producing more work when equated for leg volume following a period of strength training. Once again such benefits are not identified with the use of the simple ratio. Consequently if the focus is on muscle quality as well as absolute changes in muscle strength it is important to employ the power-function ratio as described by Jaric (2002). Use of simple ratios may mask the benefits of training.

Appropriate normalisation assists with analysing the changes in muscle quality brought about by training. The training intervention employed in these studies has demonstrated absolute changes in muscular force, with no difference in response between males and females. When analysing muscle quality using power function ratios, again the responses have been similar between genders. In terms of force and anaerobic performance, both have improved muscle quality which suggests a change in strength or performance, that was proportionally greater than the increase in muscle volume. This supports other findings that suggest that factors other than muscle mass account for performance changes (Ivey *et al.*, 2000b). Studies suggest that the muscle quality of males is greater than that of females (Winter and Maughan, 1991) and that the exact reasons remain unknown. By using correct normalisation procedures, combined with a strength training intervention it may be possible to further understand such gender differences. By reporting similar muscle quality values and similar responses to training, this study suggests that the differences between males and females may not be as great as proposed in non-training studies.

6.5.5 Conclusion

The problems associated with the use of ratio standards have been much reported (Nevill *et al.*, 1992, Winter, 1992; Rogers *et al.*, 1995; Winter and Nevill, 1996) and as a consequence alternative normalisation procedures should be adopted. Power function ratios have been identified as appropriate and in the absence of a group specific exponent the value 0.67 should be used (Jaric, 2002).

Although the correct normalisation procedures have been used for male and female comparisons they have not previously been used to compare the effects of training. This study shows that strength training improvements in muscle quality in both male and female subjects will be potentially masked if a simple ratio scale is adopted. If leg volume is raised to the power 0.67, then muscle quality in males and females improves similarly. This is the case both for isokinetic force and anaerobic performance during continuous isokinetic activity.

Therefore this study shows that muscle quality is significantly improved after strength training in males and females. Peak force and isokinetic total work increase proportionally more than changes in lean thigh volume. The use of correct normalisation procedures is required for such changes to be accurately identified.

CHAPTER 7

CONCLUSIONS

7.1 New contributions to the literature

7.1.1 Rugby league population specific data

7.1.2 Reporting of mean or peak values

7.1.3 use of the dynamic control ratio in analysis of muscle function

7.1.4 Comparison of the effects of strength training in men and women

7.1.5 Strength training effects on anaerobic performance

7.1.6 The effects of strength training on muscle quality

7.2 Study Limitations

7.2.1 Sample size

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7.3 Summary of the recommendations for future study

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7.3.2 Chapter 4

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7.1. New contributions to the literature

7.1.1 Rugby league population specific data

Little published material exists with regard to the sport of rugby league. Shortly after the advent of the English 'Super League' a review paper was published and cited only 18 references (Brewer and Davis, 1995). Super League coincided with a time of considerable interest in multiple sprint sports within the academic community. In this respect the demands placed on rugby league players are unique with high intensity efforts including sprinting, high force generation and a high degree of physical contact (McLean, 1992; Brewer and Davis, 1995). Super League was also the beginning of full-time professionalism, supported by television revenue, and a focus on more intensive training methods. New strength training procedures were being adopted in an effort to further enhance strength but little normative data existed to monitor the efficacy of the training or the progress being made. Research has developed during the time of Super League. However much of the research is based on the Australian game (Baker, 2001), focuses on amateur and college-aged players (Gabbett, 2000, 2002) or focuses on the incidence of injury (Stephenson, *et al.*, 1996; Meir *et al.*, 1997; Meir *et al.*, 2001). Data from both chapters 3 and 4 provided population specific data relating to the English game using full-time professional players.

The data from the study presented in Chapter 3 provides population- specific data from professional clubs whose players were just embarking on full-time professional careers. The data demonstrated that although the muscle strength ratios for the knee extensors and flexors fell within the previously reported normal range (Kannus, 1994), absolute strength values were lower than resistance trained sports students when tested on an isokinetic dynamometer. The lower values were not in themselves a concern because the strength between the groups from differing clubs was similar, and the players had not had the same exposure to isokinetic dynamometry as the sport students. Of greater concern were the E/C ratios. These were lower than expected and potentially reflected the reported emphasis on concentric actions during training. This highlights the importance of analysing ratios to ensure normal functioning and to ensure that training leads to favourable adaptations.

Comparisons with other groups, measured using alternative dynamometers is problematic because of the differing characteristics of each dynamometer, therefore the reporting of data for specific groups measured using specific dynamometers, is important. This study provided analysis of muscle strength and muscle strength ratios of the knee extensors and flexors in rugby league. This will allow for comparison of other groups using a Kin-Com as well as allowing for further analysis of strength training benefits and its effect on muscle function. Gabbett (2002) has recently called for standardised performance tests in rugby league. Strength and strength ratio data should be part of such assessment and the data from chapters 3 and 4 will provide useful information from which to benchmark professional players in England.

The study also provided population specific information regarding the relationship between strength, strength ratios and anthropometrically determined leg volume. The leg volume values obtained, combined with the correlations between leg volume and both force and ratio values, suggests that further determination of such indices will benefit future analysis in the sport.

Chapter 4 additionally provided analysis of force values obtained at differing velocities, and analysed ratios in more detail. It provides the acquisition of strength performance data from a group of professional players that can be used in the future for investigations into performance and injury prevention.

7.1.2 Reporting of mean or peak force values.

Ratios based on peak values have been most commonly used, although mean force values have been reported (Dvir and David, 1995). Mean and peak values share a high correlation therefore the use of either has been suggested to be appropriate (Dvir *et al.*, 1989; Tis and Perrin, 1994). Dvir and David (1995) proposed caution because despite the correlation, the relationship may differ in different conditions. In Chapter 3 of this study the ratios derived from mean force values were higher than those derived from peak force values. Mean values were more highly correlated with leg volume indices than peak values. This study supported Dvir and David (1995) and highlighted the need to be specific in reporting particular force values or ratios. In undertaking analysis of muscle function as assessment for rugby league the use of both peak and mean values along with both H/Q and E/C ratios is recommended.

7.1.3 Use of the dynamic control ratio in analysis of muscle function

H/Q strength ratios have been traditionally calculated from values obtained via concentric actions of both the knee extensors and flexors despite the fact that the quadriceps and hamstrings have opposite contraction modes. Such a ratio has been described as idiosyncratic and it has been recommended that it is not used for comparisons between groups or to establish a normative database (Kannus, 1994). A more functional ratio calculated by dividing the eccentric force value of the hamstrings by the concentric force value of the quadriceps has been recommended (Dvir, 1989; Aagaard *et al.*, 1998), but not extensively used. However, more recently the eccentric hamstrings/concentric quadriceps (DCR) ratio has been reported (Hole *et al.*, 2000; St Clair Gibson *et al.*, 2000) although these studies both focused on anterior cruciate ligament deficiency. Few papers have reported the DCR in sporting populations although it has been used when comparing ratios in adult and young elite soccer players (Gur et al., 1999).

Chapter 4 of this study provides analysis of the DCR across differing angular velocities and compares its response with the conventional H/Q ratio . Few studies have reported this ratio across differing velocities and analysed the response of the DCR in professional sportsmen. In this study, the DCR increased significantly as velocity increased. The study demonstrated that the DCR altered in line with the force-velocity characteristics of muscle, unlike the more conventional H/Q ratio. Because the change in the DCR was more consistent with change in velocity than the conventional ratio, the results of Chapter 4 would suggest that the DCR is useful in determining normal functioning. If the change with velocity does not occur then it could be an indication of irregular functioning. Clearly therefore, the DCR would be an important ratio to be used in analysing specific population groups with regard to muscle function. As DCR values are not reported in many sports, and not in professional rugby league, the data from this study again provides essential strength performance data from a professional group. This can be used for further comparison and analysis of muscle function in professional rugby league players.

The analysis of the DCR provides detail regarding the concentric and eccentric actions of the players. This is invaluable when analysing the influence of strength training and allows for more accurate monitoring of the effects of the training.

In summary, Chapter 4 demonstrated that the DCR altered differently with increasing velocity when compared with the conventional ratio. It better reflected the force-velocity characteristics of human muscle and it altered across velocity in a consistent manner. These results supported earlier work (Dvir *et al.*, 1989; Aagaard *et al.*, 1998) in suggesting that the DCR is more functional than the conventional H/Q ratio. This factor is now demonstrable in elite sports participants as well as in a clinical population. The DCR will have future efficacy in analysing strength performance, assessing the effects of training and as a diagnostic tool for injury.

7.1.4 Comparison of the effects of strength training in men and women.

Although gender comparisons of strength performance have been extensively undertaken (Kraemer *et al.*, 2001), it is only recently that attention has focused on female responses and adaptations to strength training (Holloway and Baechle, 1990). Few studies have compared men and women with regard to a similar training intervention and few studies, have examined the effects of strength training on muscle quality when properly normalised for body size.

Chapter 5 demonstrated that, with one exception, females increased strength similarly to men after exposure to a 12-week strength programme using fixed weight training apparatus. Analysis of male and female ratios showed that responses had been the same in the quadriceps and hamstrings and in both eccentric and concentric modes.

This study supported recent findings (Staron, 1991; 1994) that men and women respond similarly and improve force production after a period of strength training.

7.1.5 Strength training effects on anaerobic performance

A link between strength and anaerobic power has long been recognised (Coyle, 1981). However few have investigated the effects of a strength training intervention on more prolonged anaerobic performance or anaerobic capacity. Studies undertaken have largely focused on relationships rather than focusing on the effects of a change in strength. Additionally male and female comparisons have suffered from inconsistent normalisation and comparisons of subjects from differing backgrounds exposed to differing training stimuli.

Chapter 5 investigated the effects of strength training on anaerobic performance in men and women. The force increase brought about by a period of strength training led to significant increases in peak power production measured during cycle ergometry. These results supported previous findings with regard to the relationship between strength and power and demonstrated that training using fixed weight apparatus can increase peak power output in both men and women.

Perhaps more importantly the training led to an increase in mean power output (although this was non significant) and increases in total work performed during 30 s of continuous isokinetic concentric extension and flexion. The study demonstrated the efficacy of continuous tests performed using isokinetic dynamometry supporting the work of Baltzopoulos *et al.* (1988). The increase in total work suggested that strength training can improve the ability to perform anaerobic activity and can positively enhance anaerobic capacity in both males and females. The study further highlighted the importance of a balanced weight-training programme for those involved in activities that require a significant anaerobic contribution.

7.1.6 The effects of strength training on muscle quality

Strength per unit cross-sectional area has been compared in males and females (Maughan *et al.*, 1983; Alway *et al.*, 1990). However, few studies have compared a ratio of strength/unit of cross-sectional area with regard to a strength training response and those that have are equivocal (Castro *et al.*, 1995). More recently studies have calculated ratios by dividing by unit of muscle volume (Tracy *et al.*, 1999) and analysed the effects of a strength intervention (Ivey *et al.*,2000, Roth *et al.*, 2001). Despite this, few studies have compared muscle quality responses to a strength training intervention in men and women and few have normalised appropriately (Jaric 2002). Chapter 6 investigated the effect of strength training in muscle quality in men and women using the power function ratio strength/lean thigh volume$^{-0.67}$.

The study in chapter 6 showed that improvements brought about by strength training in both men and women, are potentially masked if the simple ratio is adopted. However if lean thigh volume is raised to the power 0.67, then improvements are demonstrable and they are similar in both males and females. Thus chapter 6 provides information relating to the effects of the differing ratios as well as demonstrating that females respond in the same manner to strength training as males.

7.2 Study Limitations

7.2.1 Sample size

Strength training studies have suffered from many limitations in the past. These include a lack of uniformity in experimental design (Hakkinen, 1989), poorly conducted studies and inappropriate length of training periods (Brooks and Fahey, 1985). An element of the poorly conducted studies has been sample size; this is a recurring problem in studies employing a training intervention. Chapter 5 cites a number of sprint training studies, only one of which, at 12, employed more than 10 subjects (Linossier *et al.*, 1997; Dawson *et al.*, 1998; MacDougall *et al.*, 1998). In addition none of those studies employed a control group.

Hence it is recognised that the sample sizes in these studies could be larger, particularly when one of the aims is to provide population-specific data. However Chapters 3 and 4 identify trends and provide helpful benchmark data. Further studies can be conducted with larger sample sizes but initial questions relating to the nature of ratios and the values in English 'Super League' have already been answered. The nature of rugby league makes it difficult to gain regular access to a population both big enough and fit enough to be worthwhile. This study benefited from assessment during pre-season but even so, many players had injuries preventing isokinetic evaluation of maximum force.

Sample size can impact on statistical analysis by influencing statistical power. In Chapter 5, despite the increase in force for both men and women, mean power output as recorded during the Wingate 30 s test was not significantly ($P > 0.05$) altered. However mean power had increased in both groups and anaerobic performance had significantly increased ($P < 0.05$) for 30 s continuous isokinetic extension and flexion. A greater number of subjects would help to identify whether the mean power change was a positive trend or simply a coincidence.

7.2.2 Duration of Training

As detailed in Chapter 2, studies have previously been criticised for being too short. Therefore the adaptations are largely neurogenic and any morphological impacts are not studied. Hypertrophy has been reported to occur after 8 weeks of maximal training (Thorstensson, 1977; Costill *et al.*, 1989) but the data from studies lasting 12-weeks has been reported to be equivocal (Abernethy *et al.*, 1994). The training intervention in this thesis is longer than many reported, but is probably at the minimum to ensure that a full range of muscle adaptations are accounted for. However the training apparatus differed from the isokinetic testing apparatus and minimised the learning effect. Longer training would be preferable but the majority of subjects in Chapters 5 and 6 were students. Therefore the control and monitoring of training was influenced by the length of the semester. The 12-week programme was the maximum that could be accommodated along with testing.

The study overcame some of the other common criticisms of training studies by employing control groups and by comparing men and women following a similar training programme.

7.2.3 Improvements in Anaerobic Performance

Chapter 5 studied the effects of strength training on force (strength) and the subsequent ability to undertake high intensity activity e.g. 30 s maximal cycling and

30 s continuous isokinetic extension and flexion. Performance in anaerobic activity was enhanced overall but this study could offer only speculative explanation as to why any improvements had occurred. The results did however demonstrate the efficacy of weight training in relation to activity of this type in both males and females.

7.3 Summary of the Recommendations for Future Study

7.3.1 Chapter 3

The sport of rugby league has not been extensively researched and much of the recent research has focused specifically on injury. This study provided initial population specific data regarding English 'Super League' players from differing clubs. More of this data is required to aid the training and monitoring of the sport.

The results indicated a relationship between performance of the thigh and leg volume indices. Because it is a relatively quick and easy procedure, the measurement of leg volume and its relationship with performance of the leg extensors and flexors should be further examined to further support the positive findings of this study.

7.3.2 Chapter 4

The results from this study support previous findings (Dvir *et al.*, 1989; Aagaard *et al.*, 1998; Coombs *et al.*, 2002) and suggest that the DCR could be a more appropriate tool than the conventional H/Q ratio for analysing muscle function. However the use of the DCR is limited and further investigations are required to monitor its efficacy with other population groups. This study deliberately used a narrow range of velocities. The DCR needs to be further analysed using a greater range of velocity including higher testing speeds.

One of the main claims for analysing ratios is that they are important as indicators of susceptibility to injury (Grace et al., 1984; Knapik, 1991). There is still limited evidence to support this and this is particularly the case with the DCR. Future developments in DCR research should very much focus on its relationship with injury and its ability to predict level of risk.

7.3.3 Chapter 5

This study suggested that strength training might positively enhance anaerobic capacity and the ability to perform anaerobic activity in both males and females. The exact reasons for such an improvement remain unclear. Sprint training studies have shown alterations in enzyme activity that lead to improvements in performance. There is need for studies using a similar design to this one i.e. males and females undergoing a strength programme compared with controls, but with additional measures including investigations of metabolic and enzyme activity.

7.3.4 Chapter 6

The results of this study demonstrated how the effects of training on muscle quality could be masked if inappropriate normalisation procedures are adopted. Few if any studies have employed correct normalisation and used it to compare male and female responses to the same training regime. Further studies should employ such measures, both in further strength training investigations and with differing activities to examine the effects of employing differing procedures.

CHAPTER 8

REFERENCES

Aagaard, P., Simonsen, E. B., Trolle, M., Bangsbo, J. and Klausen, K. (1995) Isokinetic Hamstring/Quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode. *Acta Physiologica Scandinavica,* **154,** 421-427.

Aagaard, P., Simonsen, E. B., Beyer, N., Larsson, B., Magnusson, P. and Kjaer, M. (1997) Isokinetic muscle strength and capacity for muscular knee joint stabilization in elite sailors. *International Journal of Sports Medicine,* **18,** 521-525.

Aagaard, P., Simonsen, E. B., Magnussen, S. P., Larsson, B. and Dyhre-Poulsen, P. (1998) A new concept for isokinetic hamstring:quadriceps muscle strength ratio. *American Journal of Sports Medicine,* **26,** 231-237.

Abernethy, P. J., Thayer, R. and Taylor, A. W. (1994) Acute and chronic responses of skeletal muscle to endurance and sprint exercise. A review. *Sports Medicine,* **10,** 365-389.

Abernethy, P. J., Wilson, G. and Logan, P. (1995) Strength and power assessment: Issues, controversies and challenges. *Sports Medicine,* **19,** 401-417.

Anderson, J. A., Gieck, J. H., Perrin, D. H., Weltman, A., Rutt, R. and Denegar, C. (1991) The relationship among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. *Journal of Orthapaedic and Sports Physical Therapy,* **14,** 114-120.

Alway, S.E.; Stray-Gundersen, J.; Grumbt, W.H. and Gonyea, W.J. (1990) Muscle cross-sectional area and Torque in resistance-trained subjects. *European Journal of Applied Physiology,* **60**, 86-90

Aniansson, A., Grimby, G. and Hedberg, H. (1992) Compensatory muscle fiber hypertrophy in elderly men. *Journal of Applied Physiology,* **73,** 812-816.

Antonio, J. and Gonyea, W. J. (1993) Skeletal muscle fiber hyperplasia. *Medicine and Science in Sports and Exercise,* **25,** 1333-1345.

Antonio, J. and Gonyea, W. J. (1994) Muscle fiber splitting in stretch-enlarged avain muscle. *Medicine and Science in Sports and Exercise,* **26,** 973-977.

Baker, D. and Nance, S. (1999) The relation between strength and power in professional rugby league players. *Journal of Strength and Conditioning Research,* **13**, 224-229.

Baker, D. (2001).The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *Journal of Strength and Conditioning Research,* **15**,172-177

Baldwin, G. (1991) The effect of maximal strength training on power output and anaerobic capacity. *Unpublished MSc Project*, University of Loughborough, UK.

Baldwin, G., Barrow, N. and Cox, D.A. (1997) A pilot study to determine isokinetic strength of the knee extensors and flexors and the dynamic control ratio in professional rugby league players. *Journal of Sports Sciences,* **15**. 3. P

Baltzopoulos, V., Eston, R. G. and Maclaren, D. (1988) A comparison of power outputs on the Wingate test and on a test using an isokinetic device. *Ergonomics,* **31,** 1693-1699.

Baltzopoulos, V. and Brodie, D.A. (1989) Isokinetic Dynamometry: Applications and Limitations. *Sports Medicine,* **8,** 101-116.

Baltzopoulos, V. (1997) Isokinetic Dynamometry, In Bartlett, R. (Ed).*Biomechanical Analysis of Movement in Sport and Exercise,* BASES, Leeds, pp. 53-66.

Baltzopoulos, V. and Gleeson, N.P. (2001) Skeletal muscle function. In Eston, R.G. and Reilly, T. (eds) *Kinathropometry and Exercise Physiology Laboratory Manual: Tests, Procedures and Data.* 2nd Edition, Routledge, London.

Banister, L.H., Berry, M.M, Collins, P., Dysen, M, Dussek, J.E. and Ferguson, M.W.J. (1995) *Grays Anatomy*, Churchill Livingstone, New York.

Baratta, R., Solomonow, M., Zhou, B., Letson, D., Chuinard, R. and D'Ambrosia, R. (1988) Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *American Journal of Sports Medicine,* **16,** 113-122.

Behm, D.G. and Sale, D.G. (1993) Velocity specificity of resistance training. *Sports Medicine*, **15,** 374-388.

Bell, G. J., Petersen, S. R., Quinney, H. A. and Wenger, H. A. (1989) The effect of velocity-specific strength training on peak torque and anaerobic rowing power. *Journal of Sports Sciences,* **7,** 205-214.

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D. and Cirone, J. (1998) Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers. *British Journal of Sports Medicine,* **32,** 309-314.

Bennett, J. G. and Stauber, W. T. (1986) Evaluation and treatment of anterior knee pain using eccentric exercise. *Medicine and Science in Sports and Exercise,* **18,** 526-530.

Blade, L.F.; Bailey, R.G.; McCulloch, R.G. and Harrison,E.L. (1992) Proportional cross-sectional area of the thigh muscles and isokinetic strength in women. *Sports Medicine, Training and Rehabilitation,* **3**, 297-306.

Boobis, L., Williams, C. and Wooton, S.A.(19830 influence of sprint training on muscle metabolism during brief maximal exercise in man. *Journal of Physiology.* **342,** 36-37 P

Booth, F. W. and Thomason, D. B. (1991) Molecular and cellular adaptation of muscle in response to exercise: Perspectives of various models. *Physiological Reviews,* **71,** 541-585.

Brady, E.C., O'Regan, M. and McCormack, B (1993) Isokinetic assessment of uninjured soccer players. *Science and Football II, Proceedings of the Second World Congress of Science and Football,* E and F.N Spon, London, 351-356

Brewer, J. and Davis, J. (1995) Applied physiology of rugby league. *Sports Medicine,* **20,** 129-135.

Broberg, S. and Sahlin, K. (1989) Adenine nucleotide degradation in human skeletal muscle during prolonged exercise. *Journal of Applied Physiology,* **67,** 116-122.

Brookes, G.A. and fahey, T.D. (1985) *Exercise Physiology: Human Bioenergetics and its applications.* MacMillan Publishing, New York.

Calmels, P. M., Nellen, M., Van der Bourne, I., Jourdin, P. and Minaire, P. (1997) Concentric and eccentric isokinetic assessment of flexor-extensor torque ratios at the hip, knee, and ankle in a sample population of healthy subjects. *Archives of Physical Medicine and Rehabilitation,* **78,** 1224-1230.

Camus, G. and Thys, H. (1991) An evaluation of the maximal anaerobic capacity in man. *International Journal of Sports Medicine,* **12,** 349-355.

Castro, M.J., McCann, D.J., Shaffrath, J.D. and Adams, W.C. (1995) Peak torque per unit cross-sectional area differs between strength-trained and untrained young adults. *Medicine and Science in Sports and Exercise.* **3,** 397-403.

Charette, S. L., McEvoy, L., Pyka, G., Snow-Harter, C., Guido, D., Wiswell, R. A. and Marcus, R. (1991) Muscle hypertrophy response to resistance training in older women. *Journal of Applied Physiology,* **70,** 1912-1916.

Chan, K. M. and Maffuli, N. (Eds.) (1996) *Principles and Practice of Isokinetics in Sports Medicine and Rehabilitation,* Williams and Wilkins Asia-Pacific Ltd, Hong Kong.

Chesley, A, MacDougall, J.D., Tarnopolsky,M.A., Atkinson, S.A. and Smith (1992) Changes in human muscle protein synthesis after resistance exercise. *Journal of Applied Physiology,* **73,** 1383-1388.

Clanton, T. O. and Coupe, K. J. (1998) Hamstring strains in athletes, diagnosis and treatment. *Journal of the American Academy of Orthapaedic Surgery,* **6,** 237-248.

Colliander , E. B. and Tesch, P. A. (1989) Bilateral eccentric and concentric torque of quadriceps and hamstring muscles in females and males. *Journal of Applied Physiology,* **59,** 227-232.

Colliander , E. B. and Tesch, P. A. (1991) Responses to eccentric and concentric resistance training in females and males. *Acta Physiologica Scandinavica,* **2**, 149-156.

Coombs, R., Garbutt, G. and Cramp, M (2002) Comparison of conventional and functional hamstring-quadriceps moment ratios through a 90° range of leg motion. *Journal of Sports Sciences,* **20**, 3-4.

Costill, D. L., Coyle, E. F., Fink, W. J., Lesmes, G. R. and Witzman, F. A. (1979) Adaptations in skeletal muscle following strength training. *Journal of Applied Physiology,* **46,** 96-99.

Coyle, E.F., Feiring, D.C., Rotkis, T.C., Cote, R.W., Lee, W. and Wilmore, J.H. (1981) Specificity of power improvements through slow and fast isokinetic training. *Journal of Applied Physiology,* **51**, 1437-1442.

Dawson, B., Fitzsimons, M., Green, S., Goodman, C., Carey, M. and Cole, K. (1998) Changes in performance, muscle metabolites, enzymes and fibre types after short sprint training. *European Journal of Applied Physiology,* **78**,163-169.

Delecluse, C., Van Coppenolle, H., Willems, E., Van Leemputte, M., Diels, R. and Goris, M. (1995) Influence of high-resistance and high-velocity training on sprint performance. *Medicine and Science in Sports and Exercise,* **27,** 1203-1209.

Dons, K., Bollerup, K., Bonde-Petersen, F. and Hancke, S. (1979) The effect of weight-lifting related to muscle fiber composition and muscle cross-sectional area in humans. *European Journal of Applied Physiology,* **40,** 95-106.

Dudley, G.A, Staron, R.S., Murray, T.F., Hagerman, F.C. and Luginbuhl, A. (1983) Muscle fibre composition and blood ammonia levels after intense exercise in humans. *Journal of Applied Physiology,* **54,** 582-586.

Dvir, Z., Eger, G., Halperin, N. and Shklar, A. (1989) Thigh Muscle activity and anterior cruciate ligament insufficiency. *Clinical Biomechanics,* **4,** 87-91.

Dvir, Z. (1991) Clinical applicability of isokinetics: a review. *Clinical Biomechanics,* **6,** 133-144.

Dvir, Z. and David, G. (1995) Average or peak moment: which of the two is more suitable to represent isokinetic muscle strength? *Isokinetics and Exercise Science,* **5,** 93-97.

Dvir, Z. (1996) Selected issues relating to the medico-legal applications of isokinetic dynamometry. *Isokinetics and Exercise Science,* **4,** 143-147.

Edgerton, V. R. (1973) *Physical Activity: Human Growth and Development,* Academic Press, London.

Ellenbecker, T. S. and Roetert, E. P. (1995) Concentric isokinetic quadricep and hamstring strength in elite junior tennis players. *Isokinetics and Exercise Science,* **5,** 3-6.

Eston, R.G., Winter, E. and Baltzopoulos, V. (1997) Ratio standards and allometric modelling to scale peak power output for differences in lean upper leg volume in men and women. *Journal of Sports Sciences*, **15**, 29 P

Evans, J.A. and Quinney, H.A. (1981) Determination of resistance settings for anaerobic power testing. *Canadian Journal of Applied Sport Science*, **6**, 53-56.

Fairbanks, R., Lawler, B. and Malone, T. R. (1994) The eccentric/concentric ratio of quadriceps femoris in sprinters and normals. *Isokinetics and Exercise Science,* **4,** 41-44.

Francis, K. and Hoobler, T. (1987) Comparison of peak torque values of the knee flexor and extensor muscle groups using the Cybex II and Lido 2.0 isokinetic dynamometers. *Journal of Orthapaedic and Sports Physical Therapy,* **8**, 480-483

Froese, E.A. and Houston, M.E. (1987) Performance during the Wingate anaerobic test and muscle morphology in males and females. *International Journal of Sports Medicine*, **8**, 35-39

Frontera, W.R., Meredith, C.N., O'Reilly, K.P., Knuttgen, H.G. and Evans, W.J. (1988) Strength conditioning in older men: Skeletal muscle hypertrophy and improved function. *Journal of Applied Physiology*, **64**, 1038-1044

Gabbett, T.J. (2000) Physiological and anthropometric characteristics of amateur rugby league players. *British Journal of Sports Medicine,* **34**, 303-307.

Gabbett, T.J. (2002) Influence of physiological characteristics on selection in a semi-professional first grade rugby league team: a case study. *Journal of Sports Sciences* **20**, 399-405.

Gleeson, N.P. and Mercer, T.H. (1992) Reproducibility of isokinetic leg strength and endurance characteristics of adult men and women. *European Journal of Applied Physiology*, **65**, 221-228.

Gleeson, N.P. and Mercer, T.H. (1996) the utility of isokinetic dynamometry in the assessment of human muscle function. *Sports Medicine*, **21**, 18-34.

Goldberg, A. L., Etlinger, J. D., Goldspink, D. F. and Jablecki, C. (1975) Mechanism of work-induced hypertrophy of skeletal muscle. *Medicine and Science in Sports and Exercise,* **7,** 248-261.

Goldspink, D.F., Garlick, P.J. and McNurlan, M.A. (1983) Protein turnover measured in vivo and in vitro in muscles undergoing compensatory growth and denervation atrophy. *Biochemistry Journal*, **210**, 89-98

Gonyea, W. J., Ericson, G. C. and Bonde-Petersen, F. (1977) Skeletal muscle fibre splitting induced by weight-lifting exercise in cats. *Acta Physiologica Scandinavica,* **99,** 105-109.

Gonyea, W.and Bonde-Petersen, F. (1978) Alterations in muscle contractile properties and fibre composition after weight-lifting exercise in cats. *Experimental Neurology,* **59**, 75-84.

Gonyea, W.J., Sale, D.G., Gonyea, F.B. and Mikesky A, (1986) Exercise induced increases in muscle fiber number. *European Journal of Applied Physiology*, **55**, 137-141.

Goslin, B. and Chateris, J (1979) Isokinetic dynamometry: normative data for clinical use in lower extremity (knee cases). *Scandinavian Journal of Rehabilitative Medicine* **11**, 105-109

Grace, T.G., Sweetser, E.R., Nelson, M.A., Ydens, L.R. and Skipper, B.J. (1984) Isokinetic muscle imbalance and knee-joint injuries. A prospective blind study. *Journal of Bone and Joint Surgery.* **66,** 4-40

Green, S. and Dawson, B. (1993) measurement of anaerobic capacities in humans. *Sports Medicine*, **15**, 312-327

Gulch, R. W. (1994) Force-velocity relations in human skeletal muscle. *International Journal of Sports Medicine,* **15,** S2-S10.

Gur, H., Akova, B., Punduk, Z. and Kucukoglu (1999) Effects of age on the reciporocal peak torque ratios during knee muscle contractions in elite soccer players. *Scandinavian Journal of Medicine and Science in Sports,* **9,** 81-87.

Hakkinen, K. and Komi, P. V. (1986) Training-induced changes in neuromuscular performance under voluntary and reflex conditions. *European Journal of Applied Physiology,* **55,** 147-155.

Hakkinen, K. (1989) Neuromuscular and hormonal adaptations during strength and power training. *Journal of Sports Medicine and Physical Fitness.* **29**, 9-26.

Hakkinen, K. (1991) Force production characteristics of leg extensor, trunk flexor and extensor muscles in male and female basketball players. *Journal of Sports Medicine and Physical Fitness,* **31,** 325-331.

Hansen, S.; Kvorning, T.; Kjaer, M. and Sjogaard. (2001) The effect of short-term strength training on human skeletal muscle: the importance of physiologically elevated hormone levels. *Scandinavian Journal of Medicine, Science and Sports,* **11,** 347-354.

Hermansen, L. and Medbo, J. I. (1984) The relative significance of aerobic and anaerobic processes during maximal exercise of short duration. In Marconnet, P. (Ed), *Physiological Chemistry of Training and Detraining*, Karger, New York. 56-67.

Hickson, R.C., Hidaka. K. and Foster C. (1994) Skeletal muscle fiber type, resistance training, and strength-related performance. *Medicine and Science in Sports and Exercise*, **26**, 593-598.

Hickson, R. C. (1980) Interference of strength development by simultaneously training for strength and endurance. *European Journal of Applied Physiology,* **45,** 255-263.

Hill, A.V. (1938) The heat of shortening and the dynamic constants of muscle. *Proceedings of the Royal Society of London.* (Biology) **126**:136-195

Hill, D.W. and Smith, J.C. (1993) Gender difference in anaerobic capacity: role of aerobic contribution. *British Journal of Sports Medicine*, **27**, 45-48.

Hislop, H.J. and Perrine, J.J. (1967) The isokinetic concept of exercise. *Physical Therapy*, **47**, 114-117.

Hole, C.D., Smit, G.H., Hammond, J., Kumar, A., Saxton, J. and Cochrane, T. (2000) Dynamic control and conventional strength ratios of the quadriceps and hamstrings in subjects with anterior cruciate ligament deficiency. *Ergonomics*, **43,** 1603-1609.

Holloway, J. and Baechle, T,R. (1990) Strength training for female athletes. A review of selected aspects. *Sports Medicine*, **9,** 216-228.

Holm, I., Ludvigsen, P. and Steen, H. (1994) Isokinetic hamstrings/quadriceps ratios: Normal values and reproducibility in sports students. *Isokinetics and Exercise Science,* **4,** 141-145.

Housh, T. J., Johnson, G. O., Housh, D. J., Stout, J. R., Weir, J. P., Weir, L. L. and Eckerson, J. M. (1996) Isokinetic peak torque in young wrestlers. *Pediatric Exercise Science,* **8,**143-154.

Hultman, E. and Sjoholm, H. (1986) Biochemical causes of fatigue. In Jones, N.L., McCartney, N. and McComas, A.J. (Eds) *Human Muscle Power*, Human Kinetics, Champaign, Illinois, 215-238.

Ivey, F.M., Roth, S.M., Ferrell, R.E., Tracy, B.L., Lemmer, J.T., Hurlbut, D.E., Martel, G.F., Siegel, E.L., Fozard, J.L., Metter, J.E., Fleg, J.L. and Hurley, B.F. (2000) Effects of age, gender, and myostatin genotype on the hypertrophic response to heavy resistance strength training. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55**, M641-648

Ivey, F.M., Tracy, B.L., Lemmer, J.T., NessAiver,M., Metter, J.E., Fozard, J.L. and Hurley, B.F. (2000b) Effects of strength training and detraining on muscle quality:age and gender comparisons. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* **55,** B152-157

Jakeman, P. M., Winter, E. M. and Doust, J. (1992) *Future directions for performance related research in sports physiology,* Sports Council, London.

Jaric, S. (2002) Muscle strength testing. Use of normalisation for body size. *Sports Medicine*, **32**, 615-631.

Jones, P.R. and Pearson, J. (1969) Anthropometric determination of leg fat and muscle plus bone volumes in young male and female adults. *Journal of Physiology*, **204**, 63-66P

Jones, D. A. and Rutherford, O. M. (1987) Human muscle strength training: the effects of three different regimens and the nature of the resultant changes. *Journal of Physiology,* **391**, 1-11

Jones, D. A., Rutherford, O. M. and Parker, D. F. (1989) Physiological changes in skeletal muscle as a result of strength training. *Quarterly Journal of Experimental Physiology,* **74,** 233-256.

Kadi, F., Eriksson, A., Holmner, S., and Thornell, L. (1999). Effects of anabolic steroids on the muscle cells of strength-trained athletes. *Medicine and Science in Sports and Exercise,* **31**, 1528-1534.

Kannus, P. (1992) Normality, variability and predictability of work, power and torque acceleration energy with respect to peak torque in isokinetic muscle testing. *International Journal of Sports Medicine,* **13,** 249-256.

Kannus, P. (1994) Isokinetic evaluation of muscular performance: Implications for muscle testing and rehabilitation. *International Journal of Sports Medicine,* **15,** s11-s18.

Kannus, P. and Beynnon, B. (1993) Peak torque occurrence in the range of motion during isokinetic extension and flexion of the knee. *International Journal of Sports Medicine,* **14,** 422-426.

Katch, F.I. and McArdle, W. (1983) *Nutrition, Weight Control and Exercise.* Lea and Febiger, Philadelphia.

Kellis, E. and Baltzopoulos, V. (1995) Isokinetic eccentric exercise. *Sports Medicine,* **19,** 202-222.

Kellis, E. (1998) Quantification of Quadriceps and Hamstring Anatagonist Activity. *Sports Medicine,* **25,** 37-62.

Kimura, I. F., Gulick, D. T. and Gasiewski, E. (1997) Effect of visual feedback on concentric peak torque production during knee extension and flexion exercise in males and females. *Isokinetics and Exercise Science,* **6,** 209-214.

Knapik, J. J., Jones, B. H., Bauman, C. L. and Harris, J. M. (1992) Strength, flexibility and athletic injury. *Sports Medicine,* **14,** 277-288.

Kollath, E. and Quade, K. (1992) Measurement of sprinting speed of professional and amateur soccer players. *Science and Football II, Proceedings of the Second World Congress of Science and Football,* E and F.N Spon, London. 31 –36.

Kovaleski, J. E., Heitman, R. J. and Ficca, M. H. (1994) Eccentric and concentric torque production of the knee extensors and flexors in endurance runers and cyclists. Isokinetics and Exercise science **4** 104-107. *Isokinetics and Exercise Science,* **4,** 104-107.

Kraemer, W.J., Mazzetti, S.A., , Nindl, B.C., Gotshalk, L.A., Volek,J.S., Bush, J.A., Marx, J.O., Dohi,K., Gomez, A.L., Miles, M., Fleck,S.J., Newton, R.U. and Hakkinen, K. (2001) Effect of resistance training on women's strength/power and occupational performances. *Medicine and Science in Sports and Exercise,* **33**, 1011-1025.

Lakomy, H.K.A. (1986) Measurement of work and power output using fricyion loaded cycle ergometers. Ergonomics, **29**, 509-517

Lamb, D.R. (1984) *Physiology of Exercise, Responses and Adaptations.* MacMillan Publishing, New York.

Latin, R.W. (1992) The relationship between isokinetic power and selected anaerobic power tests. *Isokinetics and Exercise Science*, **2**, 56-59

Lemmer, J.T., Hurlbut, D.E., Martel, G.F., Tracy, B.L., Ivey, F.M., Metter, E.J., Fozard, J.L., Fleg, J.L. and Hurley, B.F. (2000) Age and gender responses to strength training and detraining. *Medicine and Science in Sports and Exercise*, **32**, 1505-1512

Lesmes, G. R., Costill, D. L., Coyle, E. F. and Fink, W. J. (1978) Muscle strength and power changes during maximal isokinetic training. *Medicine and Science in Sports and Exercise,* **10,** 266-269.

Li, R. C., Maffuli, N., Hsu, Y. C. and Chan, K. M. (1996) Isokinetic strength of the quadriceps and hamstrings and functional ability of anterior cruciate deficient knees in recreational athletes. *British Journal of Sports Medicine,* **30,** 161-164.

Linossier, M.T.; Dormois, D.; Perier, C.; Frey, J.; Geyssant, A. and Denis, C. (1997) Enzyme adaptations of human skeletal muscle during bicycle short-sprint training and detraining. *Acta Physiologica Scandinavica*, **161**, 439-445.

Luthi, J. M., Howald, H., Claasen, K., Rosler, P., Vock, P. and Hoppeler, H. (1986) Structural changes in skeletal muscle tissue with heavy-resistance exercise. *International Journal of Sports Medicine,* **7,** 123-127.

MacDougall, J. D.; Tarnopolsky, M.A.; Chesley, A. and Atkinson, S.A. (1992) Changes in muscle protein synthesis following heavy resistance exercise in humans: a pilot study. *Acta Physiologica Scandinavica,* **146,** 403-404.

MacDougall, J. D., Hicks, A.L., MacDonald, J.R., McKelvie, R.S., Green, H.J. and Smith, K.M. (1998) Muscle performance and enzymatic adaptations to sprint interval training. *Journal of Applied Physiology*, **84**, 2138-2142.

Mannion, A. F., Jakeman, P. M. and Willan, P. L. T. (1992) Effects of isokinetic training of the knee extensors on isometric strength and peak power output during cycling. *European Journal of Applied Physiology,* **65,** 370-375.

Mannion, A. F., Jakeman, P. M. and Willan, P. L. T. (1994) Effects of isokinetic training of the knee extensors on high-intensity exercise performance and skeletal muscle buffering. *European Journal of Applied Physiology,* **68,** 356-361.

Margaria, R. (1966) Assessment of physical activity in oxidative and anaerobic maximal exercise. *Federation Proceedings*, **25**, 1414-1409

Maud, P.J. and Shultz, B.B. (1989) Norms for the Wingate Anaerobic Test with comparison to another similar test. *Research Quarterly for Exercise and Sport*, **60**, 144-151

Maughan, R.J., Watson, J.S. and Weir, J. (1983) Strength and cross-sectional area of human skeletal muscle. *Journal of Physiology*, **338**, 37-49

Mayhew, J.L.; Hancock, K.; Rollison, L.; Ball, T.E. and Bowen, J.C.(2001) Contributions of strength and body composition to the gender difference in anaerobic power. *Journal of Sports Medicine and Physical Fitness*, **41**, 33-38

McCall, G. E., Byrnes, W. C., Dickinson, P. M., Pattany, P. M. and Fleck, S. J. (1996) Muscle fiber hypertrophy, hyperplasia, and capillary density in college men after resistance training. *Journal of Applied Physiology,* **81,** 2004-2012.

McArdle, W.D.; Katch, F.I. and Katch, V.L. (1996) *Exercise Physiology. Energy, Nutrition and Human Performance* (4th Ed.). Williams and Wilkins, Baltimore, Maryland.

McLean, D.A. (1992) Analysis of the physical demands of rugby union. *Journal of Sports Sciences* **10**, 285-296

McNair, P. J., Depledge, J., Bretkelly, M. and Stanley, S. N. (1996) Verbal encouragement effects on maximum effort voluntary muscle action. *British Journal of Sports Medicine,* **30,** 243-245.

Meir, R.A., McDonald, K.N. and Russell, R. (1997) Injury consequences from participation in professional rugby league: a preliminary investigation. *British Journal of Sports Medicine*, **31**, 132-134.

Meir, R.A., Newton, R., Curtis, E., Fardell, M. and Butler, B. (2001) Pysical fitness qualities of professional rugby league football players: determination of positional differences. *Journal of Strength and Conditioning Research*, **15**, 450-458.

Merlini, L., Dell'Accio, D. and Granata, C. (1995) Reliability of dynamic strength knee muscle testing in children. *Journal of Orthopaedic and Sports Physical Therapy,* **22,** 73-76.

Mikesky, A. E., Giddings, C. J., Matthews, W. and Gonyea, W. J. (1991) Changes in muscle fiber size and composition in response to heavy-resistance exercise *Medicine and Science in Sports and Exercise,* **23,** 1042-1049.

Morrissey, M. C. (1987) The relationship between peak torque and work of the quadriceps and hamstrings after menisectomy. *Journal of Orthopaedic and Sports Physical Therapy,* **10***,* 405-408.

Moritani, T. (1980) Electromyographic analysis of muscular strength gains: neural and hypertrophic effects. *National Strength Coaches Journal*, **1**, 32-37

Motulsky, H. (2002) The link between error bars and statistical significance. *www.GraphPad.com.*

Nevill, M.E., Boobis, L. H., Brooks, S. and Williams, C. (1989) Effects of training on muscle metabolism during treadmill sprinting. *Journal of Applied Physiology*, **67**, 2376-2382.

Nevill, A.M.; Ramsbottom, R. and Williams, C. (1992) Scaling physiological measurements for individuals of different body size. *European Journal of Applied Physiology*, **65**, 110-117.

Nutter, J. and Thorland, W.G. (1987) Body composition and anthropometric correlates of isokinetic leg extension strength of young adult males. *Research Quarterly for Exercise and Sport.* **58,** 47-51.

Oberg, B.,Moller, M., Gillquist, J. and Ekstrand, J (1986) Isokinetic torque levels for knee extensors and knee flexors in soccer players. *International Journal of Sports Medicine.* **7** 50-63.

O'Brien, M. (1985) Women in sport. *Applied Ergonomics*, **16**, 25-39.

Oni, O. O. A. and Crowder, E. (1996) A comparison of isokinetics and muscle strength ratios following intra-articular and extra-articular reconstructions of the anterior cruciate ligament *Injury,* **27,** 195-197.

Orchard, J., Marsden, J., Lord, S. and Garlick, D. (1997) Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *American Journal of Sports Medicine,* **25,** 81-85.

Perrin, D. H. J. (1993) *Isokinetic Exercise and Assessment,* Human Kinetics, Champaign. Illinois, USA.

Posch, E., Haglund, Y. and Erikson, E. (1989) Prospective study of concentric and eccentric leg muscle torques, flexibility, physical conditioning and variation of injury rates during one season of amateur ice hockey. *International Journal of Sports Medicine,* **10,** 113-117.

Potteiger, J.A.; Lockwood, R.H.; Haub, M.D.; Dolezal, B.A.; Almuzaini, K.S.; Schroeder, J.M. and Zebas, C.J. (1999) Muscle power and fibre characteristics following 8 weeks of plyometric training.. *Journal of Strength and Conditioning Research*, **13**, 275-279

Rogers, D.M., Turley, K.R., Kujawa, K.I., Harper, K.M. and Wilmore, J.H. (1995) Allometric scaling for oxygen uptake during exercise in children. *Pediatric Exercise Science*, **7**, 12-25

Roth, S.M., Ivey, F.M., Martel, G.F., Lemmer, J.T., Hurlbut, D.E., Siegel, E.L., Metter, E.J., Fleg, J.L., Fozard, J.L., Kostek, M.C., Wernick, D.M. and Hurley, B.L. (2001) Muscle size responses to strength training in young and older men and women. *Journal of the American Geriatric Society*, **49**, 1428-1433.

Sahlin, K. and Broberg, S. (1990) Adenine nucleotide depletion in human muscle during exercise: causality and significance of AMP deamination. *International Journal of* Sports *Medicine*, **11**, S62-S67.

Sale, D. G. (1987) Influence of exercise and training on motor unit activation. *Exercise and Sport Sciences Reviews,* **15,** 95-154.

Saltin, B. and Gollnick, P. D. (1983) Skeletal muscle adaptability: significance for metabolism and performance. *Handbook of Physiology,* **10,** 555-632.

Sapega, A.A. (1990) Muscle performance evaluation in orthopaedic practice. *Journal of Bone and Joint Surgery.* **72**, 1562-1574

Schmidt, D.W. (1999) Strength and physiological characteristics of NCAA division III American footballers. *Journal of Strength and Conditioning Research,* **13**, 210-213

Shephard, R, J. (2000) Exercise and training in women, part I: influence of gender on exercise and training responses. *Canadian Journal of Applied Physiology*, **25**, 19-34.

Sjodin, B. (1992) Anaerobic function. *Sport Science Review,* **1**, 1-27

Sleivert, G. G., Backus, R. D. and Wenger, H. A. (1995) The influence of a strength-sprint training sequence on multi-joint power output. *Medicine and Science in Sports and Exercise,* **27,** 1655-1665.

Smith, D. J. (1987) The relationship between power outputs and isokinetic torque outputs. *Canadian Journal of Sport Science,* **12,** 3-5.

Staron, R.S., Malicky, E.S., Leonardi, M.J., Falkel, J.E., Hagerman, F.C. and Dudley, G.A. (1990) Muscle hypertrophy and fast fibre type conversions in heavy resistance-trained women. *European Journal of Applied Physiology*, **60**, 71-79

Staron, R.S., Leonardi, M.J., Karapondo D.L., Malicky, E.S., Falkel, J.E., Hagerman, F.C. and Hikida, R.S. (1991) Strength and skeletal muscle adaptations in heavy-resistance trained women after detraining and retraining. *Journal of Applied Physiology*, **70**, 631-640

Staron, R.S., Karapondo D.L., Kraemer, W.J., Fry, A.C., Gordon, J.E., Falkel, J.E., Hagerman, F.C. and Hikida, R.S. (1994) Skeletal muscle adaptations during early phase of heavy-resistance training in men and women. *Journal of Applied Physiolgy*, ***76***, 1247-1255

St Clair Gibson, A., Lambert, M.I., Durandt, J.J., Scales, N. and Noakes, T.D. (2000) Quadriceps and hamstrings peak torque ratio changes in persons with chronic anterior cruciate ligament deficiency.. *Journal of Orthapaedic and Sports Physical Therapy*, **30**, 418-427

Stephenson, S., Gissane, C., Jennings, D. (1996) Injury in rugby league: a four year prospective survey. *British Journal of Sports Medicine*, **30**, 331-334.

Sinclair, D. (1961) *An introduction to Functional Anatomy* (2nd Ed.*)*. Blackwell Scientific, Oxford.

Stevens, J. (1996) *Applied Multivariate Statistics for the Social Sciences*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sugden, P. H. and Fuller, S. J. (1991) Regulation of protein turnover in skeletal and cardiac muscle. *Biochemistry Journal,* **273,** 21-37.

Tabata, I., Atomi, Y., Kanehisa, H. and Miyashita, M. (1990) Effect of high-intensity endurance training on isokinetic muscle power. *European Journal of Applied Physiology,* **60,** 254-258.

Terjung, R.L., Dudley, G.A., Meyer, R. A., Hood, D.A. and Gorski, J. (1986) Purine nucleotide cycle function in contarcating muscle. In Saltin (Ed) *Biochemistry of Exercise*, Human Kinetics, Champaign IL. 131-147.

Tharp, G. D., Johnson, G. O. and Thorland, W. G. (1984) Measurement of anaerobic power and capacity in elite young track athletes using the Wingate test. *Journal of Sports Medicine and Physical Fitness,* **24,** 100-106.

Thistle, H., Hislop, H., Moffroid, M., Hofkosh, J. and Lowman, E. (1967) Isokinetic contraction: a new concept of exercise. *Archives of Physical Medicine and Rehabilitaion,* **48,** 279-282.

Thomas, J.R. and Nelson, J.K. (2001) *Research Methods in Physical Activity* (4th Ed.). Human Kinetics, Champaign, Illinois.

Thorstensson, A.G.and Karlsson, J. (1976) Force-velocity relations and fibre composition in human knee extensor muscles. *Journal of Applied Physiology*, **10**, 2-16.

Thorstensson, A. (1977) Observations on strength training and detraining. *Acta Physiologica Scandinavica,* **100**, 491-493

Tis, L. T. and Perrin, D. H. (1994) Relationship between isokinetic average force, average torque, peak force, and peak torque of the knee extensor and flexor musculature. *Isokinetics and Exercise Science,* **4,** 150-152.

Tracy, B.L., Ivey, F.M., Hurlbut, D., Martel, G.F., Lemmer, J.T., Siegel, E.L., Metter, E.J., Fozard,J.L., Fleg, J.L. and Hurley, B.F. (1999) Muscle Quality. II. Effects of strength training in 65-to 75-yr-old men and women. *Journal of Applied Physiology,* **86,** 195-201

Troup, J. P., Metzger, J. M. and Fitts, R. H. (1986) Effect of high-intensity exercise training on functional capacity of limb skeletal muscle. *Journal of Applied Physiology,* **60,** 1743-1751.

Trudelle-Jackson, E., Meske, N., Highgenboten, C. and Jackson, A. (1989) Eccentric/concentric torque deficits in the quadriceps muscle. *Journal of Orthopaedic and Sports Physical Therapy,* **11,** 142-145.

Urhausen, A. and Kindermann, W. (1992) Biochemical monitoring of training. *Clinical Journal of Sports Medicine,* **2,** 52-61.

Vandewalle, H.; Peres, G.; Heller, J. and Monod, H. (1985) All out anaerobic capacity tests on cycle ergometers: A comparative study on men and women. *European Journal of Applied Physiology*, **54**, 22-229

Vandewalle, H., Peres, G. and Monod, H. (1987) Standard anaerobic tests. *Sports Medicine* **4**, 268-289.

Voight, M. and Klausen, K. (1990) Changes in muscle strength and speed of an unloaded movement after various training programmes. *European Journal of Applied Physiology,* **60,** 370-376.

Westing, S. H. and Seger, J. Y. (1988) Eccentric torque-velocity characteristics, torque output comparisons and gravity effect torque corrections for the quadriceps and hamstring muscles in females. *International Journal of Sports Medicine,* **10,** 175-180.

Westra, H. G., De Haan, A., Van Doorn, J. E. and De Haan, E. J. (1985) The effect of intensive interval training on the anaerobic power of rat quadriceps muscle. *Journal of Sports Sciences,* **3,** 139-150.

White, T. P. and Esser, K. A. (1989) Satellite cell growth factor involvement in skeletal muscle growth. *Medicine and Science in Sport and Exercise,* **21,** S158-S163.

Wilmore, J.H. (1975) Inferiority of female athletes: Myth or reality. *Journal of Sports Medicine*, **3**, 1-6.

Winter, E. M., Brookes, F.B.C. and Hamley, E.J. (1991) Maximal exercise performance and lean leg volume in men and women. *Journal of Sports Sciences*, **9**, 3-13.

Winter, E.M. (1992) Scaling: Partitioning out differences in size. *Pediatric Exercise Science,* **4**, 296-301.

Winter, E.M. and Maughan, R. (1991) Strength and cross-sectional area of the quadriceps in men and women. *Journal of Physiology*, **43 S**, 175 P

Winter, E.M. and Nevill, A.M. (2001) Scaling: Adjusting for differences in body size. in Eston, R. and Reilly, T. (Eds). *Kinanthropometry and Exercise Physiology Laboratory Manual* (2nd Editon.). Routledge, London.

Yamanaka, K., Haga, S., Shindo, M., Narita, J., Koseki, Y., Matsuura, Y. and Eda, M. (1988) Time and motion analysis in top class soccer games. In Reilly, T. *et al.* Science and Fotball,*, Proceedings of the First World Congress of Science and Football*, E and F.N Spon, London, 334-340.

Yamomoto, T. (1988) Relationship between hamstring strains and leg muscle strength. A follow up study of collegiate track and field athletes. *Journal of Sports Medicine and Physical Fitness,* **33,** 194-199.