Neuromuscular and Metabolic Characteristics of Fatigue in Response to Heavy Resistance and Dynamic Strength Training

by

Neil Fell

A thesis submitted in partial fulfilment of the requirement for the degree of Doctor of Philosophy (Liverpool John Moores University) following work undertaken at The Research Institute for Sport and Exercise Sciences, Liverpool John Moores University.

OCTOBER 2002

APPENDIX 1 NOT COPIED

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"Thinking is to me the greatest fatigue in the world."

SIR JOHN VANBURGH, 1696

Abstract

Players engaged in teams sports (e.g. rugby) regularly use resistance type training for the development of strength and rate of force development. Such training causes fatigue and the optimal recovery period required to overcome the effect of fatigue before competition or subsequent training sessions is a major concern to both player and coach.

The aim of this thesis was to examine the acute neuromuscular and metabolic effects of fatigue and short-term recovery from fatigue in players engaged in team sports. Two strenuous but clearly different exercises were compared: heavy resistance exercise (HRE) and dynamic strength exercise (DSE). In addition, the effects of 6-week heavy resistance and dynamic strength training programmes on the fatigue and recovery characteristics were also explored.

In order to assess the neuromuscular changes during fatigue and short-term recovery from fatigue produced following strenuous resistance exercise, the use of several different measurement protocols, are required. However, these are often associated with high variability. The objective of Study 1 was therefore to establish the measurement protocols to reliably assess the neuromuscular responses to heavy resistance and dynamic strength exercise and was achieved by conducting a series of four pilot studies.

The objective of Study 2 was to quantify the acute neuromuscular and metabolic responses to heavy resistance and dynamic strength exercise in subjects engaged in team sports. Six subjects performed both exercises sessions in a counter-balanced design. The HRE session was comprised of 5 sets of 6 RM squat lifts (approx 85-90% 1RM). In DSE, the subjects performed 5 sets of 10 weighted jump squats at a load of 30% of maximum (1 RM). Neuromuscular electrical stimulation (NMES) of the quadriceps muscles was recorded before the exercise session and immediately after the session. The muscle was stimulated for 1 second at frequencies of 20Hz and 100 Hz. The same measurements were also repeated during the recovery period at intervals of 30, 60 and 120 minutes, and for 24 and 48 hours afterwards. Maximal voluntary isometric contraction force (MVC) was also recorded 1 minute after electrical stimulation in each case. Data were recorded for maximal peak force and rate of force development (RFD). Rate of force development was determined over the range of 10 - 70 % of the force slope. Surface electromyographic (EMG) activity was simultaneously recorded during the isometric contractions from the vastus lateralis (VL) muscle. Significant decreases in peak force ($p < 0.05$), rate of force development ($p < 0.05$) and in the forces elicited by electrical stimulation ($p < 0.05$) were observed after HRE and DSE. Increases in blood lactate were very similar for both loading conditions. There were no significant differences between the two distinct loading conditions, however there was a trend for the decreases in maximal peak force and rate of force development to be less and recover quicker after DSE compared to HRE. Fatigue after HRE tended to have a greater central component with a greater reduction in neural activation, whereas DSE appeared to lead primarily to peripheral fatigue. Further evidence to support the presence of central fatigue after HRE was provided by the recovery in 100 Hz force in the first two hours after the exercise session, whereas recovery of MVC did not occur until after 48 hours. The results also suggested that performing a DSE session only 24 hours before a game may have a beneficial effect on performance as indicated by the enhancement of RFD by 10% after 24 hours of recovery. Training after HRE would not be recommended until after at least 48 hours.

The objective of Study 3 was to examine the effects of a six-weeks heavy resistance and dynamic strength training programme on the acute neuromuscular and metabolic responses to a single heavy resistance and dynamic strength exercise session in subjects engaged in team sports. Subjects followed either a heavy resistance ($n = 6$) or dynamic strength training programme ($n = 6$) and trained 2 times per week under supervision. The acute neuromuscular

and metabolic responses to a single exercise session (either HRE or DSE) were examined before and after the training programme. For HRE, subjects performed 5 sets of 6 RM squat lifts although during the course of training the load was adjusted for each set and session such that fatigue always occurred on the last repetition. For DSE, subjects performed 5 sets of 10 weighted jump squats at a load of 20% of maximum (1 RM) for weeks 1 and 2, 25% 1RM for weeks 3 and 4 and 30% 1RM for weeks 5 and 6. DSE appeared to have an advantage over HRE for producing an increase in both maximal voluntary contraction force and rate of force development. Both HRE and DSE significantly reduced the decline in maximal peak force ($p < 0.05$) following the six weeks training period, with HRE appearing to have the more beneficial effect. However improved fatigue resistance was not evident for rate of force development and the 100 Hz force. Deficits in rate of force development tended to be greater following the 6 weeks training programmes, especially in response to DSE.

The overall findings suggest that in players engaged in teams sports, DSE is a superior form of resistance exercise for the development of speed-strength, however improvements in fatigue resistance are not achieved when maximal motor unit firing rates are required.

Key Words: Neuromuscular fatigue, heavy resistance exercise, dynamic strength exercise, training

Acknowledgements

I would like to extend my sincerest gratitude to the following people who have helped in the development and final unification of this thesis:

1. Professor Adrian Lees for not letting me lose sight of the bigger picture! Many thanks for a great eight years at Liverpool John Moores University.
2. Professor Don MacLaren, for his professional advice and assistance in the preparation of this thesis.
3. Professor Tom Reilly for allowing me to continue my research in light of other distractions.
4. Dr. Gail Curtis, for the completion of the blood analyses at the Liverpool Royal University Hospital.
5. The subjects for donating so much of their time, effort, sweat and blood.
6. My research colleagues; Craig Sale, Pete Jones, Neil Chester, Chris Bussell, Ben Patritti, Dave Harriss, Gareth Gilbert, and especially Phil Graham-Smith for their source of constant amusement.
7. Hannah, my girlfriend for her love and support despite my ever changing moods.
8. A special thank you must also go to Dave and Sylvie (Hannah's parents) for looking after me over the last year.
9. My brother, Martin for the inspiration to never give up.
10. Finally, Mum and Dad for their invaluable encouragement and for just knowing they have always been there.

Declaration

I declare that the work presented in this thesis is entirely my own, with the exception of the following:

The plasma potassium and creatine kinase concentrations were measured at the Liverpool Royal University Hospital by Dr. Gail Curtis and her staff.

Some of the work reported in this thesis has been presented at the International Conference on Weightlifting and Strength Training (Lahti, Finland; November, 1998), the BASES Conference (Liverpool, England; August 2000) and the Commonwealth Games Conference (Manchester, England; July 2002).

October, 2002

List of Publications

(1) Fell, N., Lees, A. and MacLaren, D. P. M. (1998). Neuromuscular characteristics of fatigue and recovery in response to heavy resistance and dynamic strength exercise in players engaged in team sports [Abstract]. In *Proceedings of the International Conference on Weightlifting and Strength Training,* Lahti, Finland. pp 153-154.

(2) Fell, N., Lees, A. and MacLaren, D. P. M. (2001). Within-session and between-day repeatability of selected neuromuscular performance variables from isometric contractions of the lower limb [Abstract]. *Journal of Sports Sciences*, **19**, 4-5.

(3) Fell, N., Lees, A. and MacLaren, D. P. M. (2001). The influence of added load on muscular performance in the counter-movement jump [Abstract]. *Journal of Sports Sciences*, **19**, 5-6.

(4) Fell, N., Lees, A. and MacLaren, D. P. M. (2002). The development of maximal voluntary contraction force and rate of force development after 6-weeks heavy resistance and dynamic strength training [Abstract]. In *Proceedings of the 12th Commonwealth International Sport Conference*, Manchester, United Kingdom. p 170.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to the thesis

Mammalian skeletal muscles are capable of generating significant forces and power outputs when appropriately activated (Åstrand and Rodahl, 1986). For example, values over 5000 N have been reported for measures of maximum voluntary bilateral isometric force for elite strength athletes (Häkkinen, 1994a), and average peak power outputs of 3900 watts have been calculated for male high jumpers (Davies and Rennie, 1968). Attempts to produce repeated mechanical efforts are characterised by a progressive deterioration in performance. In its simplest form, this deterioration has commonly been recognised as fatigue, or more precisely in the case of voluntary exercising humans, neuromuscular fatigue (Green, 1995).

A typical strenuous resistance exercise session, as used by sports people, represents a condition that leads to acute deterioration in neuromuscular performance (e.g. Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988; Tesch *et al.*, 1986). Decreases occur not only in maximal peak force, but considerable shifts in the shape of the force-time curve, as indicated by the rate of force development, take place as well (Häkkinen and Komi, 1986b; Viitasalo and Komi, 1971). The magnitude of the acute fatigue-induced decrease in the neuromuscular performance is related to the overall volume and to the loading intensity of the session (Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), as well as to the specific type of the fatiguing load (e.g. heavy resistance exercise, explosive strength exercise, plyometric training) (Linnamo *et al.*, 1998; Strojnik and Komi, 1998) and the specificity of the athletic background (e.g. strength and power trained, endurance trained, untrained) (Häkkinen and Myllylä, 1990; Kroll *et al.*, 1980; Pääsuke *et al.*, 1999).

Players engaged in team sports, such as rugby, regularly use forms of resistance exercise for the improvement of maximal peak force (strength) and rate of force development. For explosive movements such as sprints, throws and jumps, in which force production times are in the order of 100 to 300 ms (Aura and Viitasalo, 1989; Mero *et al.*, 1992; Tidow, 1990), the rate at which force is developed has been suggested to be the most important physical capacity (Schmidtbleicher, 1992; Zatsiorksy, 1995). However, the optimum resistance training method for developing fast force production is not clearly established.

It has been shown that heavy resistance exercise (HRE) is often efficient in enhancing rate of force development (Schmidtbleicher and Buehrle, 1987) to a greater extent than training with relatively light loads. On the other hand, research has also demonstrated that training with maximum loads with slow movement velocities does not always effectively increase muscular power (Bloomfield *et al.*, 1990; Häkkinen and Komi, 1985a). Kaneko *et al.* (1983) determined that using a load of 30% of the one repetition maximum (1RM), results in the highest mechanical power output of the musculature, although it is not simply a question of moving a lighter resistance as rapidly as possible. This is because during conventional resistance training exercises, even with a relative lighter load, a substantial portion of the lift involves a period when the bar is decelerated prior to achieving zero velocity at the end of the concentric movement (Elliot *et al.*, 1989; Wilson *et al.*, 1989; Newton *et al.*, 1996). The problem of the deceleration phase can be overcome if the athlete actually throws or jumps with the weight or barbell. This has been termed "dynamic" strength exercise (DSE), and when combined with the load, which maximises the mechanical power output of the musculature, this form of resistance training has been shown to be

more effective in enhancing dynamic athletic performance compared to heavy resistance exercise or plyometric training modalities (Wilson *et al.*, 1993).

Irrespective of the training method, the increasing number of games played thereby reducing the time available for training and perhaps more importantly the time available for recovery, often hinders improvements in neuromuscular performance. The process of recovery taking place during rest after the termination of strenuous fatigue loading deserves close examination as the optimal recovery period required to overcome the effect of fatigue is of major concern to both player and coach. Furthermore, it is possible to learn something more of the inter-relationships of factors in producing fatigue by studying their associations as recovery takes place (McComas, 1996).

Fatigue during voluntary muscular contractions is however a complex and multi-faceted phenomenon and may be caused by central nervous factors as well as changes in the peripheral site of the neuromuscular system. Depending on the type and intensity of muscular activity performed, fatigue may develop owing to failure at one or several sites along the pathway of force production (Bigland-Ritchie, 1984; Edwards, 1983; Pääsuke *et al.*, 1999). The major central sites of fatigue are: excitatory input to higher motor centres, excitatory drive to lower motor neurons and motor neuron excitability. Peripheral sites of fatigue may include: neuromuscular transmission, sarcolemma excitability, excitation-contraction coupling, contractile mechanism, metabolic energy supply, and metabolite accumulation (Bigland-Ritchie, 1984).

Research findings have indicated that high load resistance exercise stimuli lead to acute fatigue not only in the contractile characteristics of the exercised muscles but in the nervous system as well. Häkkinen (1993; 1994a) and Häkkinen *et al.* (1988) have all reported decreases in the force production capacity of the muscles and a decrease in the voluntary neural activation of the exercised muscles. Fatigue induced changes in the electromyogram have been suggested to be in advance of the neuromuscular junction (Bigland-Ritchie *et al.*, 1986a; Hagbarth *et al.*, 1986; Kirsch and Zymer, 1992), and therefore fatigue after heavy resistance loading appears to be of both central and peripheral origin.

The mechanisms of central fatigue can be eliminated using transcutaneous electrical stimulation of muscle, in which the failure of its force generating capacity can be demonstrated independently of motivation and voluntary effort (e.g. Bigland-Ritchie and Woods, 1984). Traditionally, from this method, two types of peripheral fatigue have been identified, and have been termed high frequency fatigue (HFF) and low frequency fatigue (LFF) (Jones, 1981; 1996a; 1996b). High frequency fatigue reflects a selective loss of force at high stimulation frequencies and may occur as a result of impaired neuromuscular transmission or impaired propagation of the muscle action potential over the sarcolemma (Edwards, 1978; 1981). Conversely, low frequency fatigue is a specific failure of force generation at low frequencies of stimulation, whereas at high frequencies the tension is close to normal. This form of fatigue has been attributed to a failure of activation of the muscle despite adequate excitation.

The peripheral mechanisms underlying the fatigue observed during repetitive, high force generating activity also appear to have both metabolic and non-metabolic

components (Davies and White, 1981; Moussavi *et al.*, 1989). Metabolic fatigue or fatigue associated with the energetic changes in the muscle would appear to be intimately involved in the ability to sustain high-intensity exercise. Following a period of repetitive, high-intensity activity, the muscles and muscle fibres are characterised by extreme metabolic perturbations. For example significant reductions in adenosine triphosphate (ATP), creatine phosphate (CP) and glycogen have been observed following an intense heavy resistance exercise session (Tesch *et al.*, 1986). However, according to current thinking it is not the reduction in ATP or other energy substrates that are the primary cause of force failure, rather it is the accumulation of selected metabolic by-products, and specifically inorganic phosphate, that precipitates the fatigue process (Allen and Westerblad, 2001; Favero, 1999; Jones, 1999; Westerblad *et al.*, 2002).

The non-metabolic component of fatigue appears to exist independently of a disturbance of the energetic potential of the muscle fibre. This type of fatigue appears to be mediated as a result of the high repetition forces that are generated and which results in muscle damage (Newham *et al.*, 1983; 1987; Byrnes *et al.* 1985a; 1985b; Fridén and Leiber, 1992). Concentric activity can produce some degree of damage to the muscle cell (Fridén and Ekblom, 1988) although eccentric exercise, most probably because of the much higher force levels that can be generated, have the most damaging effect (Fridén *et al.*, 1983). At various times, the damage has been characterised by sarcoplasmic sarcolemma disruption, Z-band streaming, myofibrillar disorganisation, leukocyte and phagocyte infiltration, loss of cytoskeletal proteins such as desmin and fibre necrosis (Armstong et *al.*, 1991; Fridén and Leiber, 1992; Leiber *et al.*, 1996). Such exercise is also commonly associated with soreness and

swelling of the tissue (Fridén *et al.*, 1983; Hikida *et al.*, 1983). The recovery from muscle damage at least in untrained individuals may take several days or even weeks (Newham *et al.*, 1983; Clarkson and Tremblay, 1988). Furthermore, following high intensity activity, muscle damage may represent a major aspect of the fatigue observed.

A number of studies have examined the acute neuromuscular fatigue and short-term recovery characteristics from fatigue after heavy resistance exercise protocols (e.g. Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), but less experimental information is available on fatigue and recovery after explosive type strength loading. Both forms of resistance exercise have been shown to improve rate of force development. In explosive or dynamic strength exercise the loads utilised are lower, but the movement velocities are kept as high as possible throughout the sets of exercise. Consequently the total work and the duration of activation are usually lower than in heavy resistance exercise, although high forces and accelerations can be achieved in explosive strength training, especially when the athlete takes off from the floor. It would therefore be of interest to examine whether the fatigue and recovery characteristics would be the same following dynamic strength exercise compared to heavy resistance exercise, two completely distinct forms of strength training.

Further research examining the phenomenon of fatigue after a strenuous resistance exercise protocol has concentrated on either elite or strength trained athletes (Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), strength and power athletes compared to endurance trained athletes (Häkkinen, and Myllylä, 1990; Kroll *et al.*, 1980; Pääsuke *et al.*, 1999) or subjects not participating in any regular training

programme (e.g. Pullinen and Komi, 1995). No data are available regarding the recovery patterns from fatiguing resistance exercise sessions for players engaged in team sports. These athletes are unique in that they require a combination of all the qualities of speed, strength and endurance respectively.

The relative contribution of central (neural) and peripheral (muscular) factors to fatigue varies depending on the type and intensity of the exercise performed (Latash, *et al.*, 1994; Linnamo *et al.*, 1998), although very few studies (e.g. Strojnik and Komi, 1998) have attempted to clarify the possible mechanisms causing fatigue following maximal voluntary exercise protocols. Equally, given the intense nature of resistance exercise, and the need for extensive high frequency recruitment of muscle fibres and motor units in a range of synergistic muscles, there is limited opportunity for compensatory strategies, to enable performance to be sustained. Increased fatigue resistance would appear to depend on carefully planned designed training programmes designed to adapt the excitation and contraction processes, the cytoskeleton and the metabolic systems, not only to tolerate but also to minimise the changes in the intracellular environment that are caused by the intense activity (Behm and St. Pierre, 1998; Green, 1997).

In order to assess the neuromuscular changes during fatigue and short-term recovery from fatigue produced following strenuous resistance exercise, the use of several different measurement protocols are required (e.g. Brown *et al.*, 1996; 1997; Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988; Linnamo *et al.*, 1998; Newham *et al.*, 1991; Strojnik and Komi, 1998), but which are often associated with high variability. Satisfactory levels of reliability however, are achieved only when the testing protocols

are sufficiently standardised. Consequently the reliability of the experimental techniques used in the present study need to be established.

1.2 Aim of the thesis

The aim of this thesis is to examine the acute neuromuscular and metabolic effects of fatigue and short-term recovery from fatigue in players engaged in team sports following two distinct types of resistance exercise.

1.3 Objectives of the thesis

The aim of this thesis will be met by the following objectives: -

1. To establish the protocols to reliably assess the neuromuscular responses to heavy resistance and dynamic strength exercise.

2. To quantify the acute neuromuscular and metabolic responses to heavy resistance and dynamic strength exercise in subjects engaged in team sports.

3. To examine the effects of a six-weeks heavy resistance and dynamic strength training programme on the acute neuromuscular and metabolic responses to a single heavy resistance and dynamic strength exercise session in subjects engaged in team sports.

It is envisaged that accomplishing these objectives will lead to a greater understanding of the neuromuscular and metabolic characteristics of fatigue and recovery in response to heavy resistance and dynamic strength training in subjects engaged in team sports. This will have implications as to the optimal recovery period required to overcome the effect of fatigue prior to competition.

1.4 Definitions of terms

Neuromuscular fatigue can be defined as a failure to generate the required or expected force or power output during sustained or repeated contractions (Edwards, 1981; 1983; McKenna, 1992; Vøllestad and Sejersted, 1988).

Maximum strength is defined as the maximal peak force that a muscle or muscle group can generate at a given speed of contraction. For the purposes of this thesis, maximum strength represents the highest tension possible within a sustained isometric contraction and is reflected by the maximum voluntary contraction force (MVC).

Rate of force development is the ability to develop high force in a short period of time and can be quantified from an isometric force-time curve.

Heavy resistance exercise is where heavy loads (80-130% of the one repetition maximum or 1RM) are lifted for relatively few (1-6) repetitions.

Dynamic strength exercise is where relatively light loads (approximately 30-70% of maximum) are lifted for a high number of repetitions (6-15), and at high speed, whereby the load is accelerated throughout the movement. E.g. bench press throws, vertical jump squats.

Reliability is defined as the amount of measurement error that has been deemed acceptable for the practical use of a measurement tool.

CHAPTER 2

LITERATURE REVIEW

2.1 The evolution of strength training in team sports

Consistent with the developments and changes in many other sports throughout the world, rugby (of either league or union codes) is no longer simply a matter of playing the game. The higher the level of competition, the greater the evidence of physical preparation (King, 1993). Training has been categorised into physical preparation, technical preparation (individual skills), tactical preparation (team skills) and psychological preparation (Bompa, 1983). The predominant qualities of physical preparation are protective and functional strength, speed, and endurance. Whilst it is agreed that the rugby player requires all three physical qualities, the extent to which each is exploited is subject to many variations (Bauer, 1984; 1986; Biddle and Whitehead, 1980; Docherty, 1984; Walsh, 1990). These variations reflect not only variations in code, playing positions and styles, and level of competition but also variations in methodology evident between coaches, clubs and countries.

The game of rugby football union is played in many countries and in fact, the only code of football exceeding rugby in universal popularity is the game of soccer. Despite turning professional in 1996, for the vast majority of participants, rugby union is still an amateur game. The culture of the game is steeped in tradition and many coaches or players are sceptical to, or oblivious of modern, training techniques. It is therefore not surprising that many of the developments in the training methods of rugby players have evolved from rugby league, a game that has been professional for over 100 years. The expansion of the Australian Rugby League professional competition in the 1980s led to significant improvements in the physical preparation

of the players by adopting new training and coaching methods from overseas, most notably American Football (Meir, 1993).

At the highest level, the application of scientific training techniques has become an integral part of the physical preparation of the rugby player of both codes. Coaches have appointed strength and conditioning specialists who possess the knowledge and skill for developing a sport specific training programme that caters for the physical demands of the sport. Even in the very 'traditional' world of professional soccer, the need for enhancements in strength and sports specific training methods has reluctantly been acknowledged.

2.2 Adaptations to strength training

Despite the obvious popularity of strength training and its increasing use in the training of players engaged in team sports, remarkably little is known about what modulates strength in either the long or short term. There are major changes in muscle strength during childhood and adolescence that are largely independent of physical activity (Round *et al.*, 1999), but after the growth spurt and adolescence, the only way of increasing strength without resorting to illegal substances is through exercise and training (Jones and Folland, 2001). The aim of the following section is therefore to highlight the major adaptations that occur in response to strength training.

To bring about positive changes in an athlete's state, an exercise overload must be applied. The training adaptation takes place only if the magnitude of the training load is above the habitual level. This is the principle of progressive overload and was first formalised by DeLorme (1946). Since muscle cross-sectional area is the largest single factor determining strength, any increase in strength might be expected to be reflected in muscle size. However some studies have highlighted the greater increases in strength compared with size, particularly in the early stages of resistance training (up to ~ 8 weeks; Jones and Rutherford, 1987; Young *et al.*, 1983). It is therefore still generally accepted that neural and morphological (muscular) adaptations contribute to strength gains during training. Hormonal influences on strength and size gains have also received extensive review (e.g. Häkkinen, 1989) however the role of endocrine hormones (e.g. testosterone, growth hormone and insulin) may be to release or potentiate the release of local growth factors (e.g. insulin-like growth factor I, IGF-I) rather than having a direct involvement (e.g. Goldspink, 1999; Jones and Folland, 2001).

2.2.1 Neural adaptations

Neural adaptation in the development of muscular strength and power has received extensive review (e.g. Häkkinen, 1989; Häkkinen, 1994b; Komi, 1986; Sale, 1987; 1988; 1992). The factors that influence strength and power can be classified into two categories: (1) intra-muscular co-ordination, which is determined by recruitment, firing rate and synchronisation of motor units, and (2) inter-muscular co-ordination, which is influenced by activation of synergists and decreased co-contraction of antagonists. Increases in motor unit firing rates and synchronisation are particularly important contributors to increase the explosiveness of the force production (Komi, 1998).

The integrated EMG (iEMG) of muscle has been used as a measure of neural drive (e.g. Häkkinen and Komi, 1983; 1985a; 1985b) however iEMG does not reveal where the increased motor unit activity comes from. Using more specific techniques such as the Hoffman (H) reflex and the M-wave, Aagard *et al.* (1997) have been able to demonstrate that the neural adaptation involves both spinal (increased motor neuron excitability and / or reduced presynaptic inhibition) as well as supraspinal (increased descending command adaptation mechanisms.

2.2.2 Muscular adaptations

2.2.2.1 Hypertrophy

Increase in muscle size (cross-sectional area) can be caused by hypertrophy, an increase in the cross-sectional area of individual muscle fibres or by hyperplasia, an increase in the number of muscle fibres. Although there remains to be controversy as to whether hyperplasia occurs in human muscle (Antonio and Gonyea, 1993; Gonyea

et al., 1986; MacDougall *et al.*, 1984; Sjöstrom *et al.*, 1991), it is unlikely to make a significant contribution to training induced-strength gains (Jones and Folland, 2001). Hypertrophy of individual muscle fibres is therefore generally regarded as the primary muscular adaptation to strength training as evidenced by numerous longitudinal studies (Häkkinen *et al.*, 1998; MacDougall *et al.*, 1980).

2.2.2.2 Specific tension

Although strength training can induce hypertrophy, differences in cross-sectional area for complex human muscle groups account for only approximately 50% of the differences in strength between individuals (Chapman *et al.*, 1984; Häkkinen and Keskinen, 1989). This raises the question of whether other changes besides neural adaptations, can occur in muscle to account for differences in strength. One possibility is differences in specific tension. Specific tension refers to the intrinsic strength of muscle and is measured as the force that muscle can exert per unit of cross-sectional area (N/cm^2). In other words, specific tension is a measure of the capability of muscle to exert force that is independent of the amount of muscle. Because the force a muscle can exert is equal to the product of cross-sectional area and specific tension, differences in specific tension can contribute to differences in strength between individuals (Enoka, 1994).

Some researchers, based on indirect estimates from studies on motor units have suggested that specific tension may vary between the different muscle fibre types with Type II motor units having a greater specific tension than Type I (Jones *et al.*, 1989), although the specific tension of isolated slow and fast twitch fibres has not been shown (Lucas *et al.*, 1987). One important difference between muscle fibre and motor

unit measurements is that the force exerted by an individual fibre can be measured directly, where as the force measured by a motor unit is measured at the tendon and is affected by all the connective tissue structures between the cross-bridges and the tendon. For this reason, differences in specific tension for the motor unit types may be related to the way that the force is transmitted from the muscle fibre to the tendon. The complex cytoskeleton that surrounds single muscle fibres is responsible for transmitting the force generated by the contractile apparatus to the intra-muscular connective tissue. It appears that the characteristics of this tissue vary with fibre type (Kovanen *et al.*, 1984a) with the concentration and hence tensile strength of endomysial collagen significantly greater for slow-twitch muscle fibres than for fast-twitch muscle fibres. Furthermore these properties are adaptable with training (Kovanen *et al.*, 1984b)

One factor that does appear to affect specific tension directly is muscle architecture. An increase in the angle of fibre pennation will allow more contractile material to attach to the tendon (Alexander and Vernon, 1975), and although the force resolved along the tendon will be reduced, the net effect is that up to an angle of 45^0 there is an increase in force per unit cross-sectional area. A number of cross-sectional studies have demonstrated a relationship between muscle size and the angle of pennation in a variety of strength-trained and control groups (e.g. Abe *et al.*, 1998). This is strong evidence suggesting that hypertrophy involves an increase in the angle of fibre pennation and hence an increase in specific tension. Preferential hypertrophy of type II fibres has frequently been reported after strength training (Tesch *et al.*, 1987; Thorstensson *et al.*, 1977) which in turn, may part explain the differences in specific tension between motor unit types due to the influence of muscle size on the angle of

pennation. It is surprising however that the only training study to evaluate the angle of pennation found no change after 12 weeks of training (Rutherford and Jones, 1992).

2.2.3 Stiffness Regulation

Both neural and muscular factors are involved in the important concept of muscle function: stiffness regulation. One of the purposes of strength and power training could be to improve the ability to become stiff, and thus sustain high impact (stretch) loads and subsequently maintain good recoil characteristics. This has been demonstrated quite conclusively through explosive power training (Häkkinen and Komi, 1985b).

In addition to structural changes in the contractile and connective tissues, facilitatory and inhibitory reflex mechanisms can be influenced by appropriate training (Komi, 1998). Komi (1986) has described two possible mechanisms for changes in facilitatory and inhibitory spinal reflex inputs during training, (i) a length feedback component, which involves the muscle spindle discharge, and its increase (facilitation) can improve the stiffness of the muscle, and (ii) a force-feedback component which involves the inhibitory effects from the Golgi tendon organ. Training can reduce its influence and the final result will be the same as in the case of increased facilitation.

2.3 Qualities of strength and methods of strength development in teams sports

In addition to the development of size, it is recognised that each of the qualities required by a team sports player, namely speed, strength and endurance can be isolated and subjected to specific training. However most activities or movements in sport are the product or combination of two or more qualities or abilities (Bompa, 1983). When speed and strength are combined it is commonly known as power (Young, 1993) and is used to describe the explosive muscular actions such as required in sprinting, jumping, sidestepping, kicking and striking (Newton and Kraemer, 1994).

Power is defined as the force applied multiplied by the velocity of movement (Knuttgen and Kraemer, 1987). As the work done is equal to the force times the distance moved (Garhammer, 1993), and velocity is the distance moved divided by the time taken, power can also be expressed as the work done per unit time or the rate of doing work. These definitions lead to the determination of instantaneous and average power output respectively.

More commonly used in Europe is the term speed-strength, although speed-strength still describes any capacity that contains both a force (strength) and a speed component to the muscular actions. The mechanical definition of power can be thought as one specific form of speed-strength. In addition to power, speed-strength may also include:

1. The maximum rate of force development (RFD_{max}), which is identical to the term explosive strength (Schmidtbleicher, 1992).
2. Starting strength – the force achieved early in the contraction, e.g. the initial 30 ms (Baker *et al.*, 1994; Tidow, 1990; Wilson *et al.*, 1995; Young 1995).
3. Reactive strength – the ability to utilise the muscle pre-stretch in a stretch-shortening cycle (SSC) movement (Schmidtbleicher, 1992) and to quickly switch from an eccentric contraction to a concentric contraction (Poliquin and Patterson, 1989).

Values for maximum strength (maximum voluntary contraction force, MVC), maximum rate of force development and starting strength are identified from a force-time curve obtained from a maximum effort isometric contraction, and are indicated in Figure 2.1. The use of isometric tests of muscular function will be discussed in more detail later in this thesis.

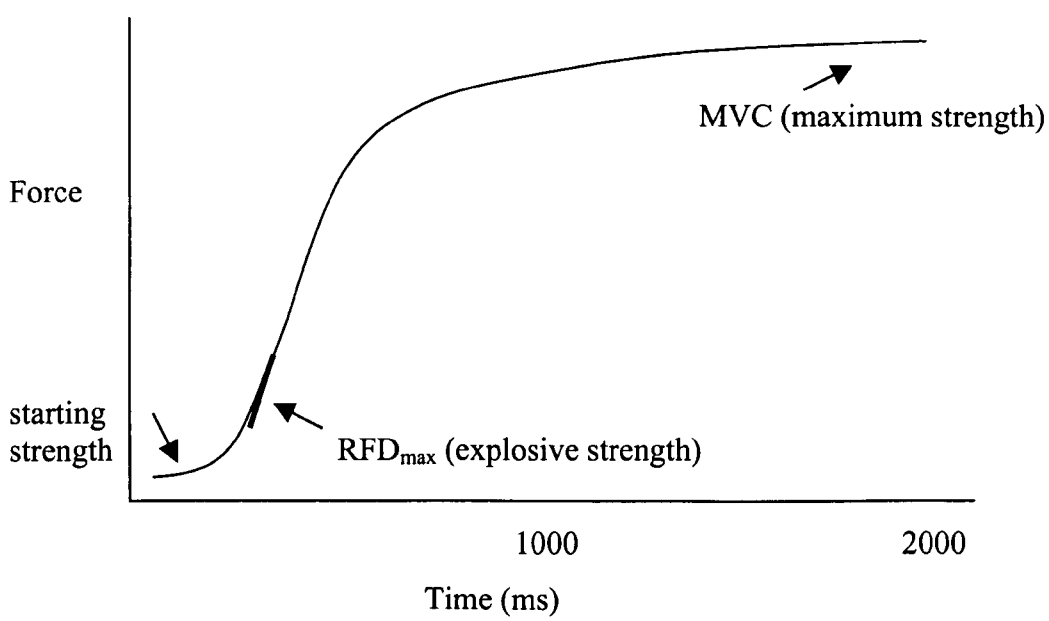


Figure 2.1 Isometric force-time curve indicating maximum, explosive and starting strength.

2.3.1 Training for speed-strength: heavy versus light loads

It is universally agreed that musculo-skeletal power or speed-strength is an important requirement for sport, although the optimal training resistance to develop fast force production is not always clearly established. The two main opposing beliefs are that:

(i) speed-strength is influenced significantly by maximum strength (Schmidtbleicher, 1992; Tidow, 1990) and therefore loads used in the concentric range are critical (1-6 repetitions, 80-130% of the one repetition maximum or 1 RM). Exponents of this philosophy do not deny the need for inclusion of other types of training, but stress that maximum strength influences all other qualities of strength to a greater extent than does any other single strength quality (Ajan and Baroga, 1988; Poliquin, 1989; Schmidtbleicher, 1985). For the purpose of this thesis, this type of training is referred to as heavy resistance exercise (HRE).

(ii) speed-strength is influenced by a high movement velocity in the strength exercise, therefore there is a requirement for sub-maximal loads (30-70% 1RM) and higher repetitions (6-15) (Sale and MacDougall, 1981). Furthermore the intention of the athlete is to accelerate the load throughout the movement and release or jump with the bar, e.g. bench press throws and vertical jump squats (Newton *et al.*, 1999; Newton *et al.*, 1996; Newton and Wilson, 1993; Wilson *et al.*, 1993). For the purpose of this thesis, this type of training is referred to as dynamic strength exercise (DSE).

2.3.2 Evidence of velocity specificity

A comprehensive review of the scientific literature on the velocity specificity of resistance training and the associated neuromuscular mechanisms is offered by Behm and Sale (1993a). Much of the research evidence in favour of using light loads however is based on studies that required subjects to train on isokinetic dynamometers (e.g Caiozzo *et al.*, 1981; Ewing *et al.*, 1990; Kanehisa and Myashita, 1983; Lesmes *et al*, 1978; Moffroid and Whipple, 1970). On the other hand, analysis of isometric force-time curves has revealed favourable changes in speed-strength as a result of heavy resistance exercise in some studies, but not in others. For example, Schmidtbleicher and Buehrle (1987) directly compared three training groups: a maximum strength (MS) group performed training sessions with high loads and few repetitions (3 sets of 3 repetitions at 90% MVC, 2 x 2 x 95% MVC, 1 x 1 x 100% MVC and 1 x 1 x 100% MVC + 1kg); the power training group carried out 5 sets of 8 repetitions with 45% load of MVC; and the maximum repetition (MR) group practised 3 sets of 12 repetitions with 70% of MVC. All training groups had four weekly sessions and practiced a concentric arm shot put movement on a special apparatus.

The following parameters were evaluated to describe the force-time characteristics: maximum strength (the maximum level of isometric strength or MVC) and the maximum rate of force development (RFD_{max}). In addition, the maximum rate of rise of electrical activity (RREA) and the period of time from the innervation onset until the maximum level of electrical activity was reached (RT) were determined from surface electromyography recordings of the triceps brachii muscle. Following 12 weeks of training, the largest improvements in the speed-strength measures were

obtained from the maximum strength group. The findings from all training groups are summarised in Table 2.1.

Table 2.1 Mean values (± SD) and percentage of alterations of selected neuromuscular performance parameters before and after training (Schmidtbleicher and Buehrle, 1987).

Parameter	MS group (n=15)			Power group (n=15)			MR group (n=14)			Control group (n=15)		
	mean	SD	%	mean	SD	%	mean	SD	%	mean	SD	%
MVC (N)												
Pre	450	94		452	65		430	52		430	82	
Post	533	98	18	529	80	17	519	68	21	428	77	-0.7
RFD ($N.s^{-1}$)												
Pre	4400	1200		4500	1000		4500	1200		4.9	1.9	
Post	5900	1600	34	5000	900	11	4700	1200	4	4.6	1.4	-6
RT (ms)												
Pre	62	28		53	23		57	16		54	23	
Post	57	20	8	52	23	3	59	23	-4	54	20	-2
RREA (t^{-1})												
Pre	19	8.0		23	8.1		22	13.4		21	9.0	
Post	21	9.1	12	24	12.3	4	20	7.8	-4	20	6.8	-4

MS – Maximum Strength
Power – 45% load of Maximum Voluntary Contraction (MVC) force
MR – Maximal Repetition

Häkkinen and co-workers in a number of studies have demonstrated the velocity specificity of heavy resistance and dynamic strength (jump squat) training. Squat training with high loads ranging from 70-120% of the one repetition maximum produced significant improvements in maximum isometric strength (Häkkinen *et al.*, 1981; Häkkinen *et al.*, 1985a; Häkkinen and Komi, 1986a), although it failed to produce significant improvements in the isometric rate of force production (Häkkinen *et al.*, 1985a), or the time to reach various relative force levels (Häkkinen *et al.*, 1981; Häkkinen *et al.*, 1985a; Häkkinen and Komi, 1986a). In contrast, jump training with

comparatively light resistances produced smaller gains in isometric strength (Häkkinen and Komi, 1986a), but significant gains in many speed-strength qualities as measured from the force-time curve (Häkkinen, *et al.*, 1985b; Häkkinen and Komi, 1986a).

2.3.3 Mechanisms of velocity specificity

The mechanisms responsible for the velocity-specific response to training are still equivocal. Specific training adaptations could occur within the nervous system (neural adaptation) or the muscles. Most studies have examined specificity with tests of voluntary contractions done at different movement velocities; therefore, these studies have not been able to distinguish the relative roles of neural and muscle adaptations (Behm and Sale, 1993a).

One of the few studies to indicate muscular velocity specific adaptations was demonstrated on the basis of tetanic contractions electrically evoked at different shortening velocities and evoked isometric twitch contractile properties (Duchateau and Hainaut, 1984). In the study, two groups of subjects trained with either isometric or dynamic concentric training at one-third of maximal isometric strength over three months. Both training programmes produced increases in tetanic tension and peak rate of tension development. However the dynamic training provided increases in maximal shortening velocity, greater increases in twitch and tetanic rate of tension development, and smaller increases in peak torque. This would suggest that the contractile kinetics can be specifically altered depending on the nature of the training programme.

Other studies have shown, on the basis of EMG recordings, that velocity-specific neural adaptations could be involved. In one study, explosive jump training resulted in significant EMG increases at the onset of motor unit activation while heavy resistance training caused only a small increase in EMG later in the activation period (Häkkinen *et al.*, 1985b). Conversely Schmidtbleicher and Buehrle (1987) demonstrated greater neuronal adaptation following very heavy resistance exercise when compared to the power training group as indicated by the changes in the maximum rate of rise of electrical activity (RREA) and the period of time from the innervation onset until the maximum level of electrical activity was reached (RT) (Table 2.1). In essence the subjects had learned to activate the motor neuron pool in a shorter period of time.

One of the main arguments in favour of heavy resistance exercise versus training with relatively light loads performed at high speed has been based on a belief in selective activation of fast twitch (Type II) motor units. Gradations of force can be achieved by altering the activation of the contractile proteins that is by changing the stimulation frequency. More importantly for larger muscles such as the quadriceps, this can be achieved by altering the recruitment of motor units (Edwards, 1978). Several studies (Clamann and Henneman, 1976; Henneman *et al.*, 1974) have noted that during gradation of contraction a preferential sequence of motor unit recruitment occurs from the smaller motor neurons to the larger neurons. This is known as "the size principle" of motor unit recruitment. The recruitment sequence implies that to train the fast twitch motor units, which are dominantly responsible for dynamic performance, very high force contractions and hence heavy loads must be used in training as only heavy load training will guarantee the recruitment of all motor units (Schmidtbleicher, 1988).

Some evidence suggests however that very high velocity, also termed ballistic (Behm and Sale, 1993b) contractions may alter the recruitment sequence and allow high threshold motor neurons to begin contracting before or simultaneously with low threshold motor units (Desmedt and Godaux, 1977; ter Haar Romney *et al.*, 1982). Additionally, the manner in which the brain organises the initiation of fast versus slow contractions may be different (Desmedt and Godaux, 1979). A feature of the most brief and rapid ballistic movements is that they are pre-programmed; that is, once the central command is dispatched to the motor neurons, the ensuing motor unit discharge cannot be modified on the basis of a new command or proprioceptive feedback. Thus, it has been shown that when the intent is to make a ballistic movement, the motor unit discharge is the same whether the involved limb is unrestrained and free to move rapidly, in which case the associated muscle contraction is concentric (shortening), or whether the limb is restrained so that little or no movement occurs, in which case the agonist muscle contraction is isometric (Desmedt and Godaux, 1979).

Based on these findings, Behm and Sale (1993b) hypothesised that a rapid movement through the range of movement may not be necessary to produce a velocity-specific training response. The authors conducted a study whereby subjects trained both of their legs with attempted ballistic ankle dorsiflexion movements. In one leg the imposed resistance rendered the resultant muscle contractions isometric. In the other leg the imposed resistance allowed the leg to move and the involved muscles to shorten at a relatively high velocity of 5.23 rad s^{-1} (300 deg s^{-1}). To test for a high-velocity-specific training response, voluntary strength of ankle dorsiflexion was measured at several concentric contraction velocities. In addition, measurements of evoked muscles contractile properties were made to identify possible high-velocity-

specific contractile adaptations to the training. Subjects executed 5 sets of 10 repetitions, three times per week for 16 weeks. Subjects were instructed to attempt to make maximal ballistic dorsiflexion movements with both legs. Specific instructions were for the subjects to attempt to move as rapidly as possible regardless of the imposed resistance. Both the concentric and isometric contractions lasted approximately 0.5 s.

Training produced the same high-velocity-specific response in both limbs, although peak torque increased most (38%) at the training velocity (5.23 rad s^{-1}). Both limbs also showed similar increases in voluntary isometric rate of torque development (26%) and relaxation (47%) and in evoked tetanus rate of torque development (14%). Similar decreases in evoked twitch time to peak torque (6%) and half relaxation time (11%) were also observed. Thus, all of these training responses, previously associated specifically with high-velocity resistance training were produced by a training regimen that prevented an actual rapid movement through a range of movement. It therefore appears that the principle stimuli for the high-velocity-specific training response are the repeated attempts to perform ballistic contractions (i.e. the high frequency stimulation the muscle receives) and the high rate of force development of the ensuing contraction. The type of muscle action (concentric or isometric) appears to be of lesser importance.

These findings provide a suitable explanation for the large gains in speed-strength measures from heavy resistance exercise observed by Schmidtbleicher and Buehrle (1987). Both heavy and light load groups were specifically instructed to produce ballistic contractions in training. In other studies, involving heavy resistance exercise

that failed to produce impressive gains in speed-strength (e.g. Häkkinen *et al.*, 1985a), no instructions were given regarding the 'explosiveness' of training efforts.

2.3.4 Evaluation of training methods

Strong arguments can be made for either heavy or light resistance training methods for the development of speed-strength, and therefore strength and conditioning specialists will incorporate both forms of resistance exercise into the training macrocycle. Each form of training produces high forces and high rates of force development, consequently both require the generation of high frequency action potentials. However, heavy resistance exercise must result in slower movements, and therefore a longer duration of muscular tension. The near maximum loads compel the motor neurons to fire high frequency impulses for comparatively long times. Therefore, although intra-muscular coordination can be developed (i.e. increased recruitment, firing rate and synchronisation of motor units) with either heavy or light load methods, it has been suggested that heavy loads are superior (Schmidtbleicher and Buehrle, 1987). On the other hand development of inter-muscular co-ordination (activation of synergists and decreased co-contraction) may be optimised using relatively light loads that encourage an execution of the skill that is very similar to the competitive skill. The differences in motor unit activation between HRE and DSE may therefore have an effect on the fatigue and recovery characteristics.

2.4 Mechanisms of muscular fatigue in intense exercise

2.4.1 Neuromuscular characteristics of fatigue

Neuromuscular fatigue has been defined as a 'failure to maintain the required or expected force' (Edwards, 1981) or as 'a decreased force generating capacity' (Vøllestad and Sejersted, 1988). For dynamic exercise, fatigue may be defined as a decrease in the force or power generating capacity of the muscle (McKenna, 1992). Such failure becomes apparent quite quickly after the onset of very intense activity (Häkkinen, 1994a). Following the activity, a sustained weakness may persist not just for several hours after the training session but even several days, which will consequently have an effect on subsequent training or competitive performance (Green, 1997). If the recovery is insufficient, not only will strength and power gains diminish but movement patterns and technique are likely to be affected in other aspects of the athlete's training thus increasing the potential for injury.

Nevertheless, the development of fatigue following resistance exercise and the influence of recovery, are often discussed more on a hypothetical basis: e.g. supercompensation theory (Bompa, 1983; Zatsiorsky, 1995) and fitness-fatigue theory (Zatsiorsky, 1995), rather than on the results of empirical studies (Frick and Schmidtbleicher, 1999; Häkkinen, 1993; 1994a; Häkkinen, *et al.*, 1988; Linnamo *et al.*, 1998). Based on tradition, one day of recovery is generally recommended between training sessions for a particular muscle group (Atha, 1981; Fleck and Kraemer, 1997), whereas Frick and Schmidtbleicher (1999) state that further progressions of the efficiency of training should be based on a clear understanding of the recovery processes. Knowledge of the basic concepts related to the physiology of fatigue can

help the strength and conditioning specialist understand the biological basis of their training programmes (Bilcheck *et al.*, 1992).

It may be argued that each step in the chain of events for muscle contraction could be a site for fatigue. The control chain for the processes, which eventually lead to force generation are summarised in Figure 2.2 below. Consequently, the first requirement is often to establish whether this failure to sustain the expected or required force is due to a failure of neural drive (central fatigue or fatigue 'in the mind') rather than in the muscle (peripheral fatigue) (Edwards, 1978).

2.4.1.1 Central mechanisms of fatigue

Central fatigue is associated with extreme pain and perceived exhaustion, with the impairment located in the central nervous system (CNS). Force levels will decrease if the motor drive from the CNS declines below the level required for sufficient muscle activation, which may occur if the subject simply lacks motivation or is not prepared to tolerate the increasing sensation of discomfort (Bigland-Ritchie and Woods, 1984). Events that control this central activation failure and its progressive manifestation during repeated or sustained efforts are considered vital for optimal athletic performance (Gandevia, 1992).

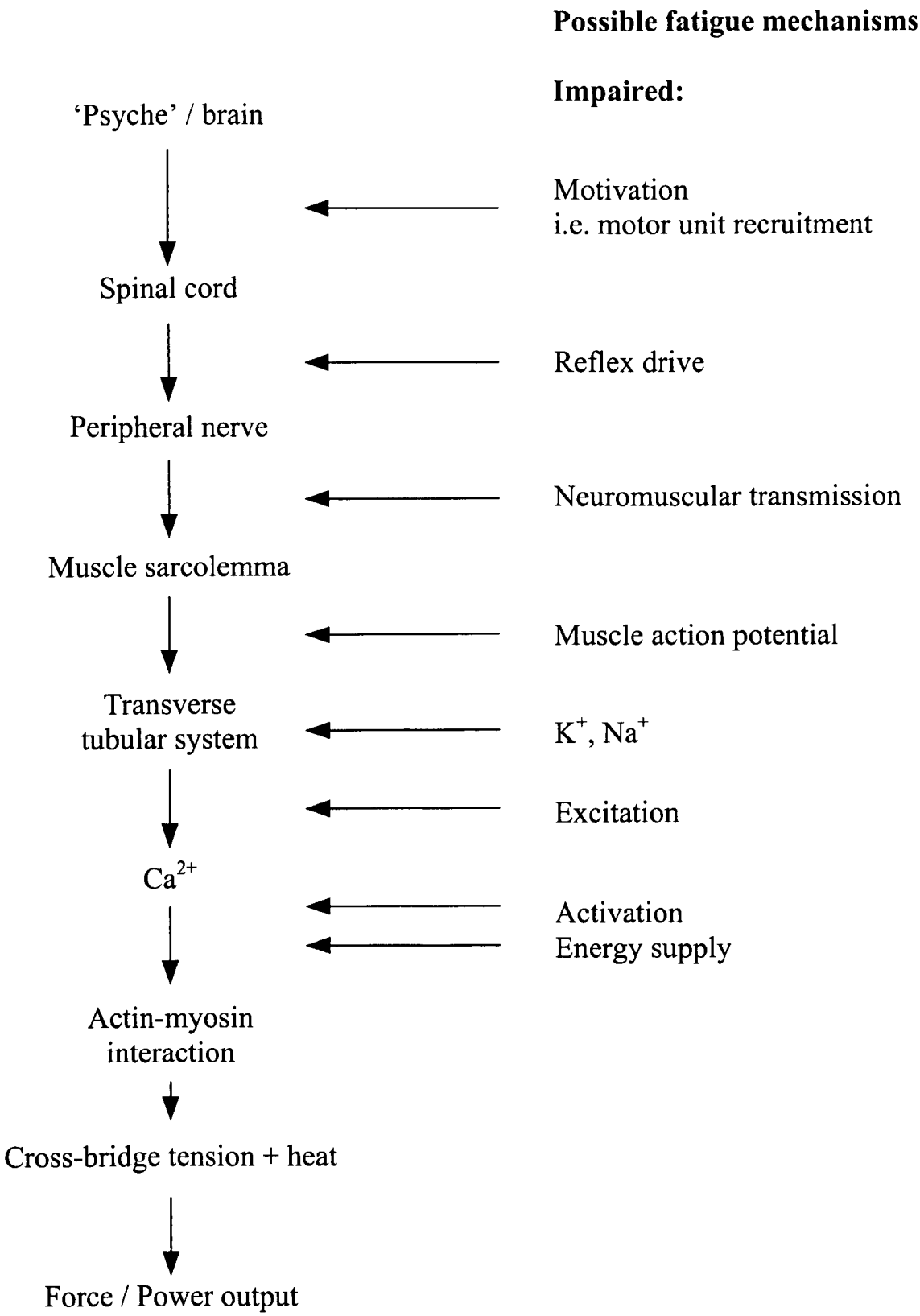


Figure 2.2 Current summary of command chain for human muscular contraction (after Edwards, 1983).

Central and peripheral fatigue can be differentiated experimentally by electrically induced muscle contraction. In well-motivated subjects it has been shown that maximum force produced by direct stimulation of the adductor pollicis and the quadriceps femoris muscle decreased in parallel with the maximum voluntary contraction force, indicating peripheral limitation of the contraction process (Bigland-Ritchie and Woods, 1984). In soleus muscle intra-muscular factors were also of major importance but part of the decline in force was attributed to a reduced motor drive and hence central fatigue (Bigland-Ritchie *et al.*, 1986b).

Changes in the degree of muscle activation by the central nervous system and hence the development of fatigue can also be assessed by superimposing electrically induced twitches during a maximal voluntary effort (twitch interpolation technique) (Merton, 1954) and by measuring the changes in various parameters of the electromyographic signal, recorded from the surface of a muscle (Bigland-Ritchie *et al.*, 1981; Hagberg, 1981). The technique of surface electromyography and the various methods of electrical stimulation will be discussed in more detail later in this thesis.

2.4.1.2 Peripheral mechanisms of fatigue

Peripheral fatigue is thought to be located at or beyond the motor nerve possibly even including the neuromuscular junction and the contractile apparatus of the muscle. This may result in disrupted actin-myosin cross-bridge coupling, impaired activation-excitation of motor units, or disrupted energy supply (Boobis, 1987; Sahlin, 1992; Sjödin, 1992).

The transformation of excitation into contraction is a series of chemical reactions converging on the final step, cross-bridge cycling. Successful muscle activation depends on the propagation of the action potential over the entire sarcolemma and down the t-tubules. Alterations in the transmembrane ionic gradients may impair muscle activation due to changes in electrolyte concentration. The signal is transferred from the t-tubules to the sarcoplasmic reticulum during the excitation-coupling process, resulting in the release of Ca^{2+}. Activation of the actin-myosin complex leading to contraction is ultimately caused by the elevation of intracellular Ca^{2+}. A decrease in Ca^{2+} availability for release from the sarcoplasmic reticulum will cause a gradual decline in force generating capacity. Various intracellular changes can also depress the sensitivity of troponin for Ca^{2+} and thereby affect performance in the same way as Ca^{2+} release. Factors that interact with the actin-myosin cross bridging will reduce the power output of each cross bridge turnover thus causing fatigue (Vøllerstad and Sejersted, 1988).

The energy required for muscular contraction is provided by the hydrolysis of adenosine triphosphate (ATP).

$$ATP + H_2O \longrightarrow ADP + Pi + H^+$$

Three different ATP splitting reactions are coupled to the actin-myosin contraction relaxation cycle via 3 ATPases; actomyosin ATPase for the formation and breaking of cross-bridges, Ca^{2+} ATPase for the Ca^{2+} transport across the membrane of the sarcoplasmic reticulum, and the Na^+, K^+ ATPase for electrolyte transport in the sarcolemma and the t-tubule system membrane restoring the membrane potential

(Hultman *et al.*, 1987). During high intensity exercise ATP is resynthesised by the creatine kinase system and the anaerobic breakdown of glycogen.

$$CrP + ADP + H^{+} \rightleftharpoons ATP + Cr$$

creatine kinase system

$$Glycogen + 3ADP + 3Pi \longrightarrow 3ATP + 2La^{-} + 2H^{+}$$

Phosphocreatine (CrP) is in near equilibrium with ATP via the creatine kinase reaction. The total intramuscular stores of ATP and CrP (the phosphagens) are extremely small and in theory could be exhausted in as little as two seconds (Shephard, 1992; Sjodin, 1992). Some characteristics of fatigue associated with high intensity exercise include muscle lactic acid accumulation and phosphocreatine depletion. Boobis (1987) showed by studies during dynamic exercise that the complete depletion of energy stores does not occur (Table 2.2). Complete substrate depletion of CrP does not always occur during dynamic exercise as the activity may not be performed under total anaerobic conditions and creatine is rephosphorylated via the CrP-Cr shuttle.

Table 2.2 Percentage of energy stores remaining after all out sprints on cycle ergometer (Boobis, 1987).

	% Remaining	
Duration of sprints (s)	6	30
ATP	91	56
CrP	65	34
Glycogen	83	70

Fatigue during sustained voluntary static contraction is also characterised by high muscle lactic acid accumulation and depleted CrP stores similar to those observed during intensive dynamic exercise (Sahlin, 1992). There is no immediate decrease in the ATP store during high intensity exercise as the rephosphorylation of ADP is accelerated to the same rate as ATP utilisation by the degradation of CrP and the breakdown of glycogen. Glycolysis is switched on within seconds of the start of exercise, which accounts for the accumulation of lactic acid (Boobis, 1987). Lamb (1984) stated that the relationship between depletion of energy stores and fatigue may be merely associative and not causative. Spriet (1987) observed that during extreme acidosis of electrically stimulated muscle, the metabolic production of ATP did not limit force production as phosphofructokinase (PFK), the regulatory enzyme of glycolysis, remained active despite a reduction in pH from 6.7 to 6.45. However, glycolytic activity decreased significantly at pH levels below 6.45.

Hultman *et al.* (1987) compliment the suggestion that fatigue is due to an impairment of the activation/excitation of the contractile system and the actin-myosin coupling. Their studies showed that fatigue is closely linked to the inhibitory influence of the

metabolites, ADP, H^+ and Pi on cross bridge cycling, produced during ATP-CrP splitting and glycolysis. The consumption of ATP during contraction is proportional to the activity of the cross-bridges and hence force production (Sjodin, 1992). Fatigue may therefore be due to the inhibition of ATP utilisation rather than ADP formation.

It is suggested that an increase in acidity can reduce force production at a number of sites in the excitation/contraction process thus reducing the demand for ATP. This could explain the fact that there is no complete depletion of energy stores (Spriet, 1987). It is believed that a reduction in muscle pH causes a decrease in the binding of calcium to troponin thereby reducing the activation of the actin-myosin cross bridges in muscle contraction. It is thought that a reduced affinity of Ca^{2+} for the binding sites on the troponin complex causes a decrease in the sensitivity of the Ca^{2+} ATPase. Increase of hydrogen ion concentration itself may inhibit actomyosin ATPase directly and lower cross-bridge tension (Metzger and Moss, 1990; Sahlin, 1986).

The transformation of phosphorylase from the inactive b to the active a form in glycogenolysis is mediated by phosphorylase kinase and a phosphatase respectively. During high intense activity immediate activation is mediated via an increase in cytoplasmic Ca^{2+} ions, which also initiates muscle contraction. During intense exercise there is a transformation of glycogen phosphorylase a to the inactive b form. This retransformation usually parallels a decrease in contraction force and could therefore be explained as an effect of the decreased calcium release from the sarcoplasmic reticulum due to the inhibitory effect of the increased hydrogen ion concentration.

A near maximal isometric contraction force and maximal power output during dynamic exercise however can be attained during acidic conditions (Spriet, 1987). The loss of force during exercise cannot be explained by a direct cause and effect of acidosis on the contraction process. Therefore the indirect effects through impairment of the energetic processes must also be considered (Sahlin, 1992). The accumulation of Pi and H^+ and a fall in the ATP / ADP ratio, due to a decreased glycolytic rate, is thought to decrease the free energy charge from further ATP hydrolysis to values that may be too low for maintenance of electrolyte concentrations across cells. This might explain high levels of potassium ions in the interstitial and extracellular fluids contributing towards fatigue.

Large K^+ fluxes across the muscle membrane may lead to impaired excitation of the sarcolemmal and t-tubular membranes thus causing fatigue (Sjøgaard *et al.*, 1985; Sjøgaard, 1990; 1991). The increase in the extracellular potassium concentration and a decline in the intracellular K^+ concentration cause a depolarisation of the cell membrane and can lead to the inactivation of fast sodium channels and hence to a decline in action potential amplitude (Hodgkin and Huxley, 1952; Hodgkin and Katz, 1949). It has also been suggested that prolonged membrane depolarisation results in a failure of Ca^{2+} release form the sarcoplasmic reticulum and a lack of activation of the myofibrillar ATPase (Hultman *et al.*, 1987), and consequently a reduction in muscular tension development (Ashley and Ridgway, 1970).

The stores of CrP are limited therefore some substrate depletion will occur. Levels of ADP increase during muscle contraction as the ATP turnover rate from CrP and glycolysis decreases. A small decline in ATP concentration can cause a major

relative increase in ADP. The adenylate kinase reaction increases to sustain a high ATP-ADP ratio ensuring maintenance of sufficient free energy liberation during ATP hydrolysis. ADP provides the substrate for the formation of AMP and ATP. The function of the AMP deaminase reaction is to adjust the equilibrium of the adenylate reaction and promote the continued formation of ATP from ADP. There is no resynthesis of AMP, and IMP is accumulated together with NH_4^+ resulting in reduced total adenine nucleotide and hence ATP concentrations. Ammonia is a potential neurotoxin and the accumulation is thought to impair the function of the CNS and hence peripheral fatigue (Sahlin, 1992) However ammonia and AMP can counteract the inhibiting effect of increased hydrogen ions on PFK. AMP and IMP can stimulate phosphorylase b to phosphorylase a in glycogenolysis. Inorganic phosphate stimulates glycolysis but as discussed may inhibit the actomyosin ATPase.

$$2ADP \longrightarrow AMP + ATP$$

adenylate kinase reaction

$$AMP + H^+ \longrightarrow IMP + NH_4^+$$

AMP deaminase reaction

The production of AMP can have an inhibitory effect (Davies, 1973). In the final steps of decomposition of AMP, as hypoxanthine is oxidized to uric acid in the presence of xanthine oxidase, free radicals are produced which may initiate membrane destruction of the sarcoplasmic reticulum. This leads to an impairment of the calcium pumps and a reduction in the release of Ca^{2+} from the sarcoplasmic reticulum, slowing down the contraction relaxation cycle in the myofibrils (Sjodin, 1992).

Fatigue is associated with a reduced capacity to generate ATP. Muscular fatigue is partially caused by a relative deficit of ATP and not its total absence. The decrease in the ATP turnover rate both by glycolysis and from CrP leads to a decrease in the force that the muscle is able to generate. The temporary increases in ADP may cause fatigue by impairing the contraction processes in configuration with the metabolites Pi and H^+ and hence the force generating capacity (Sahlin, 1992; Vøllerstad and Sejersted, 1988). Acidosis is unlikely to affect the contraction processes by a direct affect, but in combination with the impairment of the energetic processes. It was suggested that contraction fails due to the inhibition of activation/excitation processes and cross-bridge formation before energy stores drop to critical levels. ATP levels decrease significantly due to increased adenylate kinase and AMP deaminase activity but there appears to be some safety mechanism preventing the complete depletion of ATP.

2.4.2 Muscle damage and soreness

Intense activity can also result in non-metabolic fatigue and weakness as a consequence of a disruption in internal structures, mediated by the high force levels (Green, 1997). Muscle damage is caused by strenuous and unaccustomed exercise, especially exercise involving eccentric muscle contractions, where muscles lengthen as they develop tension (Appell *et al.*, 1992). The damaging nature of unaccustomed eccentric contractions is well documented (Fridén *et al.*, 1983; Newham *et al.*, 1987; Stauber, 1989), and possible mechanisms have been extensively reviewed (Armstrong, 1984; Armstrong *et al.*, 1991; Byrd, 1992; Clarkson and Sayers, 1999; Pyne, 1994), although still remain to be elucidated.

Focal myofibril disruption and subcellular Z disc streaming have been shown to typify the structural damage to skeletal muscle, visible following repetitive high force eccentric muscle contractions (Fridén *et al.*, 1983; Newham *et al.*, 1983). The initial disruption may predispose certain myofibres to progressive degeneration (Jones *et al.*, 1986), and may be further accompanied by efflux of intra-muscular proteins into the circulation and margination of monocytes and neutrophils (Round *et al.*, 1987; Smith, 1991).

Equally, muscles are often sore after an initial bout of resistance exercise, or after exercises with high force eccentric components. Muscle soreness was first theorised to be associated with muscle damage in 1902, but supporting evidence has only recently been provided (Fridén *et al.*, 1983; Hikida *et al.*, 1983). There are essentially two types of muscle soreness that develop in response to an exercise bout. The first type develops during the later stages of an exercise bout and the subsequent recovery period. This type of soreness has been referred to as immediate-onset muscle pain (Ebbeling and Clarkson, 1989) and can be recognised by a burning sensation in the localised muscles. It has been attributed to a depletion of energy substrates, the accumulation of metabolic waste products (e.g. lactic acid) and tissue oedema (shifting of fluid from the blood plasma in to the tissues) (Ebbeling and Clarkson, 1989; Smith, 1991).

The second type of muscle soreness becomes apparent between 24 and 48 hours after a strenuous exercise session and has even been reported to last up 168 hours (1 week) after stimulated eccentric exercise (Brown *et al.*, 1996). Hence it is referred to as delayed onset muscle soreness (DOMS), producing sore muscles often described as

being stiff or tender, especially to palpation and / or movement, and their ability to produce force is reduced (Byrnes *et al.*, 1985b; Fridén, *et al.*, 1983a; Newham *et al.*, 1983b). Therefore in addition to structural damage, it is widely accepted that the experience of severe DOMS can adversely affect various aspects of sports performance, which may present an athlete with a higher risk of injury (Smith, 1992).

Immediate-onset muscle pain and delayed onset muscle soreness (typically assessed using some of rating scale), and leakage of muscle enzymes into the circulation are characteristic of unaccustomed eccentric exercise, and have been used as indirect evidence of exercise-induced muscle injury. One of the most commonly studied of the muscle enzymes is creatine kinase (CK). Although the muscle enzyme activity from strenuous resistance exercise has been evaluated (Kleiner *et al.*, 1996; McBride *et al.*, 1995), the majority of studies have evaluated the CK response from high force eccentric (e.g. Brown *et al.*, 1996; 1997; Fridén, 1984; Fridén *et al.*, 1983; Newham *et al.*, 1987; Rodenburg *et al.*, 1993) or stretch-shorten cycle (SSC) type activities (e.g. Nosaka and Kuramata, 1991; Pullinen and Komi, 1995; Strojnik and Komi, 1998).

2.5 The role of fatigue as a stimulus for the development of muscle strength

The optimisation of strength training programmes is of interest both to the strength and conditioning specialists who prescribe exercise and to physiologists interested in the mechanisms by which training induces increases in strength. It is clear from the discussions above that high force muscle actions are required to increase strength (Schmidtbleicher, 1988; Schmidtbleicher and Buerhle, 1987), but beyond this there is considerable uncertainty (Folland *et al.*, 2002; Jones and Folland, 2001).

Traditionally training to failure to induce muscle fatigue has been seen as the primary stimulus, although the mechanisms by which fatiguing contractions could facilitate training induced increases in strength are unclear. One possibility which is consistent with the prevailing view that that short term training induced strength increases are brought about largely by neural mechanisms (Enoka, 1988; Sale, 1987; 1988; 1992) is that high intensity fatiguing protocols bring about greater activation of motor units than high intensity non-fatiguing protocols and that the degree of activation of motor units determines the magnitude of the training response. It is suggested that fatiguing high-intensity contractions provide a better way of activating high threshold motor units, as during a typical set of resistance training, as lower threshold motor units become fatigued and drop out, additional higher threshold motor units must be recruited if the activity is to be continued (Atha, 1981; Rooney *et al.*, 1994; Zatsiosky, 1995).

It is also important to consider that the high forces used in strength training will cause metabolic changes within the muscle. Although the majority of strength training

regimens utilise low numbers of repetitions, considerable metabolic flux occurs because the blood flow is occluded during the high-force contractions. Accumulation of metabolic by-products metabolites (e.g. H^+, lactate, P_i, Cr and K^+, together with smaller amounts of ADP, AMP, and ammonia) both inside and outside muscle fibres is associated with muscular fatigue, as well as pain and discomfort, and hence a reduction in force generation capacity (Jones and Folland, 2001). It has therefore been suggested that metabolite during high resistance work may be the primary stimulus for gains in strength (Carey-Smith and Rutherford, 1995; Schott *et al.*, 1995).

In contrast, two studies found high metabolite accumulation not to benefit strength gains. Robinson *et al.* (1995) found that a rest interval of 3 minutes between sets, which minimised metabolic disturbance, produced significantly greater increases in squatting than only 30 seconds of rest. More recently, Folland *et al.* (2002) investigated the role of fatigue and metabolite accumulation in strength gains by comparing highly fatiguing and non-fatiguing isotonic training protocols. The high fatigue protocol consisted of 10 repetitions with 30 seconds rest between sets to maximise metabolic stress whereas the low fatigue protocol consisted of 40 repetitions with 30 seconds rest between each repetition to minimise changes. The training load for both training protocols was specified as 75% of 1RM. After 9 weeks of training all the strength measurements (1RM, isometric and isokinetic) showed similar improvements for both groups. Folland *et al.* (2002) therefore concluded that fatigue and metabolite accumulation do not appear to be critical stimuli for strength gains. Interestingly however, at the midpoint of the 9 weeks training programme, the high fatigue protocol group did have 50% greater gains in isometric strength, although

this was not significant. These greater gains in strength in the short-term may be explained in part by the neural mechanisms described above.

Another possible stimulus for training-induced gains in strength is the acute muscle damage that occurs as a result of unaccustomed exercise, particularly involving eccentric muscle actions. However Folland *et al.* (2001) demonstrated that a single bout of damaging eccentric work did not enhance the response to conventional strength training and significantly compromised strength gains for several weeks.

In summary there is some evidence to suggest that greater short-term increases in strength are achieved when subjects are required to lift to failure, provided that heavy loads are used. These findings suggest that processes associated with fatigue contribute to the strength-training stimulus. In addition to examining the effects of a six-weeks heavy resistance and dynamic strength training programme on the acute neuromuscular and metabolic responses to a single heavy resistance and dynamic strength exercise session, the third study of this thesis will also compare the changes in strength and rate of force development in response to the two distinct loading conditions. In the heavy resistance exercise group, subjects will train to failure whereby in the dynamic strength exercise group, subjects will perform explosive jumps with relatively light loads.

2.6 Assessment of neuromuscular fatigue

2.6.1 The use of isometric tests of muscular function

Isometric assessment of muscular function is a widely employed testing modality which has been used to assess the force-producing capacity of the neuromuscular system, with respect to muscle fibre type (Bemben *et al.*, 1991; Mero *et al.* 1981; Viitasalo *et al.*, 1981), age (Bemben *et al.*, 1991; 1992; Going *et al.*, 1987), gender (Ryushi *et al.*, 1988) and fatigue (Brown *et al.*, 1996; 1997; Häkkinen, 1993; 1994b; Häkkinen *et al.* 1988; Linnamo *et al.*, 1988; Strojnik and Komi, 1998).

Isometric tests involve participants producing a maximal force or torque performed at a specified joint angle against an immovable resistance which is in series with a strain gauge, or a cable tensiometer, or a force platform or similar device whose transducer measures the applied force. Isometric assessments are generally performed to quantify various force-time characteristics such as the maximum voluntary isometric force (MVC) and the maximum isometric rate of force development (RFD_{max}), as illustrated in Figure 2.1.

The maximum rate of force development is typically quantified as the greatest slope of the force-time curve. The time period which the rate of change in force is determined has varied from an interval of 5 ms (Wilson *et al.*, 1993) through to 60 ms (Christ *et al.*, 1994) with most researchers tending to use a value towards the lower end of this range as this produces significantly higher values for RFD (Wilson and Murphy, 1996). The ability of the muscles to rapidly develop force, has also been quantified by the force produced at 30 ms after initiation (starting strength), and the

impulse generated over the first 100 ms of the force-time curve produced during an isometric test (Baker *et al.*, 1994; Wilson et *al.*, 1995; Young, 1995a).

It is evident that a number of performance variables can be obtained from an isometric force-time curve. Subsequent methodological considerations designed to enhance the reliability and validity of these variables, including the standardisation of testing procedures will be discussed later in this review of the literature.

2.6.2 Surface electromyography

Commonly recorded simultaneously in conjunction with the isometric assessment of muscular function, surface electromyography (EMG) is a well-established technique, which has been used widely as a non-invasive tool to detect muscle fatigue (Arendt-Nielson and Mills, 1988; Grabiner *et al.*, 1991; Lindstrom *et al.*, 1977). The most frequently used parameters to evaluate fatigue are the median frequency of the power spectrum and the root mean square (RMS) of the raw signal (Basmajian and De Luca, 1985). More recently electrical mechanical delay has received increased attention in the assessment of neuromuscular performance (Jöllenbeck, 1999; Zhou *et al.*, 1996; Zhou *et al.*, 1995a; 1995b).

2.6.2.1 Amplitude of the signal

The root mean square (RMS) is the square root of the average power (voltage squared) of the signal in a given time. The RMS is regarded as the preferred temporal descriptor of the EMG signal (De Luca and Knaflitz, 1990) as it is considered to provide a measure of the number of recruited motor units during voluntary

contractions (Basmajian and De Luca, 1985). The RMS value can be obtained from the following equation:

$$RMS[m(t)] = \sqrt{\frac{1}{T}\int_{t}^{t+T} m^{2}(t)dt}$$

(Basmajian and DeLuca, 1985)

The amplitude of the EMG signal changes with fatigue. Increases in RMS have been shown during fatigue protocols (e.g. Arendt-Nielson and Mills, 1988; Vaz *et al.*, 1996) where a sub-maximal force (<70% of maximum) has been maintained without a loss of force. This increase has been associated with changes in shape of the motor unit action potentials (Stulen and De Luca, 1978), and with an increased recruitment and firing rates of the motor units (Edwards and Lippold, 1956, Maton, 1981; Moritani *et al.*, 1986; Viitasalo and Komi, 1977). When the force can no longer be sustained, the RMS starts to decrease. The decrease in RMS has been associated with a loss in the ability to activate motor units, and a possible decrease in the average motor unit firing rate with increasing fatigue when a force cannot be maintained (Vaz *et al.*, 1996).

During repeated maximal contractions, EMG amplitude (integrated EMG) has also been shown to significantly decrease in some investigations (e.g. Komi and Rusko, 1974; Komi and Tesch, 1979), but not in others (e.g. Nilsson *et al.*, 1977). Conflicting results can be partially explained not only by differences in fibre type with fast twitch fibres showing greater reductions in amplitude (e.g. Komi and Tesch, 1979), but also by the possibility of migration of electrical activity from one muscle to another. This

migration has been demonstrated in finger muscles by Lippold (1955), and possibly also in leg extensor muscles by Komi and Viitasalo (1976).

2.6.2.2 Frequency analysis

The study of the EMG signal in the frequency domain has received much attention because of the loss of the high frequency content of the signal with increasing muscular fatigue (Bigland-Ritchie *et al.*, 1981; Hagberg, 1981; Komi and Tesch, 1979; Lindström *et al.*, 1977; Petrofsky *et al.*, 1982). During fatiguing contractions, the frequency content of the EMG shows a clear shift towards lower frequencies (Arendt-Nielsen and Mills, 1985; Cobb and Forbes, 1923; Mills, 1982; Petrofsky and Lind, 1980a; Sadoyama and Miyanono, 1981). This can be detected as a decrease in the median frequency (MDF) (Vaz *et al.*, 1996). The power density spectrum of the EMG signal can be obtained readily by using the Fast Fourier Transformation technique (Herzog *et al.*, 1994).

The median frequency is then defined as the frequency that divides the power of the EMG spectrum into two parts of equal power (i.e. the areas under the power spectrum to the two sides of the median frequency are equal) (Acierno *et al.*, 1995; De Luca and Knaflitz, 1990), and is given by:

$$\int_0^{f_m} \delta(f)df = \int_{f_m}^{\infty} \delta(f)df$$

(Acierno *et al.*, 1995)

The median frequency is also less sensitive to noise, less sensitive to signal aliasing, and in most cases more sensitive to the biochemical and physiological processes that

occur within the muscles during sustained contractions when compared to other characteristic indicators of the frequency spectrum such as the mean power or mode frequency (De Luca, 1997; De Luca and Knaflitz, 1990). The shift in median frequency is caused by an increase in the duration of the motor unit action potential. This results either from a lowering of the conduction velocity of all the action potentials (Arendt-Nielsen and Mills, 1985; 1988; Komi and Tesch, 1979; Lindstrom *et al.*, 1970; 1977; Merletti *et al.*, 1990) or through faster, higher frequency motor units switching off while slower, lower frequency ones remain active (Bartlett, 1997).

2.6.2.3 Electromechanical delay

Electromechanical delay (EMD) refers to the time lag between the onset of electrical activity (EMG) and tension development in skeletal muscle. This latency has been reported to include the time courses of action potential propagation along the sarcolemma and transverse t-tubules, the release of calcium ions (Ca^{2+}) from the sarcoplasmic reticulum (SR) and subsequent cytosolic Ca^{2+} accumulation, the formation of cross-bridges between actin and myosin filaments and the subsequent tension development, and the stretching of the series elastic components (Cavanagh and Komi, 1979).

Several authors (Nilsson *et al.*, 1977; Viitasalo and Komi, 1981; Zhou *et al.*, 1995a; 1995b) have found EMD to be negatively correlated to the maximum voluntary contraction (MVC) force, rate of force development (RFD) and muscle fibre composition. Based on these findings, a change in EMD might be expected when there are substantial changes in the functional and structural properties of the muscle

induced by either acute exercise or as the result of physical training (Zhou *et al.*, 1996).

For example, Nilsson *et al.* (1977) have reported an increase in EMD from 95 ms in a non-fatigued vastus lateralis muscle (VL) to 121 ms after 100 maximal isokinetic knee extensions in which the peak torque, work and power all decreased by approximately 50%. Similarly Zhou *et al.* (1996) observed a lengthening of EMD of the knee extensors from 40.4 ms at rest to 63.4 ms after 4 periods of 30 seconds all-out sprint cycling exercise. In contrast, Vos *et al.* (1991) have found no significant change in EMD of the quadriceps femoris muscle following 150 isometric knee extensions although these were only at 50% of the maximal force level. At present no studies have examined changes in EMD following heavy resistance or dynamic strength exercise.

2.6.3 Use of neuromuscular electrical stimulation: the identification of three forms of peripheral fatigue

The force generation of human skeletal muscle during electrical stimulation at increasing stimulation frequencies can provide beneficial information concerning the contractile properties of the stimulated muscle (Edwards *et al.*, 1977a). Such information can be obtained via supra-maximal stimulation of the nerve innervating certain human skeletal muscles, although a safer method for larger muscle groups such as the quadriceps involves the transcutaneous application of neuromuscular electrical stimulation (NMES).

It is worth considering which sites in the excitation-contraction coupling sequence are affected in muscle fatigue and how. As described above, many different mechanisms are involved in the development of fatigue, and their contributions vary according to the type of muscle activity (Westerblad *et al.*, 1991). The mechanisms of peripheral fatigue can be divided into at least categories based on the type of stimulation and the time course of recovery (Lamb, 1999).

2.6.3.1 High -frequency fatigue with rapid recovery

If a muscle is stimulated continuously at a very high frequency, there is rapid decline in force production, and upon cessation of stimulation there is a rapid recovery occurring in a matter of seconds (Lamb, 1999). It seems that this type of muscle fatigue is caused by a progressive depolarisation of the t-tubular system, owing to an increase in K^+ and a decrease in the Na^+ in the t-tubular system lumen due to the repeated action potentials. It is presumed that this depolarisation results in progressively more of the voltage dependent Na^+ remaining in an inactivated state, thus preventing action potential propagation down the t-tubular system (Cairns and Dulhunty, 1995; Jones *et al.*, 1979).

2.6.3.2 Low-frequency fatigue or long-lasting fatigue

This form of fatigue, first described in humans by Edwards *et al.* (1977a) can be observed after virtually any form of intense exercise (Westerblad *et al.*, 1993). It is often called low-frequency fatigue as it is characterised by a substantial reduction in tension at low frequencies of stimulation, whereas at high frequencies the tension is close to normal. However, it is perhaps more appropriately called "long lasting fatigue" (Allen *et al.*, 1995) as it can sometimes take >1day for full recovery and may

make a considerable contribution to the feeling of weakness in muscle groups after intense exercise (Westerblad *et al.*, 1993). The exact cause of this type of fatigue has not been established (Lamb, 1999), but the very prolonged period of recovery suggests that it is not related to cellular energy supplies or metabolic products, that should return to normal resting levels in a matter of hours. In their original study Edwards *et al.* (1977a) used muscle biopsies to indeed show that the major metabolites (ATP and CrP) had returned to normal after 60 min, a time at which low-frequency fatigue was established.

It has been suggested that chronic low-frequency fatigue following unaccustomed eccentric exercise (Jones, 1981), indicates structural damage to the t-tubular network or sarcoplasmic reticulum (SR). However Fridén (1984) has suggested that SR disruption following high force eccentric exercise is unlikely, since such damage would manifest itself in contraction clots visible in muscle biopsy specimens. Westerblad *et al.* (1993) have argued that low frequency fatigue is most likely to be caused by a reduced Ca^{2+} release from the SR or structural damage to one of the proteins involved in excitation-contraction coupling, although the same authors have expressed concern in extrapolating these mechanisms to human systems.

2.6.3.3 Repeated, intermittent stimulation causing metabolic changes

The third form of fatigue and probably recognised as the most common, is a consequence of metabolic changes within the fibres. If a muscle fibre is subjected to repeated intermittent stimulation, force declines in several distinct phases, with the timing dependent on fibre type and fully recovers again after a time course of tens of minutes. With repeated stimulation there is a progressive breakdown of creatine

phosphate (CrP) with the fibre and accompanying accumulation of inorganic phosphate (P_i), H^+ and lactate, and if stimulation is prolonged and long enough there is a reduction in the amount of ATP and increase in ADP, AMP and IMP (Lamb, 1999). The initial decline in force when normal Ca^{2+} is maintained is probably due to effects of P_i and H^+ on the contractile apparatus (Allen *et al.*, 1995). However during the final and rapid phase of force decline when there is a reduction in the amount of Ca^{2+}, recent studies on mammalian muscle have shown very little direct effect of acidosis on muscle function. Therefore the major cause of muscle fatigue appears to be caused by the rise in intra-cellular P_i, which can enter the lumen of the sarcoplasmmic reticulum and precipitate with the Ca^{2+}, and hence reduce the amount available for release (Allen and Westerblad, 2001; Favero, 1999; Lamb, 1999 Westerblad *et al.*, 2002).

2.6.3.4 Summary

Numerous studies have used electrical stimulation techniques to examine fatigue in skeletal muscle resulting from sustained isometric contractions (e.g. Bigland-Ritchie *et al.*, 1978; Byström and Kilblom, 1991; Cooper *et al.*, 1988; Edwards *et al.*, 1972; Jones *et al.*, 1979; Stephens and Taylor, 1972). On the other hand, few studies have examined the effect of dynamic resistance exercise on electrically stimulated muscle force production in humans (Strojnik and Komi, 1998; Skurvydas, 1998). Consequently this paucity of literature provides a further spur for a more detailed study of the central and peripheral components of fatigue in response to strenuous resistance exercise.

2.7 Neuromuscular fatigue and recovery during resistance exercise

2.7.1 Factors affecting fatigue and recovery characteristics

The types of strenuous resistance exercise protocols utilised by athletes for their training purposes lead to acute decrease not only in maximal peak force but also to considerable shifts in the force-time curve of the exercised muscles indicating a decrease in the explosive force production capability of the neuromuscular system (Häkkinen and Komi, 1986b; Häkkinen *et al.*, 1988). The magnitude of the acute fatigue-induced decrease in the neuromuscular performance is related to the overall volume and to the loading intensity of the session (Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), as well as to the specific type of the fatiguing load (e.g. heavy resistance exercise, explosive strength exercise, plyometric training) (Linnamo *et al.*, 1998; Strojnik and Komi, 1998).

2.7.1.1 Effect of type of resistance exercise

The fatigue and recovery characteristics following two distinct types of resistance training has recently been examined by Frick and Schmidtbleicher (1999). The two methods of strength training were directed to (i) intra-muscular co-ordination (recruitment, firing rate and synchronisation of motor units) for enhanced speed-strength characteristics, and (ii) muscle hypertrophy. The intra-muscular training regimen consisted of 5 sets of 3 repetitions at a load of 90% 1RM with 5 minutes rest interval between sets and 15 seconds rest interval between repetitions, whereas the hypertrophy training regimen consisted of 5 sets of 8 repetitions at a load of 80% of the individual one-repetition maximum (1RM) with 3 minutes rest interval between sets and none between reps.

Muscular performance (maximum movement velocity [MMV] under minimum and high load conditions [60% 1RM]) was tested before, immediately, 1 hour, 3, 34, 48, 72 and 168 hours (1 week) after the respective training session. Training and performance testing movements were bench press (upper body) and leg press (lower body). Recommendations for succession of training of the same muscle group were based on the measure of MMV 60% 1RM for the next strength training session and MMV minimum load for the next speed or technique training session and are presented in Table 2.3. Frick and Schmidtbleicher (1999) concluded that athletes normally continue with their training earlier than these recommendations and although gains in performance can be achieved, it is likely that they are training under sub-optimal conditions due to inadequate recovery.

TABLE 2.3 Recommendations for the succession of training following two distinct types of resistance exercise (adapted from Frick and Schmidtbleicher, 1999).

	Strength Session	Speed / Technique
Upper body		
Intra-muscular	48 hrs	72 hrs* optimal
Hypertrophy	48 hrs	72 hrs minimum
Lower body		
Intra-muscular	72 hrs	48 hrs** optimal
Hypertrophy	72 hrs	72 hrs minimum

* Speed or technique training for the upper body is possible after 24 hours as MMV (with minimum load) scores were above pre-training values. However these scores increased to a maximum at 72 hours.

** Speed or technique training is possible for the legs after 24 hours but 48hrs is optimal.

In addition to the differences in magnitude of the decreases in neuromuscular performance, the various mechanisms leading to muscle fatigue and recovery may also be related in part to the type of fatiguing load (Häkkinen and Komi, 1986b). For example, neuromuscular fatigue and recovery in the period up to 48 hours post exercise has been investigated following maximum strength loading (MSL) and explosive strength loading (ESL) (Linnamo *et al.*, 1998). MSL consisted of 5 sets of 10 RM bilateral leg extensions, and in ESL, the load was 40% from that used in MSL although the subjects were instructed to extend their legs during the loading contractions as explosively as possible. It should be noted that the subjects were not instructed to accelerate through the movement and take-off from the floor as described for dynamic strength exercise. A decrease in force production of the loaded muscles was observed after MSL and ESL, although this was greater and the recovery was slower after MSL than after ESL. There was a lower integrated EMG (iEMG) in ESL than MSL during the early phase of the force-time curve (0-100 ms). The authors attributed this difference to the specific motor unit recruitment patterns which may occur during explosive training. Linnamo and co-workers also suggested that fatigue after heavy resistance loading is of both central and peripheral origin, supporting the findings by Häkkinen (1993; 1994a), whereas fatigue after explosive loading seems to be primarily central.

A more detailed examination of the possible sites of fatigue during short lasting maximally intensive stretch-shorten cycle (SSC) type exercise has been examined by Strojnik and Komi (1998). The measurements of maximal voluntary contraction force and neural activation, and also the force evoked during high- and low frequency stimulation were recorded immediately post exercise, although not during recovery,

e.g. 24 and 48 hours post exercise. The authors concluded that the impairment of action potential propagation may be the dominant reason for the fatigue in exercise of this type. However as discussed above, the depression in force is more likely to be explained by metabolic changes within the fibre.

2.7.1.2 Effect of athletic background

Athletes who have undergone specific training for several years may also pose an additional interest in the study of neuromuscular fatigue. It has been found that elite strength and speed-strength (power) athletes are more susceptible to fatigue and have a lower potential to recover from resistance exercise compared with endurance trained athletes (e.g. Häkkinen and Myllyla, 1990; Komi and Tesch, 1979; Kroll *et al.*, 1980; Thorstensson and Karlsson, 1976). Such differences in fatigue and recovery characteristics have been largely attributed to muscle fibre composition (Komi and Tesch, 1979; Thorstensson and Karlsson, 1976) although Kroll *et al.* (1980) showed that both maximum isometric strength and muscle mass may be even more important.

2.7.1.3 Effect of training

The specific adaptations to different resistance exercise protocols for the improvement of neuromuscular performance have been well documented (e.g Kaneko *et al.*, 1983; Häkkinen and Komi, 1985a; 1985b; Häkkinen *et al.*, 1985a; 1985b; Newton *et al.*, 1996; Toji *et al.*, 1997; Weiss *et al.*, 1999). However, the advantages of performing strength training for fatigue resistance are not as readily apparent. Further, it has been stated that the mechanisms regulating strength adaptations may not always correspond to adaptations with fatigue (Behm and St-Pierre, 1998).

Unlike cardiovascular endurance training adaptations, strength training can lead to a relative decrease in the oxidative potential of the muscle (MacDougall *et al.*, 1980), potentially diminishing resistance to fatigue (Burke, 1975). It has been discussed that the aim of players in engaged in teams sports is to enhance speed-strength characteristics. Hence modes of resistance exercise are chosen to selectively activate the fast twitch muscle fibres, characterised by high myosin ATPase activity, high glycolytic, but low oxidative capacity (Close, 1972). However absolute submaximal loads have been shown to be better maintained with a strength trained muscle (Pierce *et al.*, 1993) since the load represents a smaller percentage of the original load. Consequently fewer motor units need to be recruited providing a greater neural reserve (Pierce *et al.*, 1993; Green, 1997).

There is even evidence to suggest that the changes in the intra-cellular environment which are associated with fatigue can be minimised with high intensity training. For example the sarcolemma Na^+ -K^+ ATPase has been shown to be quickly up-regulated with sprint activity (McKenna *et al.*, 1993) and there is evidence that these adaptations result in an improvement in Na^+ and K^+ homeostasis (McKenna, 1995). If an improved ability to re-establish Na^+ and K^+ gradients occurs, the sarcolemma should allow for a more rapid re-establishment of the resting membrane potential an improved ability to conduct action potentials at a high frequency (Clausen and Nielson, 1994).

Preparing the muscle and muscle cells for the trauma invoked by repeated, high force generation would also appear to be an area where improvement is possible. Following a programme of acute concentric or eccentric contractions, an adaptation has been

demonstrated which after the repair period, the muscle appears to be able to tolerate the same exercise task, not only with less damage, but with a faster recovery (Byrnes *et al.*, 1985b; Clarkson and Tremblay, 1988). Speculation on the mechanisms for such an adaptation have included the damage and removal of a pool of susceptible or vulnerable fibres (Armstrong *et al.*, 1983) increased ability to repair initial damage (Clarkson and Tremblay, 1988) and increased muscle connective tissue content (Lapier *et al.*, 1995).

2.8 Measurement issues: methods and reliability

2.8.1 Definition of terms

Numerous studies have examined the effects of different modalities of strength training on variables such as maximum voluntary isometric force (MVC), maximum isometric rate of force development (RFD_{max}) and electromyographic characteristics (e.g. Häkkinen and Komi, 1983; 1985a; 1985b; Häkkinen *et al.*, 1985a; 1985b). Any investigation into the effects of training on neuromuscular fatigue requires the measurement of several variables simultaneously (e.g. Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988; Linnamo *et al.*, 1998; Strojnik and Komi, 1998). A fundamental concern is the reliability and validity of the particular measurement tools used to detect changes in these variables, where validity is, generally, the ability of the measurement tool to reflect what it is designed to measure (Atkinson and Nevill, 1998).

Reliability can be defined either as the consistency of measurements, or 'the absence of measurement error' (Safrit and Wood, 1989). Atkinson and Nevill (1998) state that 'realistically, some amount of error is always present with continuous measurements.' Therefore, reliability should be considered as the amount of measurement error that has been deemed acceptable for the practical use of a measurement tool. Logically it is reliability that should be first tested in a new measurement tool, since it will never be valid if it is not adequately consistent in whatever value it indicates from repeated measurements. Terms that have been used interchangeably with 'reliability' in the literature, are 'repeatability', 'reproducibility', 'consistency', 'concordance' and 'stability'.

The type of reliability associated with repeated measurements has been termed absolute reliability (Baumgarter, 1989) and is expressed either in the actual units of measurement or as a proportion of the measured values. Baumgarter further divided reliability in terms of the source of measurement error, namely: (i) internal consistency reliability, the variability between repeated trials within a day, and (ii) stability reliability, the day-to-day variability in measurements.

Irrespective of the type of reliability that is assessed, there are two components of variability associated with each assessment of measurement error. These are systematic bias and random error (Atkinson and Nevill, 1998). Systematic bias refers to a general trend for measurements to be different in a particular direction, either positive or negative between repeated tests. For example, there might be a trend for a retest to be higher than a prior test due to a learning effect being present (e.g. Coldwells *et al.*, 1994), or bias may be due to there being insufficient recovery between tests. It may be after a large number of repeated tests, systematic bias due to fatigue or transient decreases in motivation becomes apparent. In addition, Atkinson and Reilly (1996) expressed caution in the interpretation of internal consistency reliability, as the results might be influenced by systematic bias due to circadian variation. The other component of variability between repeated tests is the degree of random error. Large amounts of random differences can arise due to inconsistencies in the measurement protocol, for example not controlling posture in a consistent way during measurements of strength (e.g. Clarke, 1948; Coldwells *et al.*, 1994). The reliability and validity of isometric tests of muscular function in the assessment of neuromuscular performance will be discussed in detail below.

2.8.2 Statistical methods for assessing reliability

Many statistical tests have been proposed in the literature for the appraisal of measurement issues and have been reviewed in detail by Atkinson and Nevill (1998). The most common methods involve the use of hypothesis tests (paired t-tests, ANOVA), correlation coefficients (e.g. Pearson's product-moment, intra-class correlation), or coefficient of variation.

A paired t-test would be used to compare the means of a test and re-test, i.e. it tests whether there is any significant bias between the tests, although Altman (1991) stressed caution in the interpretation of using paired t-tests to assess reliability, since the detection of a significant difference is actually dependent on the amount of random variation between tests. ANOVA with repeated measures, preferably with a correction for 'sphericity' (Vincent, 1999) has been used for comparing more than one re-test with a test (Thomas and Nelson, 1990; Vincent, 1999). With appropriate *post hoc* multiple comparisons (e.g. Tukey tests), it can be used to assess systematic bias between tests (Atkinson and Nevill, 1998). The sole use of ANOVA is associated with exactly the same drawback as the paired t-test in that the detection of systematic bias is affected by large random variation. Consequently, the mean squared error term from ANOVA can be used in the calculation of indicators of absolute reliability (Bland, 1995; Nevill and Atkinson, 1998).

Although widely employed as a method of assessing reliability, the use of some form of correlation coefficient, e.g. Pearson's product-moment or intra-class correlation has been criticised by the fact they are sensitive to population heterogeneity and therefore are not true indicators of absolute reliability. On the other hand, a common method for

analysing absolute reliability is the coefficient of variation (CV). For data from repeated measurements on a single case, the CV has simply been calculated by dividing the SD of the data by the mean and multiplying by 100 (Sale, 1991). An extension of this on a sample of individuals is to calculate the mean CV from individual CVs.

It should however be noted that there are also limitations in the use of CV. Firstly the use of CV assumes that the between test variation increases as absolute values increase (Bland, 1995). In other words, with measurements of strength, it assumes that test-retest variability is greatest with the strongest subjects (Atkinson, 1995). The data are then said to be heteroscedastic. It is therefore recommended (Atkinson and Nevill, 1998), that heteroscedasticity is actually explored and quantified before assuming it is present.

Another cautionary note on the use of CV centres around the choice of cut-off for indicating adequate reliability. Some researchers have chosen quite arbitrarily an analytical goal of the CV being 10% or below (Stokes, 1985). This does not mean however that all variability between tests is always less than 10% of the mean. A CV of 10% obtained on an individual actually means that, assuming that the data are normally distributed, 68% of the differences between tests lie within 10% of the mean of the data (Strike, 1991), and hence the variability is not described for 32% of the individuals. It has been suggested that it will be more informative if the SD of the repeated tests is multiplied by 1.96 before being expressed as a CV for each individual (Bishop, 1997), as this would cover 95% of the repeated measurements. However Atkinson and Nevill (1998) stressed that if a sample mean CV is then

calculated, this still may not reflect the repeated test error for all individuals, but only the 'average individual', i.e. 50% of the individuals in the sample.

In light of the limitations described above, Altman and Bland (1983) introduced the method of 'limits of agreement' as an indicator of absolute reliability, although it is only recently that the limits of agreement method has been applied to multiple retests using an ANOVA approach (Bland, 1995). By fitting the subject and trial main effects, the ANOVA identifies any significant trial bias and at the same time estimates the within-subject measurement error, s_w^2. The standard deviation or expected difference between two trial measurements can then be estimated as follows, SD = 2 x s_w^2. Provided the residual errors are normally distributed and are not related to the size or level of the measurements, the random error component of the 95% 'limits of agreement' is given as $\pm$ 1.96 x SD. Heteroscedasticity in the data (whether the differences depend on the magnitude of the mean) can be examined formally by plotting or correlating the absolute residual errors against the predicted or fitted measurements (Nevill and Atkinson, 1998).

2.8.3 Methodological considerations in isometric assessment

2.8.3.1 Reliability

Depending on the variables measured, isometric tests of muscular function have been declared to have high test-retest reliability, although the vast majority of this research has examined the reliability of isometric testing via Pearson's product-moment or intra-class correlation analysis (e.g. Bemben *et al.*, 1990; 1992; Christ *et al.*, 1994; Clarke, 1948; Going *et al.*, 1987; Pryor *et al.*, 1994; Sleivert and Wenger, 1992;

Strass, 1991; Wilson *et al.*, 1993). It is important to remember that such analyses have limitations in determining reliability (Atkinson and Nevill, 1998).

On the other hand, very few studies (e.g. Viitasalo *et al.*, 1980) have reported coefficients of variation as the measure of reliability. Viitasalo *et al.* (1980) although not measuring day to day variation, have developed a procedure which produces relatively low coefficients of variability for maximum voluntary isometric force and rate of force development of the leg extensor muscles within one session. Within-session reliability was determined for the variables between the mean of the first and third, and that of the second and fourth contraction of the same test. The coefficient of variation for maximal force (MVC) was 4.1%, although the variability for rate of force development was 17.8%. It is important to note however that there was no test for heteroscedasticity and the CV values were not calculated from the mean square error term derived from a repeated measures ANOVA.

Setting the appropriate choice of statistical test aside, in terms of the reliability of isometric tests, one factor that needs to be considered is the discomfort associated with the rapid development of isometric force. For example, Pryor *et al.* (1994) reported that the magnitude of RFD in isometric bench press tests was significantly lower than recorded in a concentric bench press test. The authors suggested that the deficit in rate of force development may have been due to an 'inhibitory' effect during the isometric test, as rapid development of muscular force in an isometric activity can be uncomfortable, and as such subjects may not apply a maximum effort as instructed. Similar concerns were expressed by Sleivert and Wenger (1992) who reported poor test reliability for isometric RFD, in both single joint knee extension and multi-joint

leg press positions. The authors rationalised the poor results stating that various neural inhibitory mechanisms may be responsible for the low reliability.

Multi-joint isometric tests such as the bench press, squat and leg press are often used in an effort to modify the testing modality to be more specific to movements prevalent in gross motor task. Wilson *et al.* (1993) however, reported that a participant was injured while performing an isometric squat test. Consequently, some isometric testing positions may be uncomfortable and potentially injurious which may compromise the reliability and validity of the test. This is probably more of a concern in multi-joint actions, such as the squat, compared with isolated single joint movements, such as the knee extension (Wilson and Murphy, 1996).

2.8.3.2 Familiarisation

It is apparent that the level of familiarisation an individual has with a given test will have a direct influence on the reliability and validity of the test data. This is particularly the case with single joint isometric testing because the rapid development of maximum isometric force is relatively uncommon in sporting or functional movements. As a participant becomes more accustomed to performing an isometric test, intra-muscular coordination (i.e. motor unit recruitment, rate coding or firing rate of motor units, and motor unit synchronisation) may conceivably be enhanced through learning such that performance values may increase from testing day 1 to day 2. For example, Coldwells *et al.* (1994) reported small but significant increases (4.5%) in back strength, between isometric testing sessions held 6 days apart, although subjects had not been given a pre-test familiarisation session.

Interestingly in their comprehensive review of the literature, Wilson and Murphy (1996) suggested that the poor reliability reported in some studies (e.g. Sleivert and Wenger, 1992) may be partially explained by the fact that participants were not given a familiarisation session. On the other hand, Wilson and Murphy noted in the study performed by Viitasalo *et al.* (1980), which reported relatively good reliability of selected neuromuscular performance variables, subjects were required to attend a familiarisation session one week prior to the main testing session.

In addition to pre-test familiarisation, some research has demonstrated the need for adequate warm-up and practice trials during the testing session. For example, Bemben *et al.* (1992) observed a gradual increase in the maximal forces produced over three successive trials, when examining the repeatability of isometric force of the dorsiflexors and plantar flexors after only a brief one minute warm-up period. This trend has been termed warm-up decrement (Ainscoe and Hardy, 1987), although Bemben and co-workers stated that the size of muscle groups tested may be related to the amount of warm-up required as the described trend was not as noticeable in the smaller muscle groups tested such as the finger flexors, thumb abductors and forearm extensors. It is worth noting that in the study by Viitasalo *et al.* (1980), subjects performed 9-11 warm-up contractions prior to the recorded maximal trials.

2.8.3.3 Type of instruction

Given the widespread use of isometric assessment in the literature, only a few studies (e.g. Bemben *et al.*, 1990; Schlumberger *et al.*, 1999). have examined the effect of instruction on various parameters of the isometric force-time curve. Bemben and co-workers (1990) used a hand grip test to examine the effect of various instructions on

maximum isometric force and RFD in men and women. The instructions given were designed to elicit specific responses from the neuromuscular system and were as follows: (i) 'peak force is to be obtained with concentrated, slow, steady maximal effort', (ii) 'peak force is to be obtained as hard and fast as possible', and (iii) 'peak force is not of concern, only how fast you can produce force...as fast as possible'. The latter instruction was found to produce significantly higher values for maximum RFD compared with the other instructions, although the second instruction produced the highest value for maximum force. The first instruction was significantly lower on both values. Similar results were produced for the male and female participants. The authors concluded that force-time parameters can be significantly affected by the form of instruction given. Furthermore, the results even suggest that to obtain maximum force and maximum RFD values it may be necessary to perform 2 isometric tests with differing instructions.

More recently Schlumberger *et al.* (1999) examined the effect of instruction during isometric tests of the leg extensors in a seated leg press. The effect of the four tested instructions on mean values of MVC and RFD are presented in Table 2.3 below. It can be seen that to obtain the highest readings for MVC, the instruction 'hard' must be given. With regards RFD, although the instruction to produce force 'as fast as possible' (irrespective of maximum force) gave the highest values, in contrast to the study by Bemben *et al.* (1990), the result was not significantly greater than when the instruction 'hard and fast' was given. It can therefore be concluded that separate tests with differing instructions are not required in order to produce optimal results, and a combined instruction to produce force as 'hard and fast' as possible can be given. It is

also apparent from Table 2.3, that RFD results are more variable when the single instruction of 'fast' is given.

TABLE 2.4 Means values (± SD) of maximum force and rate of force development: effect of pre-test instruction, n = 24 (Schlumberger *et al.*, 1999).

	Instruction (I)			
	(1) Gradual	(2) Gradual and hard	(3) Fast	(4) Fast and hard
MVC (N)	1867 (639)	1954 (647)	1977* (726)	1995* (711)
RFD (Ns^{-1})	3670 (1430)	4460 (1880)	9660^{+} (3490)	9050^{+} (2610)

* significantly different from Instruction 1
$^{+}$ significantly different from Instruction 1 and 2

Discussion of measurement instruction should also include the effect of verbal encouragement during an isometric contraction. To generate maximum force in a muscle requires an individual to recruit all of the motor units of the muscle at their maximum firing rates (Bélanger and McComas, 1981). In some individuals, there is evidence that during a maximum voluntary contraction, the activation of the motor units may be inhibited (Merton, 1954). This inhibition has been linked to 'supraspinal drive' acting on the motor units' (Bélanger and McComas, 1981). In this respect, the idea and motivation for generating maximum muscle tension evolves in the brain and involves the limbic system and cerebral cortex (Enoka, 1994). There is evidence that unusually stressful situations, for example seeing a person trapped under an object, or specific sensory stimuli may disengage this supraspinal inhibition and lead to an enhancement of strength (Ikai and Steinhaus, 1961). In regard of the latter scenario, pathways have been identified between the components of the auditory system and the

motor system, for example the startle system (Rossignol, 1975). However there is conflicting evidence that verbal commentary can lead to improvements in strength (Rube and Secher, 1981; Johansson, 1983), although more recently McNair *et al.* (1996) demonstrated that when verbal encouragement in the form "Come on, you can do it" was presented, mean peak force increased by 5%. Although RFD was not measured, it is very likely, based on the results of Bemben *et al.* (1990) and Schlumberger *et al.* (1999), that verbal encouragement during an isometric contraction will help overcome any inhibition caused by the discomfort associated with the rapid development of isometric force.

2.8.3.4 Testing position and joint angle

In all isometric tests of muscular function, testing position and joint angle must be standardised because reliability may be adversely affected if the muscles being assessed are not effectively controlled (Clarke, 1948; Coldwells *et al.*, 1994) and maximum force and RFD will vary markedly through the range of movement (Hertzog and Ter Keurs, 1988; Williams and Stutzman, 1959).

Although using correlation analysis, Clarke (1948) clearly demonstrated that changes in test protocol, made predominantly to isolate the effect of the specific muscle group being measured and limit the involvement of compensatory muscle groups increased the reliability coefficients for maximum isometric strength. The results from this study highlight the need to effectively standardise a test and isolate the muscle group of interest when performing isometric tests of muscular function. Furthermore the amount of pre-tension (i.e. the degree of tension in contact between limb and lever)

must also be minimised as this has been shown to significantly reduce the magnitude of rate of force development (Viitasalo 1982).

In the assessment of neuromuscular fatigue, studies have reported both single joint (Brown *et al.*,1996; 1997; Strojnik and Komi, 1998) and multi-joint (Häkkinen, 1993; 1994b; Häkkinen *et al.* 1988b) testing protocols for the isometric assessment of muscular function, although it has been recommended that single joint assessment may be more suitable for experimental research where a high degree of control is required (Wilson and Murphy, 1996).

Single joint assessment is required in the measurement of forces produced by neuromuscular electrical stimulation (e.g. Bigland-Ritchie *et al.*, 1986b; Binder-Macleod and McDermond, 1992; Brown *et al.*, 1996; 1997; Strojnik and Komi, 1998), although these studies have differed in the choice of knee angle. In the studies performed by Bigland-Ritchie *et al.* and Binder-Macleod and McDermond, the knee was held at an angle slightly less than 90°, and 90° respectively, whereas in the studies by Brown *et al.* and Strojnik and Komi (1998), the subjects sat in an isometric knee extension measuring device, with the knee at 45° of flexion (from the horizontal). The position of 45° of flexion has been found to provide the least amount of discomfort during stimulation and still allow a muscle contraction of 60% of maximum voluntary isometric force to be obtained (McDonnel *et al.*, 1987). The 45° knee flexion position was also selected by McDonnel and co-workers to decrease the chance of lateral patella dislocation during electrical stimulation. It is important to remember however that during electrical stimulation the subjects should be relaxed as possible (Binder-Macleod *et al.*, 1995) which is perhaps more likely to be achieved with the knee angle

slightly less than 90°. Furthermore, positioning the lower limb at an angle of 45° will place the quadriceps in a state of muscular pre-tension which has been shown above to have a significant effect on RFD (Viitalsalo, 1982).

For the assessment of maximum voluntary isometric contraction force, Sale (1991) has recommended that testing be performed at the joint angle which corresponded to the peak of the strength curve for that particular muscle group to reduce the variability in force output associated with the small errors in the determination of the angle. In an attempt to establish the length-tension relationship of the quadriceps under isometric conditions, Newham *et al.* (1991) established that peak forces were generated with the knee at 70-85° flexion. This is in agreement with other published data for these muscles (Herzog and Ter Keurs, 1988; Ivy *et al.*, 1981; Moffroid *et al.*, 1969; Williams and Stutzman, 1959). It is also interesting to note that in the reliability study performed by Viitasalo *et al.* (1980), the knee angle was 90°. Further support of selecting a joint angle of 90° is provided by Signorile *et al.* (1995). Signorile and co-workers recorded significantly higher EMG readings of the vastus medialis, vastus lateralis and rectus femoris muscles during isometric knee extension exercise at a knee angle of 90°, compared to 15° and 30° of flexion (i.e. from the horizontal). It is therefore recommended for the present study for the assessment of both maximal voluntary contraction force and the forces elicited by electrical stimulation, the selected knee angle is 90°.

2.8.4 Validity of isometric assessment

It may be difficult to accept that measurements from a static or isometric contraction can describe speed-strength or explosiveness as it relates to athletic performance. Nevertheless, Viitasalo *et al.* (1981) have reported moderate but significant correlations (r = 0.49 to 0.66) between isometric RFD and jump height measured for a static squat jump, counter-movement vertical jump and depth jump from various heights up to 1m. Similarly, Viitasalo and Aura (1984) reported a significant correlation (r = 0.9) between isometric RFD and high jump performance throughout the training season of elite athletes. Further support for the validity of isometric tests was provided by Häkkinen *et al.* (1986) who reported that 3 out of the 7 variables used to quantify the time of isometric force production were moderately related to various performances (r = -0.50 to -0.58) in weightlifters. More recently, Haff *et al.* (1997) have shown moderate to strong correlations between isometric rate of force development and peak dynamic rate of force development produced during a mid-thigh clean pull, although the loads lifted were close to maximum, 80, 90 and 100% 1RM respectively.

On the other hand Mueller and Buehrle (1987) using an arm extension movement reported a close relationship (r = 0.83) between isometric and concentric RFD measured with a light load (4.30 kg). Examination of muscle activation patterns (Mueller and Schmidtbleicher, 1987) showed no significant difference between explosive isometric and fast ballistic concentric contractions. It is important to remember that when the intent is to make a ballistic contraction, the motor unit discharge is the same for both concentric or isometric contractions (Desmedt and Godeaux, 1979).

Such findings have resulted in the isometric RFD test becoming a standard method of muscular assessment (Behm and Sale, 1993b; Bemben *et al.*, 1990; Bemben *et al.*, 1992; Häkkinen *et al.*, 1985a; 1985b; Linnamo *et al.*, 1998; Strojnik and Komi, 1998; Tidow, 1990). It is therefore concluded, that provided subjects are instructed to produce force as hard and fast as possible, reliable and valid measures of speed-strength can be obtained.

2.8.6 Methodological considerations in using surface electromyography

2.8.6.1 Reliability

Reliable EMG measurements are essential for quantitative analyses. Although EMG equipment has improved considerably during recent years, there have been few representative investigations, which have examined the accurate reproduction of measurements (Hering *et al.*, 1988; Viitasalo and Komi, 1975).

Hering *et al.* (1988) measured surface EMG of the triceps bracchii on 9 different days. Measurements of EMG were recorded for isometric contractions at the levels of 10, 20, 40, 60, 80 and 100% of maximum voluntary contractions (MVC). For each condition, five trials were performed with a rest of 30 seconds between contractions. On all force levels, the coefficients of variation were determined for the 5 repetitions in a single force level condition (CV-rp) and also for the day-to-day measurements within subjects (CV-dd). Whereas only small variations were observed in the 5 repetitions on single force levels (CV-rp = 4.6-8.7%), the day-to-day variability was quite large (CV-dd = 15.6-28%). However it is important to note that the variability tended to be lower for the higher force levels, where at 100% MVC, CV-rp = 5.3%, and CV-dd = 15.8%.

Viitasalo and Komi (1975) investigated the reliability of integrated EMG (amplitude) and mean power frequency (frequency characteristic) of surface EMG recorded from the rectus femoris muscle during maximal isometric contractions. The knee joint angle was 90°. Reliability was better within the test session, than between the different test days.

2.8.6.2 Electrode placement, skin preparation and use of filters

Several major factors have been identified which should be considered when attempting to reduce the variability in EMG measurements. These include, type of electrode used, electrode contact area, and placement of electrodes. It is often considered that the results of an electromyographic investigation are only as good as the preparation of the electrode attachment sites. This is especially true when using passive surface electrodes and amplifiers with input impedances lower than those of high performance amplifiers (Bartlett, 1997).

The location of the electrodes is the first consideration. DeLuca (1997) in a review of the use of surface electromyography has recommended that the electrodes should be placed between the myotendinous junction and the nearest innervation zone. DeLuca added that this is particularly important when the spectral variables of the signal are to be measured as the configuration will detect the superposition of action potentials that have positive and negative phases and that pass by the electrodes with relatively small time delays among them. The resulting short-time delay subtractions generate high frequencies that augment the energy content in the high-frequency end of the EMG signal spectrum and consequently yield a higher value for the median frequency. On the other hand the placement of electrodes close to the innervation zone has been

shown to result in strong dampening of the low frequency components of the signal (Lindström and Petersén, 1983); in fact a high-pass filter is installed. Zuniga *et al.* (1970) and Kramer *et al.* (1972) have advised the placing of electrodes as close as possible to the middle of the muscle belly, in order to obtain maximal EMG potentials from fusiform muscles.

As the motor end point moves according to the level of contraction and the complexity of the movement, Clarys and Cabri (1993) recommend that for the most reliable technique, electrodes must be placed over the mid-point of the muscle belly, an easily implanted recommendation. Furthermore the two detector electrodes should lie at the appropriate place along the muscle belly with the orientation of the electrode pair being on a line parallel to the direction of the muscle fibres. This is somewhat consistent with the results observed above, where reliability was better for iEMG and for selected variables of the average motor unit potential computed from EMG signals recorded from near the muscle belly when compared to signals recorded from over the motor-end plate (Viitasalo and Komi, 1975). Interestingly however, reliability of spectral parameters was better when signals were recorded from over the motor-end plate.

When considering the reliability of EMG measurements, Viitasalo and Komi (1975) also pointed out the difficulties and possible errors in placing the electrodes on the same position on the muscle. Despite careful marking of the skin for electrode sites, the authors stated that one still cannot be confident on the exactness of the replacement. However, surface electrodes are not considered to be selective, and are hence used to collect as much activity as possible from one muscle. They have a large

detection area, and thus can detect signals from many motor units; this makes surface EMG recording more reliable than when using wire or needle electrodes, as it is less specific and therefore not as dependent upon exact positioning (Harris and Wertsch, 1994). Nevertheless the inter-electrode spacing needs to be kept small to reduce the electrode impedance and hence reduce the level of noise in the signal (Norris, 1963). This is especially important for collecting detailed information concerning muscle co-ordination. For example Basmajian and De Luca (1985) recommend a standard electrode separation of 1cm. However for the gathering of more general information, such as the state of muscle activity, a more widely spaced electrode configuration is preferred (Clarys and Cabri, 1993).

In addition to keeping the inter-electrode distance small, reducing the skin impedance, by careful preparation, e.g. shaving and light abrasion (Basmajian and DeLuca, 1985) or gently scratching the surface of the skin using a sterile lancet (Okamoto *et al.*, 1987) also lowers the noise level. Furthermore noise can be reduced by using filters. Low-pass filters are recommended to eliminate high frequency noise and prevent signal distortion from aliasing, whereas high pass filters are used to stabilise the base-line of the EMG signal and to remove low frequency noise generated by the electronics of the amplifier, thermal noise from electrode impedance, and movement artefacts. Movement artefacts can occur due to poor adhesion of the electrodes, poor skin preparation, or the motion of the muscle under the skin, which can still occur during isometric contractions (Acierno *et al.*, 1995).

2.8.7 Methodological considerations in using neuromuscular electrical stimulation

Neuromuscular electrical stimulation is also to be used in the present study to assess changes in muscle contraction properties following fatiguing dynamic exercise. However there is often a large disparity in the literature regarding the methodologies used when quantifying the changes in neuromuscular function. Different protocols for the programmed stimulation electro-myogram test have been cited in the literature in relation to the duration of stimulation (e.g. (Cooper *et al.*, 1988; Edwards *et al.*, 1977a), the use of either a continuous or split train of impulses (McDonnel *et al.*, 1987; Ratkeviius *et al.*, 1998; Sale, 1997) as well as the time interval required between successive bouts of stimulation for the accurate assessment of fatigue and recovery (Sale, 1997).

For example Cooper *et al.* (1988) stimulated the adductor pollicis at 20, 50 and 100 Hz for 1 second, although for 2 seconds at 10 Hz. Brown *et al.* (1996), for the quadriceps, and Edwards *et al.* (1977a), for the adductor pollicis and quadriceps, have reported using 1 second of stimulation for both 20 Hz and 100 Hz, whereas Jereb and Strojnik (1995), and also Strojnik and Komi (1996a; 1998) stimulated the quadriceps at 20 Hz for 1 second duration, and at 100 Hz for 0.8 second duration.

In a study examining the fatigue effects caused by electrical stimulation *per se*, Sale (1997) determined that a time interval of 10 minutes between bouts of stimulation could often cause large decreases in force production, even when no exercise session had taken place. This study investigated the use of a continuous train of electrical impulses where there was no recovery between stimulation at each frequency. Here the muscle was stimulated for a period of 2 seconds at each frequency of 10, 20, 50

and 100 Hz over one half hour period, i.e. at 0, 10, 20 and 30 minutes. Sale (1997) has also examined the use of a split train of electrical impulses whereby each stimulation of 3 seconds was interspersed with 5 seconds of recovery. Considerable fatigue was induced in several subjects using both protocols. A rest period of at least 2 seconds between contractions has been recommended by McDonnel *et al.* (1987) to prevent confounding variables such as ischemia. This type of protocol has also been used by Ratkeviius *et al.* (1998), whereby stimuli were applied for 1 second at 7, 10, 15, 20, 50 and 100 Hz, with 2 second rests interspersed between the trains.

2.8.8 Evaluation of the methodological procedures

In reviewing the literature, it is quite apparent that maximum isometric force is consistently a more reliable parameter than isometric rate of force development (RFD) and that to achieve satisfactory levels of reliability for RFD tests, it is important that the study participants are well familiarised with the testing protocol and the testing protocol is sufficiently standardised.

Reliability within the same session, particularly for RFD measurements, has only been established after making several measurements (e.g. Christ *et al.*, 1994; Mueller and Schmidtbleicher, 1987). However in studies examining the characteristics of fatigue, where assessments are made at regular intervals, for example over an initial recovery period of two hours (e.g. Häkkinen, 1993; 1994a), it is not possible to repeat the same measurement several times without concomitant influences on the measured variable (Atkinson, 1994). Equally in studies where measurements are made over several days, the reliability of measurements between test days needs to be established.

Firstly the number of trials required to obtain reliable within-session and between-day measurements of maximum voluntary neural activation, maximum voluntary isometric force and rate of force development, needs to be determined. It is then necessary to establish that there is no significant trial bias due to fatigue when taking successive measurements at each time interval over the recovery period.

No definitive protocol with regard the duration of stimulation has been cited in the literature for the assessment of high and low frequency fatigue following dynamic exercise. Furthermore, the degree of fatigue induced by taking successive measurements of neuromuscular electrical stimulation over the immediate recovery period needs to be established. Finally, it is necessary to establish that there is no significant trial bias due to fatigue when taking successive measurements of both maximum voluntary contraction force and measurements of force elicited by electrical stimulation.

With regards the choice of statistics, Atkinson and Nevill (1998) recommend in any reliability study: -

(i) the inclusion of an examination of the presence or absence of heteroscedasticity;

(ii) a full examination of any systematic bias in the measurements, coupled with recommendations on the number of pre-test familiarisation sessions, practice trials, measured trials, as well as the advised recovery time between tests so that any bias due to fatigue is minimised.

(iii) the citation of the most popular measures of absolute reliability, depending on whether heteroscedasticity is present (coefficients of variation) or absent ('limits of agreement'). Also it is preferable that these are calculated from the mean square error term in a repeated-measures ANOVA model. The described percentile of measurement error (68 or 95%) should also be stated.

(iv) It is also recommended that since the measurements in this study are effected by learning or fatigue of testing, the bias between trials is always reported separately from the random error component.

It is important to note that Atkinson (1995) has recommended that when data are homoscedastic, in other words, when there is no relation between the error and the size of the measured value, they should not be expressed as a coefficient of variation, and 'limits of agreement' should be used. On the other hand, Atkinson and Nevill (1998) commented in their review of the literature that the 'limits of agreement' method has been applied mostly to the reliability and validity of adipose tissue measurements, although Atkinson *et al.* (1995) adopted this method in assessing the variation in leg strength measured with an isokinetic dynamometer. It can be seen from the above that the majority of the studies assessing the reliability of isometric tests of muscular function have used either correlation coefficients or coefficient of variation. For the described studies using CV above, there was no consideration of heteroscedasticity, it was not made clear whether the values were not calculated from the mean square error term and the percentile of measurement error was not stated although it is assumed to 68%.

Another point to note is that traditionally, muscle soreness data and ratings of perceived exertion (RPE) scores have been analysed using non-parametric statistical tests (Brown *et al.*, 1996; 1997), although no appropriate non-parametric statistical test exists for a repeated measures experimental design. More recently it is believed that 'non-parametric' data can be analysed using parametric tests if the appropriate assumptions are made (Field, 2000). Consequently for the purpose of this thesis it is assumed that the muscle soreness data (and RPE scores) are measured at the interval level and that the distance between points of the scale are equal at all points along the scale. This means that a soreness rating of 6 is assumed to be exactly three times that of a soreness rating of 2. Brown *et al.* (1997) have reasoned that rating soreness on a scale of 1-10 for example, may be subjective and depend on inter-individual differences to pain. However inter-individual variability is not a consideration for repeated measures ANOVA designs (Vincent, 1999) and it is therefore assumed that each subject's rating of soreness is consistent for each experimental condition. Further perception of effort during resistance exercise using Borg's 6-20 scale has previously been analysed using repeated measures ANOVA (Pierce *et al.*, 1993).

2.9 Summary

Players engaged in team sports such as rugby regularly use forms of resistance exercise for the improvement of maximal peak force (strength) and rate of force development. The ability of the muscles to develop high rates of force development may even be more important than maximum force production capability (Wilson, 1992). Two distinct forms of resistance exercise that are commonly used by players engaged in team sports are heavy resistance exercise (HRE) and dynamic strength exercise (DSE). It has been suggested that HRE may be superior for the enhancement of speed-strength characteristics due to the significantly longer time under tension (i.e. the high loads compel the motor neurons to fire high frequency impulses for comparatively long times). The differences in duration of motor unit activation between HRE and DSE may therefore have an effect on the fatigue and recovery characteristics.

Whilst a number of studies have examined the acute-induced fatigue and short-term recovery characteristics from fatigue in response to heavy resistance exercise protocols, less information is available after explosive type strength loading and no data are apparent for dynamic strength exercise. Research examining the phenomenon of fatigue after a strenuous resistance exercise protocol has also concentrated on either elite or strength trained athletes (Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), strength and power athletes compared to endurance trained athletes (Häkkinen, and Myllylä, 1990; Kroll *et al.*, 1980; Pääsuke *et al.*, 1999) or subjects not participating in any regular training programme (e.g Pullinen and Komi, 1995). No data are available regarding the recovery patterns from fatiguing resistance exercise sessions for players

engaged in team sports. It is envisaged that close examination of the process of recovery taking place during rest after the termination of strenuous fatigue loading will provide valuable information as to the optimal recovery period required to overcome the effect of fatigue prior to subsequent training or competition.

Investigation of the neuromuscular changes during fatigue and short-term recovery from fatigue produced following strenuous resistance exercise requires the use of several different measurement protocols, although these are often associated with high variability. Satisfactory levels of reliability are achieved only when the testing protocols are sufficiently standardised or after making several measurements. Consequently the reliability of the experimental techniques used in the present study need to be established.

CHAPTER 3

DEVELOPMENT OF THE MEASUREMENT PROTOCOLS

3.1 Background to the study

In order to reliably assess the neuromuscular changes during fatigue and short-term recovery from fatigue produced following strenuous resistance exercise it is necessary to use several different measurement protocols. The protocols for measurement of maximal peak force, rate of force development and electromyographical variables are associated with high variability or measurement error. Further, for the technique of neuromuscular electrical stimulation, the reliability of measurements has not been reported in the literature.

The main components of measurement error are systematic bias (e.g. general learning or fatigue effects on the tests) and random error due to inconsistencies in the measurement protocol (e.g. not controlling posture in a consistent way during measurements of strength). The main concern is the control of systematic bias. If the systematic bias detected is significant or large enough to be important, then the measurement protocol would need to be adapted to remove the learning or fatigue effect on the test (e.g. include more familiarisation trials or increase the time between repeated measurements, respectively).

The objective of the following four studies is to establish the measurement protocols to reliably assess, using appropriate statistical techniques that control for inter-subject variability, the neuromuscular responses to heavy resistance and dynamic strength exercise. Specifically these will be in relation to: -

1. The number of trials required to obtain within-session reliability of selected force and electromyographical variables of the lower limb and the between-day reliability of these variables.
2. The degree of fatigue (systematic bias) caused by successive measurements of maximum voluntary contraction force.
3. The degree of fatigue (systematic bias) caused by successive measurements of the force elicited by neuromuscular electrical stimulation.
4. The degree of fatigue (systematic bias) caused by successive measurements of maximum voluntary contraction force and the force elicited by neuromuscular electrical stimulation.

3.2 Study 1A: Within-session and between-day reliability of selected neuromuscular performance variables from isometric contractions of the lower limb

3.2.1 Rationale for the study

In measurements of neuromuscular performance, several variables are measured simultaneously, not only within the same test session, but also between test days. Few studies have examined the within-session and between-day reliability of both force and electromyographical variables determined from an isometric contraction of the lower limb. In those that have, the methods employed have been characterised by high variability or have been analysed using inappropriate statistical tests such as product-moment correlation coefficients. Satisfactory levels of reliability of peak force and rate of force development (RFD) are achieved when the testing protocol is sufficiently standardised with respect to the amount of familiarisation and warm-up, choice of test position and joint angle as well as the type of instruction given to produce peak force and RFD. Similarly, with regards to electromyographical variables (Root Mean Square values and Median Frequency), the procedures employed for careful skin preparation, electrode placement and day-to-day replacement can affect reliability. More importantly however, reliability within the same session has only been established after making several measurements, but this can cause fatigue.

3.2.2 Objectives of the study

The objectives of this study were to determine (i) the number of trials required to obtain within-session reliability of selected force and electromyographical variables of the lower limb and (ii) the between-day reliability of these variables.

3.2.3 Methodology

Eight male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. The mean (± SD) age, height and body mass of the subjects were 25 ± 2 years, 1.78 ± 0.04 m, and 80.8 ± 12.2 kg, respectively. All the subjects were well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University.

Measures of maximum voluntary unilateral isometric force of the right leg extensor muscles were obtained using a strain gauge dynamometer attached to an adapted Lido Isokinetic Dynamometer chair (Loredan, Davis, CA) (Plate 3.1). The strain gauge dynamometer was calibrated prior to testing by applying a series of known weights and converting the resulting voltage into force. For the assessment of neuromuscular function, the subject sat in the test chair with a knee joint angle of 90° (Zhou *et al.*, 1996) with the attachment from the strain gauge securely anchored just above the malleolus (Tornvall, 1963). The ankle cuff was attached to the strain gauge via a metal bar, fed through a bottleneck arrangement as illustrated in Plate 3.2. The ankle cuff and strain gauge could be moved vertically and horizontally to account for differences in subjects' physical characteristics. The subjects were seated in the adjustable, straight-backed chair and firmly strapped across the chest and waist. In addition, subjects were requested to keep their arms in a folded position with hands clasping the opposite shoulder throughout the duration of the contraction. Thus, the position of the subjects in the force chair was standardised. The uninvolved leg was allowed to hang freely.

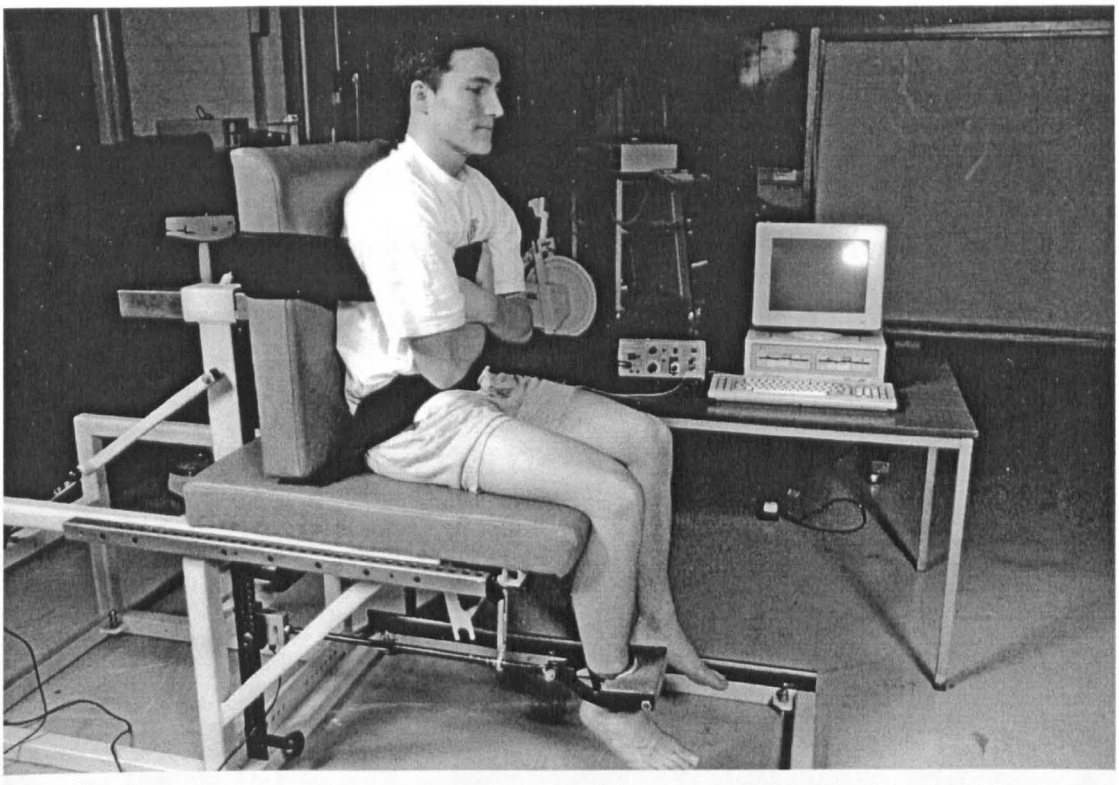


Plate 3.1 Isometric strength testing chair adapted from a Lido Isokinetic Dynamometer (Loredan, USA).

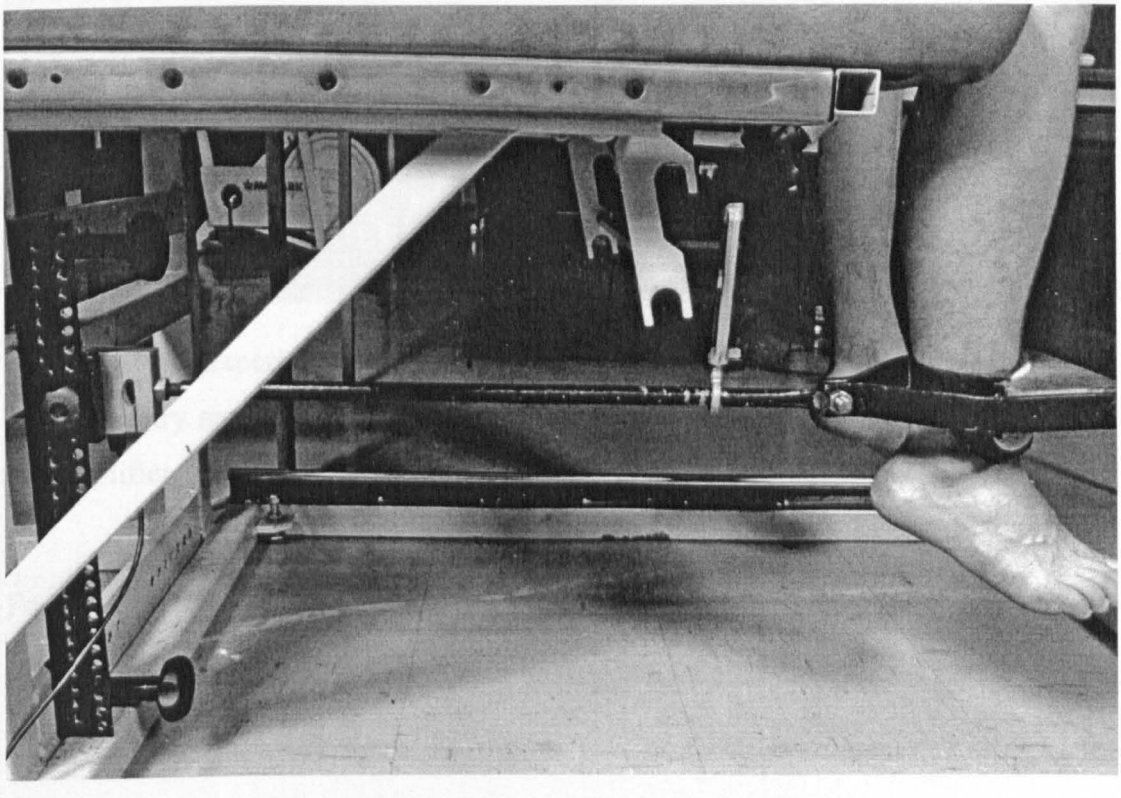


Plate 3.2 Experimental set up for the recording of maximum voluntary isometric force of the quadriceps with the ankle cuff attached to the strain gauge via a metal bar.

The subjects were instructed to exert their maximal force as *"hard and fast"* as possible (Bemben *et al.*, 1990; Schlumberger *et al.*, 1999), and maintain that force for 3 seconds. Verbal encouragement was given to each subject during the performance of each maximal contraction (McNair *et al.*, 1996). The words spoken were "Come on, you can do it", and they were repeated for the duration of the contraction.

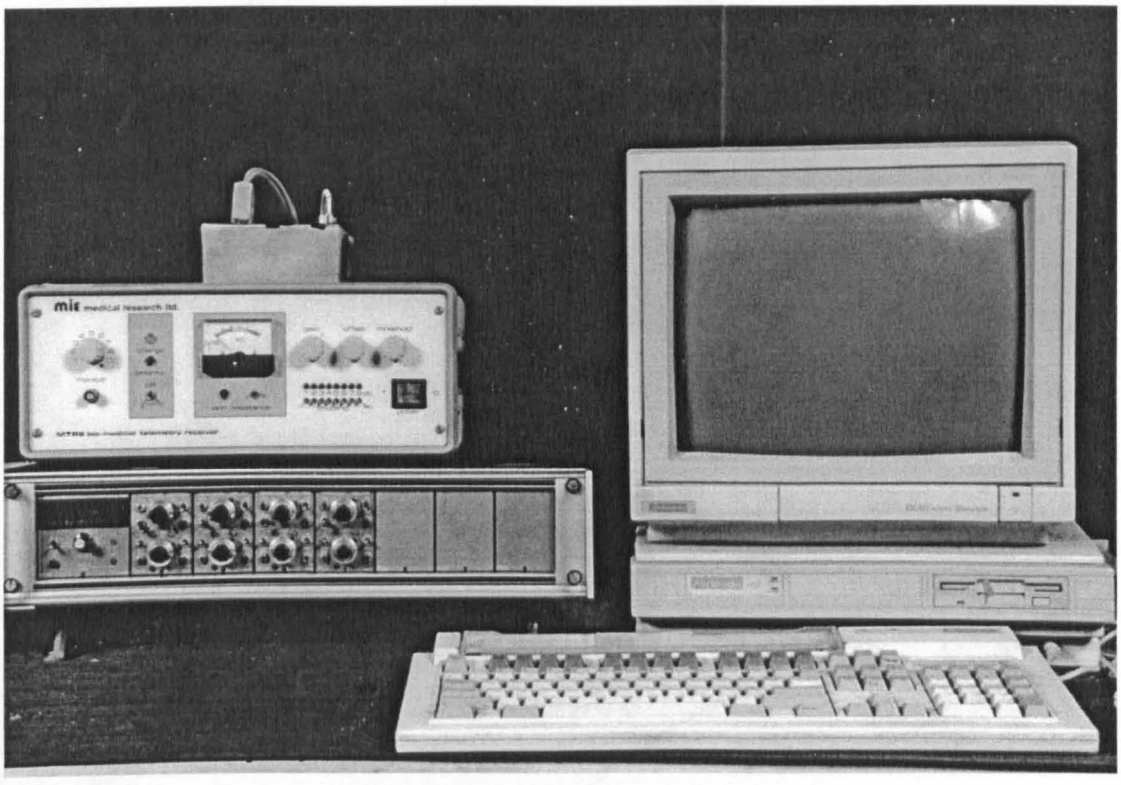


Plate 3.3 Experimental set-up for the amplification and recording of force data. The telemetry receiver for the recording of surface EMG signals is situated on top of the amplifier.

Force data from the strain gauge were amplified and collected on-line by an Archimedes 310 Computer via a 12 bit analogue-to-digital converter (Plate 3.3). Data were recorded for peak force, maximum rate of force development (RFD_{max}, the steepest gradient of the force-time curve over a 5 ms period) (Wilson *et al.*, 1993) and the average rate of force development (RFD_{avg}, determined over the range of 10% -

70% of the force slope) (Viitasalo *et al.*, 1980) (Figure 3.1a). The ability of the muscles to rapidly develop force, was also quantified by the force produced at 30 ms after initiation (F_{30}), and the impulse generated over the first 100 ms of the force-time curve (I_{100}) (Baker *et al.*, 1994; Wilson et *al.*, 1995; Young, 1995) (Figure 3.1b).

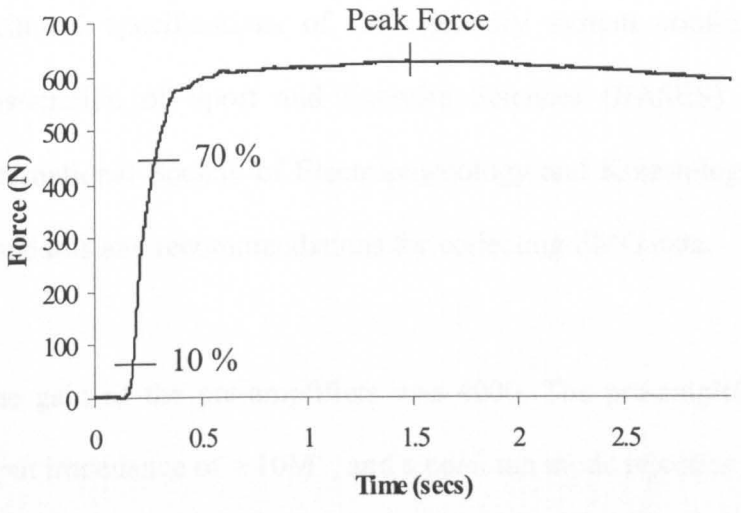


Figure 3.1a Typical isometric force-time curve for leg extensor muscles.

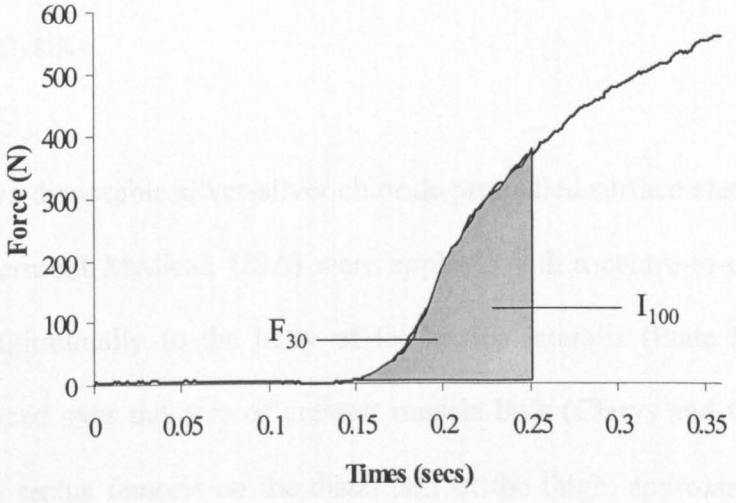


Figure 3.1b Isometric force-time curve expanded to illustrate force produced at 30 ms after initiation (F_{30}), and the impulse generated over the first 100 ms (I_{100}).

Surface electromyographic activity (EMG) was simultaneously recorded during the maximal isometric testing contractions from the vastus lateralis (VL) muscle of the right leg onto a second channel. The EMG signals were recorded telemetrically (MTR8 Biomedical Telemetry Receiver, I.M.I.E. LTD., Leeds, U.K.) (Plate 3.3) and passed through pre-amplifiers, located no further than 10 cm from the electrodes. The technical specifications of the telemetry system conformed to both the British Association of Sport and Exercise Sciences (BASES) (Bartlett, 1996), and the International Society of Electrophysiology and Kinesiology (ISEK) (Merletti, 1999) standards and recommendations for collecting EMG data.

The gain of the pre-amplifiers was 4000. The pre-amplifiers possessed a balanced input impedance of > 10M , and a common mode rejection ratio of > 110 dB. The use of pre-amplifiers mounted on the skin near the detection electrodes can help reduce cable artefact noise (Bartlett, 1997; Gans, 1992). Both force and EMG data were sampled at 1000 Hz. The data obtained were stored on magnetic discs for later analysis.

Two disposable silver-silver chloride pre-gelled surface electrodes of 10 mm diameter (Vermont Medical, USA) were applied, with a centre-to-centre distance of 35 mm, longitudinally to the belly of the vastus lateralis (Plate 3.4). The electrodes were placed over the area of greatest muscle bulk (Clarys and Cabri, 1993) just lateral to the rectus femoris on the distal half of the thigh, approximately one hand's breadth above the patella (Winter, 1988). The reference electrode was located on the lateral side of the knee of the tested thigh (Plate 3.4).

The skin was carefully prepared by shaving the required area to remove unwanted body hair. The surface was then cleaned and degreased using a clean tissue moistened with warm soapy water until no grease was evident on the tissue (Bartlett, 1997). This ensured that the inter-electrode resistance was always below 2.0 kΩ on each day (Viitasalo *et al.*, 1980). Slight pressure was applied to improve contact between the electrodes and the skin, by fixing the electrodes with adhesive tape (Herzog *et al.*, 1994). Skin resistance was recorded on each day of testing using a moving coil meter. A permanent marking pen was used to outline the position of the EMG electrodes on the muscles. This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999).

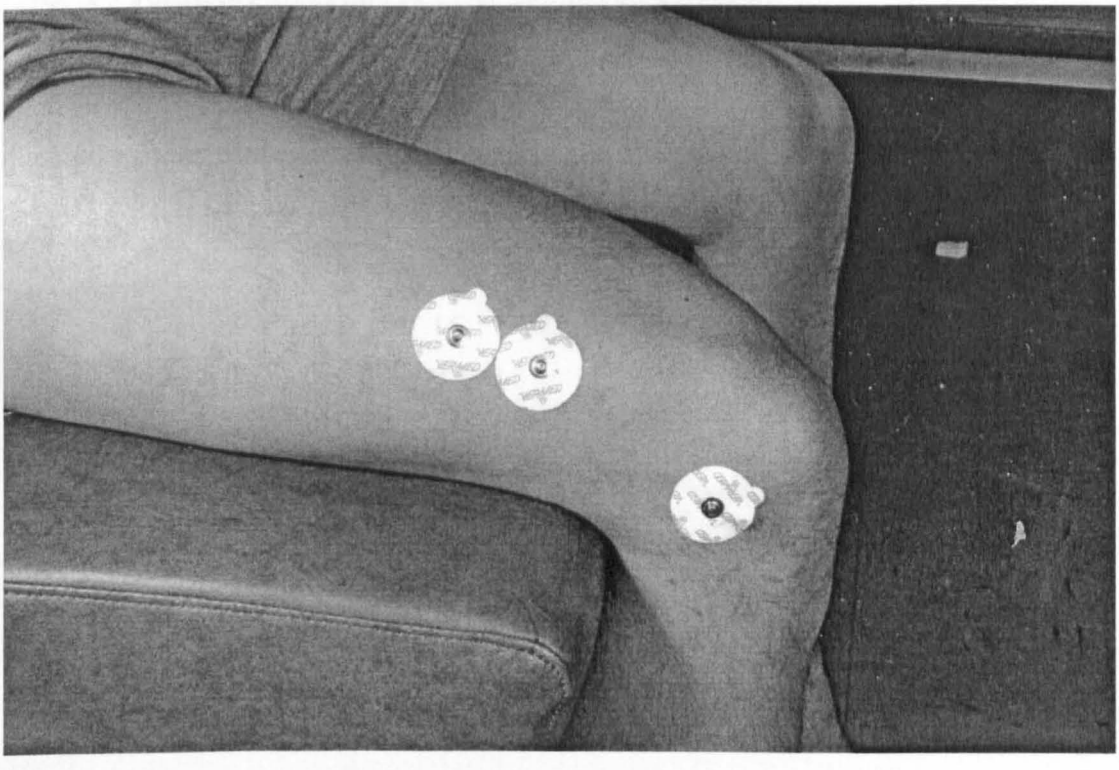


Plate 3.4 Placement of electrodes for measurement of maximum voluntary neural activation from the vastus lateralis muscle.

A typical EMG signal recorded during a maximal voluntary contraction from the vastus lateralis muscle is presented in Figure 3.2. Root mean square (RMS) and median frequency (MDF) values were determined from the raw signal (Basmajian and De Luca, 1985). RMS values were calculated for the time periods of 0-100 ms, 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998). Herzog *et al.* (1994) have stated that the root mean square of the EMG signal is an excellent indicator of the magnitude of the signal, and that it is frequently used in studying muscular fatigue.

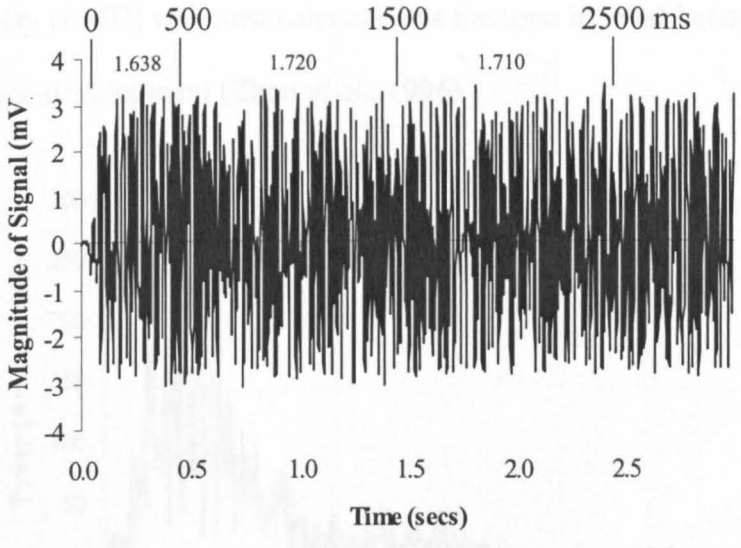


Figure 3.2 Typical raw EMG signal and RMS values recorded from the vastus lateralis muscle during a maximal voluntary isometric contraction. The EMG signal was recorded telemetrically.

In order to determine MDF, EMG data were extracted for exactly 1024 data points, from the middle of the MVC trial. This was to ensure that the signals were stationary (Vaz *et al.*, 1996). Frequency analysis of the EMG signals was performed using a Fast Fourier Transform (FFT) algorithm (1024 data points; spectral resolution 0.98)

(Figure 3.3). Prior to taking the FFT, a Hamming window was used to avoid end effects. MDF was then calculated from the power frequency spectrum.

For the calculation of the force and electromyographical variables, the onset of force was defined as the first value, which exceeded 4 SDs above the mean residual base-line (calculated from the first 20 data points), provided that the subsequent 3 points were not lower than the threshold value of 4 SDs. Similarly, the onset of EMG was defined as the first absolute value, which exceeded at least 3 SDs above the mean residual base-line (calculated from the first 20 data points). The electromechanical delay (EMD) was then calculated as the time interval between the onset of EMG and force development (Zhou *et al.*, 1996).

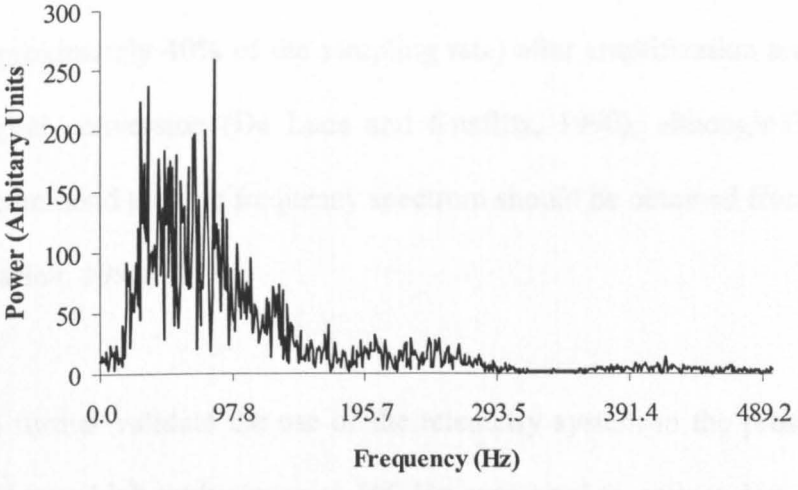


Figure 3.3 Frequency content of raw EMG signal recorded during a maximal voluntary isometric contraction. The EMG signal was recorded telemetrically.

Johnson (1988) and Nilsson *et al.* (1993) have recommended that a minimum sampling frequency of 1000 Hz should be used for surface EMG, as it is essential that the sampling frequency be greater than twice the highest frequency in the EMG signal. If sampling rates at least twice the highest signal frequency cannot be

achieved, signal distortion can occur due to aliasing (Bartlett, 1996). This problem will often arise in conjunction with multiplexing telemetry systems.

It should be noted therefore, that the telemetry system described above, does multiplex the EMG signal such that the highest frequency that can be reproduced is 250 Hz. This means that any values above 250 Hz should be disregarded. However as illustrated in Figure 3.3 (a typical FFT), most of the EMG signal is below 200 Hz. Equally, when comparing with other data presented in the literature (e.g. Bigland-Ritchie *et al.*, (1981), these authors have determined that over 90% of the energy in an EMG signal is contained below 250 Hz. Therefore the problem of aliasing in the present study should be minimal even without filtering. Aliasing can be avoided by use of an analogue anti-aliasing filter (i.e. a low-pass filter with a cut-off frequency of approximately 40% of the sampling rate) after amplification and before analogue-to-digital conversion (De Luca and Knaflitz, 1990), although BASES guidelines do recommend that the frequency spectrum should be obtained from the raw EMG signal (Barlett, 1996).

To further validate the use of the telemetry system in the present study, a BIOPAC system which multiplexes at 500 Hz, was used to collect data at 1000 Hz, 2000 Hz and 3000 Hz. The signals produced from the FFT of the electromyographic signal were visually similar to those produced by the telemetry system. The telemetry system was therefore deemed suitable for the purposes of this study.

The subjects were measured on four different testing occasions. The first session was used for the purpose of familiarisation of the subjects with the details of the test

contractions. The subjects were then required to attend the laboratory on three successive days at the same time of day to control for circadian variation (Atkinson and Reilly, 1996). One week was allowed between familiarisation and the testing sessions. No strength training was allowed before (48 hours) and during the experimental period.

On each testing day, subjects were allowed 5 warm-up contractions at 75% of their maximum force. Subjects were then required to perform five maximal contractions. The time interval between maximal efforts was 2 minutes. The within-session and between-day reliability of the force and electromyographical variables were then determined by comparing the test results from test days 1, 2 and 3.

Data reduction and statistical methods

In order to evaluate the within-session and between-day reliability of measurements, the data were analysed using a two-way analysis of variance (ANOVA) with repeated measures (day, trial and trial by day interaction) and also with a correction for 'sphericity' (Vincent, 1999). For further analysis, the averages of the first and third, and second and fourth of the five contractions were calculated for each variable (Viitasalo *et al.*, 1980) and hereafter called as A and B respectively for day 1, C and D for day 2, and E and F for day 3. Trial 5 was discarded for the purpose of this second analysis. Tukey's post hoc test of honestly significant differences was used to assess the systematic bias between tests. The mean squared error term from ANOVA was used in the calculation of indicators of absolute reliability (Bland, 1995; Nevill and Atkinson, 1998). Statistical significance was set at $p<0.05$.

3.2.4 Results

The means and standard deviations of the repetitive measurements for the selected force variables for within-session and between-day measurements are presented in Table 3.1. The means and standard deviations of the electromyographical variables simultaneously recorded during the maximal isometric contractions are presented in Table 3.2.

The results from the two-way ANOVA with repeated measures (Table 3.3) indicate that there is no significant bias between trials within the same session or between days for the 5 repetitions of maximum voluntary contraction force (MVC). A plot of the absolute residual errors against the fitted measurements for MVC confirmed the absence of a relationship between the residual errors and the size of the measurements ($r = -0.015$). It was therefore assumed that the residual errors for all measurements were normally distributed. Consequently, the within-subject measurement error calculated from the ANOVA, was then used to determine the random error component of the 95% 'limits of agreement' for both within-session and between-day measurements of the force (Table 3.4) and electromyographical (Table 3.5) variables respectively. For each variable, the random error is quoted with the systematic bias error to form the 'limits of agreement'.

Although the data were homoscedastic, to provide comparison with earlier reliability studies, the coefficients of variation (68^{th} percentile) were also determined for the 5 repetitions (CV_{trial}), and also for the day-to-day measurements within subjects (CV_{day}). The coefficients of variation for the force and electromyographical variables are presented in Table 3.6 and Table 3.7 respectively.

Although no significant day effects were observed, there were significant trial effects for RFD_{max} and maximum voluntary neural activation for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms, with a trend for the magnitude of the variables to decrease from the first to the fifth trials. Post hoc analysis revealed that for RFD_{max}, the only significant difference ($p<0.05$) was between the second trial on day 1, compared to the fifth trial on day 2 ($HSD_{0.05}$ = 1705N). For the electromyographical data; time interval of 0-500 ms ($HSD_{0.05}$ = 0.117), there were no significant trial effects for day 1 and day 2. However for day 3, the amplitude of the signal, for trial 1 was significantly greater than for the other 4 trials. For the time interval of 500-1500 ms ($HSD_{0.05}$ = 0.068), there were no significant trial effects for day 1, although there were significant differences between the first, and the fourth and fifth trials respectively on day 2. Finally, for the time interval of 1500-2500 ($HSD_{0.05}$ = 0.084), significant differences were observed between; the first trial on day 3, compared to both the fourth and fifth trials on day 1 and the fifth trial on day 2.

It is interesting to note from Table 3.1, that although five warm-up contractions were allowed, peak force was not produced on trial 1. On each testing day, maximum force was produced on trial 2. Furthermore when comparing the averages of the first and third trials, and the second and fourth trials (Table 3.8), a significant trial effect ($p<0.05$) can be observed (Table 3.9). Nevertheless, when the averages of two trials are taken, the 'limits of agreement' and the coefficients of variation (68^{th} percentile) for both within-session and between-day measurements for all variables are considerably less than when individual measurements are taken.

TABLE 3.1 Mean (± SD) for n = 8 subjects from days 1, 2 and 3 of the selected force variables. The daily group means (± SD) for each variable are also presented.

TRIAL	MVC (N)	RFD_{max} ($N.s^{-1}$)	RFD_{avg} ($N.s^{-1}$)	F_{30} (N)	I_{100} (N.s)
DAY 1					
1	635.1	7416	2827	49.3	13.3
	(75.40)	(2284)	(879.9)	(34.3)	(3.60)
2	651.0	7885	2701	44.9	12.3
	(70.62)	(2422)	(730.3)	(45.9)	(4.70)
3	643.9	7192	2828	52.7	13.4
	(71.69)	(1360)	(743.2)	(42.8)	(3.28)
4	639.6	6894	2634	43.1	11.2
	(72.54)	(1339)	(729.3)	(45.0)	(4.42)
5	647.9	6227	2631	49.7	12.7
	(78.03)	(1744)	(585.5)	(48.0)	(4.70)
Mean	**643.5**	**7123**	**2724**	**47.9**	**12.6**
(SD)	**(73.66)**	**(1830)**	**(733.6)**	**(43.2)**	**(4.14)**
DAY 2					
1	630.4	7473	2620	38.0	11.7
	(70.94)	(2753)	(797.1)	(28.9)	(2.89)
2	648.3	7445	2618	35.8	11.9
	(74.24)	(2627)	(499.6)	(15.9)	(3.54)
3	647.9	7223	2330	40.6	12.5
	(77.14)	(2778)	(709.3)	(33.1)	(3.42)
4	653.8	7237	2656	40.2	11.4
	(72.92)	(2224)	(473.5)	(38.9)	(3.88)
5	648.7	6161	2480	37.8	11.8
	(93.93)	(2199)	(658.4)	(34.8)	(4.13)
Mean	**645.8**	**7108**	**2541**	**38.5**	**11.8**
SD	**(77.83)**	**(2517)**	**(627.6)**	**(30.3)**	**(3.57)**
DAY 3					
1	651.2	7446	2838	46.2	13.0
	(72.98)	(1463)	(477.3)	(32.3)	(3.05)
2	662.3	7384	2711	40.9	12.2
	(82.79)	(2064)	(634.5)	(29.2)	(3.71)
3	648.3	7119	2752	49.4	12.3
	(88.14)	(2638)	(737.6)	(51.6)	(4.97)
4	651.3	6865	2641	49.1	12.3
	(76.64)	(2266)	(622.9)	(43.6)	(4.45)
5	645.4	6832	2622	35.6	10.7
	(96.10)	(2179)	(704.4)	(29.4)	(4.54)
Mean	**651.7**	**7129**	**2713**	**44.2**	**12.1**
(SD)	**(83.33)**	**(2122)**	**(635.3)**	**(37.2)**	**(4.14)**

TABLE 3.2 Mean (± SD) for n = 8 subjects from days 1, 2 and 3 for the selected electromyographical variables. The daily group means (± SD) for each variable are also presented. RMS values are presented as arbitrary units.

TRIAL	EMD (ms)	RMS values (arbitrary units) 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF (Hz)
DAY 1						
1	28.9	1.283	1.339	1.420	1.444	58.10
	(8.10)	(0.280)	(0.202)	(0.164)	(0.200)	(4.53)
2	31.0	1.121	1.277	1.410	1.430	59.69
	(11.1)	(0.247)	(0.251)	(0.173)	(0.196)	(5.28)
3	27.8	1.208	1.336	1.394	1.416	55.90
	(9.92)	(0.354)	(0.157)	(0.121)	(0.181)	(6.22)
4	27.6	1.110	1.286	1.373	1.381	59.08
	(11.0)	(0.270)	(0.142)	(0.159)	(0.202)	(5.48)
5	33.0	1.200	1.321	1.356	1.380	58.10
	(11.5)	(0.422)	(0.153)	(0.156)	(0.232)	(4.59)
Mean	**29.7**	**1.184**	**1.312**	**1.390**	**1.410**	**58.17**
(SD)	**(10.3)**	**(0.314)**	**(0.181)**	**(0.155)**	**(0.202)**	**(5.22)**
DAY 2						
1	29.4	1.045	1.215	1.409	1.428	57.61
	(6.65)	(0.227)	(0.315)	(0.260)	(0.330)	(5.76)
2	28.0	1.092	1.216	1.387	1.426	56.26
	(6.50)	(0.408)	(0.296)	(0.201)	(0.273)	(5.80)
3	28.9	1.039	1.146	1.403	1.409	58.83
	(5.36)	(0.475)	(0.292)	(0.241)	(0.330)	(5.35)
4	27.9	0.962	1.215	1.316	1.411	58.22
	(7.86)	(0.451)	(0.241)	(0.260)	(0.333)	(4.12)
5	30.0	0.887	1.179	1.327	1.374	58.34
	(8.67)	(0.383)	(0.312)	(0.226)	(0.278)	(4.53)
Mean	**28.8**	**1.005**	**1.194**	**1.368**	**1.410**	**57.85**
(SD)	**(7.00)**	**(0.389)**	**(0.291)**	**(0.238)**	**(0.309)**	**(5.11)**
DAY 3						
1	30.0	1.337	1.433	1.478	1.489	57.49
	(5.37)	(0.226)	(0.232)	(0.231)	(0.241)	(4.34)
2	30.3	1.049	1.316	1.402	1.498	58.34
	(5.78)	(0.420)	(0.216)	(0.223)	(0.254)	(6.21)
3	30.9	1.109	1.245	1.358	1.473	56.38
	(7.30)	(0.404)	(0.248)	(0.234)	(0.237)	(5.73)
4	31.9	1.143	1.322	1.402	1.411	57.97
	(9.01)	(0.385)	(0.247)	(0.194)	(0.259)	(5.65)
5	31.8	0.977	1.268	1.378	1.411	58.83
	(11.8)	(0.426)	(0.272)	(0.184)	(0.219)	(5.47)
Mean	**31.0**	**1.123**	**1.316**	**1.404**	**1.456**	**57.80**
(SD)	**(7.84)**	**(0.372)**	**(0.242)**	**(0.213)**	**(0.242)**	**(5.48)**

TABLE 3.3 Two-way ANOVA with repeated measures results for within-session and between-day reliability of the neuromuscular performance variables for n = 5 trials.

	DAY		TRIAL		DAY BY TRIAL	
	F-value	P-value	F-value	P-Value	F-value	P-value
Force variables						
MVC (N)	0.19	0.831	1.08	0.386	0.83	0.555
RFD_{max} ($N.s^{-1}$)	0.00	0.999	3.75	0.014*	0.34	0.947
RFD_{avg} ($N.s^{-1}$)	1.17	0.340	1.05	0.401	1.22	0.305
F_{30} (N)	1.70	0.218	0.78	0.509	0.78	0.548
I_{100} (N.s)	0.46	0.639	1.16	0.349	1.05	0.409
EMG variables						
EMD (ms)	0.54	0.594	0.40	0.806	0.69	0.698
RMS values (Arbitrary Units)						
0-100 ms	2.65	0.106	2.10	0.107	1.28	0.292
0-500 ms	3.27	0.099	4.16	0.009*	2.16	0.045*
500-1500 ms	0.35	0.714	11.8	0.000*	1.75	0.107
1500-2500 ms	0.61	0.557	6.47	0.001*	0.53	0.826
MDF (Hz)	0.06	0.944	0.63	0.578	1.01	0.429

* $p<0.05$

TABLE 3.4 95% 'limits of agreement' (systematic bias ± random error) for force variables for n = 5 trials.

	MVC (N)	RFD_{max} ($N.s^{-1}$)	RFD_{avg} ($N.s^{-1}$)	F_{30} (N)	I_{100} (N.s)
Trial	37.28 ± 70.08	1705 ± 3205	476.8 ± 896.5	23.56 ± 44.30	3.52 ± 6.62
Day	80.46 ± 170.5	2418 ± 5124	787.3 ± 1668	30.26 ± 64.09	5.44 ± 9.51

TABLE 3.5 95% 'limits of agreement' (systematic bias ± random error) for electromyographical variables for n = 5 trials.

	EMD (ms)	RMS values (± arbitrary units) 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF (Hz)
Trial	11.7 ± 21.9	0.370 ± 0.696	0.117 ± 0.220	0.068 ± 0.127	0.084 ± 0.158	5.29 ± 9.94
Day	12.0 ± 25.5	0.464 ± 0.984	0.317 ± 0.672	0.251 ± 0.532	0.282 ± 0.598	6.87 ± 14.56

TABLE 3.6 Coefficients of variation for force variables for n = 5 trials.

	MVC	RFD_{max}	RFD_{avg}	F_{30}	I_{100}
CV_{trial} (%)	5.5	23.0	17.2	51.8	27.7
CV_{day} (%)	13.4	36.7	32.0	75.0	39.8

TABLE 3.7 Coefficients of variation for electromyographical variables for n = 5 trials.

	EMD	RMS values 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF
CV_{trial} (%)	37.5	32.2	8.8	4.7	5.6	8.8
CV_{day} (%)	43.7	45.4	26.9	19.5	21.4	12.8

TABLE 3.8 Mean (± SD) of the measurements A and B, C and D, and E and F for the force and electromyographical variables. A and B, C and D, E and F denote the specific combinations taken for the reliability analysis.

	DAY 1		DAY 2		DAY 3	
	A	B	C	D	E	F
Force variables						
MVC (N)	639.5	645.3	639.1	651.0	649.7	656.8
	(72.84)	(70.62)	(72.60)	(71.42)	(79.22)	(79.23)
RFD_{max} ($N.s^{-1}$)	7304	7390	7348	7341	7283	7124
	(1733)	(1796)	(2614)	(2365)	(1843)	(2088)
RFD_{avg} ($N.s^{-1}$)	2827	2667	2475	2637	2795	2676
	(787.5)	(692.2)	(731.8)	(444.6)	(563.8)	(606.7)
F_{30} (N)	51.03	44.00	39.31	37.99	47.82	44.99
	(37.90)	(45.16)	(29.97)	(25.46)	(39.94)	(35.93)
I_{100} (N.s)	13.37	11.72	12.12	11.62	12.65)	12.26
	(3.30)	(4.50)	(2.83)	(3.38)	(3.58)	(4.04)
EMG variables						
EMD (ms)	28.3	29.3	29.1	27.9	30.4	31.1
	(8.62)	(10.4)	(4.15)	(5.28)	(5.77)	(6.67)
RMS values (Arbitrary Units)						
0-100 ms	1.245	1.115	1.042	1.027	1.223	1.096
	(0.301)	(0.226)	(0.287)	(0.420)	(0.295)	(0.376)
0-500 ms	1.338	1.281	1.180	1.216	1.339	1.319
	(0.175)	(0.189)	(0.301)	(0.263)	(0.238)	(0.230)
500-1500 ms	1.407	1.391	1.406	1.351	1.418	1.402
	(0.136)	(0.164)	(0.249)	(0.226)	(0.231)	(0.205)
1500-2500 ms	1.430	1.406	1.418	1.419	1.481	1.455
	(0.184)	(0.195)	(0.326)	(0.299)	(0.237)	(0.255)
MDF (Hz)	57.00	59.38	58.22	57.24	56.93	58.16
	(4.17)	(4.58)	(5.26)	(4.03)	(4.76)	(4.21)

TABLE 3.9 Two-way ANOVA with repeated measures results for within-session and between-day reliability of the measurements A and B, C and D, and E and F for the neuromuscular performance variables from Table 3.6.

	DAY		TRIAL		DAY BY TRIAL	
	F-value	P-value	F-value	P-Value	F-value	P-value
Force variables						
MVC (N)	0.44	0.651	6.08	0.043*	0.37	0.698
RFD_{max} ($N.s^{-1}$)	0.06	0.938	0.02	0.890	0.26	0.774
RFD_{avg} ($N.s^{-1}$)	1.19	0.332	0.37	0.561	3.32	0.066
F_{30} (N)	1.93	0.183	5.67	0.049*	0.84	0.454
I_{100} (N.s)	0.64	0.542	3.70	0.096	1.65	0.238
EMG variables						
EMD (ms)	0.68	0.521	0.02	0.886	0.62	0.552
RMS values (Arbitrary Units)						
0-100 ms	2.11	0.176	3.66	0.097	0.68	0.525
0-500 ms	3.16	0.103	1.48	0.263	1.86	0.192
500-1500 ms	0.23	0.801	11.4	0.012*	1.64	0.229
1500-2500 ms	0.56	0.583	3.10	0.122	0.68	0.523
MDF (Hz)	0.19	0.831	3.66	0.097	5.00	0.023*

* $p<0.05$

TABLE 3.10 95% 'limits of agreement' (systematic bias ± random error) of the measurements A and B, C and D, E and F for the force variables.

	MVC (N)	RFD_{max} ($N.s^{-1}$)	RFD_{avg} ($N.s^{-1}$)	F_{30} (N)	I_{100} (N.s)
Trial	13.72 ± 32.22	751.2 ± 1763	260.9 ± 612.3	6.40 ± 15.01	1.80 ± 4.21
Day	44.52 ± 94.33	1690 ± 3581	514.5 ± 1090	18.22 ± 38.61	2.39 ± 5.06

TABLE 3.11 95% 'limits of agreement' (systematic bias ± random error) of the measurements A and B, C and D, E and F for the electromyographical variables.

	EMD (ms)	RMS values (arbitrary units) 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF (Hz)
Trial	4.0 ± 9.5	0.193 ± 0.453	0.046 ± 0.108	0.035 ± 0.081	0.039 ± 0.092	1.88 ± 4.41
Day	7.6 ± 16.2	0.284 ± 0.601	0.208 ± 0.439	0.175 ± 0.371	0.199 ± 0.421	4.00 ± 8.47

TABLE 3.12 Coefficients of variation of the measurements A and B, C and D, E and F for the force variables.

	MVC	RFD_{max}	RFD_{avg}	F_{30}	I_{100}
CV_{trial} (%)	2.5	12.3	11.7	17.3	17.5
CV_{day} (%)	7.4	25.0	20.8	44.6	21.0

TABLE 3.13 Coefficients of variation of the measurements A and B, C and D, E and F for the electromyographical variables.

	EMD	RMS values 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF
CV_{trial} (%)	16.4	20.6	4.3	3.0	3.3	3.9
CV_{day} (%)	28.1	27.3	17.5	13.6	15.0	7.5

It appears from the analyses above, that the average of two different trials is sufficient to obtain reliable within-session and between-day measurements for most of the neuromuscular performance variables. However due to the evidence of a possible warm-up or learning effect for maximum voluntary contraction force, to confirm that it is only necessary to record the first two trials, the averages of the first and second, and third and fourth of the five contractions were compared for each variable and hereafter called as A^1 and B^1 respectively for day 1, C^1 and D^1 for day 2, and E^1 and F^1 for day 3. Trial 5 was again discarded. The means and standard deviations for the measurements A^1 and B^1 (C^1 and D^1, E^1 and F^1) are presented in Table 3.14. It should be pointed out that the 'limits of agreement' and coefficients of variation for between-day measurements are the same when comparing the average of the first and second trial to the averages of the first and third trials, as the within-subject measurement error is calculated from the same four trials.

The 'limits of agreement' for within-session measurements were only slightly worse for MVC and RFD_{max} (Table 3.16), but better for RFD_{avg}, when compared to the values presented in Table 3.10. It should be noted that when the average of the first and second trials for MVC is determined, there is no significant bias between trials within the same session. It is also quite noticeable that although there is no significant trial bias for RFD_{max}, the average of the first and second trials is consistently higher than the average of the third and fourth trials (Table 3.14) for all three days. This provides further evidence for recording the first two trials only.

TABLE 3.14 Mean (± SD) of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the force and electromyographical variables. A^1 and B^1, C^1 and D^1, and E^1 and F^1 denote the specific measurements taken for the reliability analysis.

	DAY 1		DAY 2		DAY 3	
	A^1	B^1	C^1	D^1	E^1	F^1
Force variables						
MVC (N)	643.1	641.7	639.3	650.8	656.7	649.8
	(72.46)	(71.87)	(71.81)	(73.69)	(76.62)	(81.65)
RFD_{max} ($N.s^{-1}$)	7651	7043	7459	7230	7415	6992
	(2276)	(1253)	(2556)	(2489)	(1638)	(2392)
RFD_{avg} ($N.s^{-1}$)	2764	2731	2619	2493	2775	2696
	(765.3)	(724.2)	(632.0)	(562.4)	(548.5)	(643.4)
F_{30} (N)	47.11	47.92	36.89	40.41	43.58	49.23
	(39.23)	(43.52)	(21.17)	(35.51)	(30.35)	(47.12)
I_{100} ($N.s^{-1}$)	12.81	12.28	11.81	11.93	12.60	12.32
	(3.95)	(3.73)	(2.90)	(3.44)	(3.24)	(4.66)
EMG variables						
EMD (ms)	29.9	27.7	28.7	28.4	30.1	31.4
	(8.99)	(10.1)	(5.18)	(5.80)	(4.17)	(7.62)
RMS values (Arbitrary Units)						
0-100 ms	1.202	1.159	1.068	1.000	1.193	1.126
	(0.225)	(0.282)	(0.288)	(0.416)	(0.308)	(0.387)
0-500 ms	1.308	1.311	1.216	1.180	1.374	1.283
	(0.221)	(0.147)	(0.301)	(0.257)	(0.222)	(0.244)
500-1500 ms	1.415	1.383	1.398	1.360	1.440	1.380
	(0.164)	(0.138)	(0.228)	(0.249)	(0.225)	(0.212)
1500-2500 ms	1.437	1.399	1.427	1.410	1.493	1.442
	(0.193)	(0.187)	(0.300)	(0.329)	(0.246)	(0.247)
MDF (Hz)	58.89	57.49	56.94	58.53	57.91	57.18
	(4.46)	(5.67)	(5.59	(4.27)	(4.16)	(4.90)

TABLE 3.15 Two-way ANOVA with repeated measures results for within-session and between-day reliability of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the neuromuscular performance parameters from Table 3.14.

	DAY		TRIAL		DAY BY TRIAL	
	F-value	P-value	F-value	P-Value	F-value	P-value
Force variables						
MVC (N)	0.44	0.651	0.05	0.835	1.89	0.187
RFD_{max} ($N.s^{-1}$)	0.06	0.938	4.57	0.070	0.15	0.860
RFD_{avg} ($N.s^{-1}$)	1.19	0.332	1.76	0.226	0.17	0.847
F_{30} (N)	1.92	0.183	0.39	0.552	0.32	0.773
I_{100} (N.s)	0.64	0.543	0.12	0.736	0.48	0.631
EMG variables						
EMD (ms)	0.68	0.521	0.07	0.797	2.59	0.110
RMS value (Arbitrary Units)						
0-100 ms	2.11	0.176	0.94	0.365	0.05	0.955
0-500 ms	3.16	0.103	4.78	0.065	2.66	0.105
500-1500 ms	0.23	0.801	37.6	0.000*	0.46	0.639
1500-2500 ms	0.56	0.583	4.93	0.062	0.61	0.566
MDF (Hz)	0.19	0.830	0.03	0.870	1.46	0.269

* $p<0.05$

TABLE 3.16 95% 'limits of agreement' (bias ± random error) of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the force variables.

	MVC (N)	RFD_{max} ($N.s^{-1}$)	RFD_{avg} ($N.s^{-1}$)	F_{30} (N)	I_{100} (N.s)
Trial	20.55 ± 48.24	803.3 ± 1856	244.0 ± 572.8	21.8 ± 51.12	2.69 ± 6.31
Day	44.52 ± 94.33	1690 ± 3581	514.5 ± 1090	18.22 ± 38.61	2.39 ± 5.06

TABLE 3.17 95% 'limits of agreement' (bias ± random error) of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the electromyographical variables.

	EMD (ms)	RMS values (arbitrary units) 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF (Hz)
Trial	6.7 ± 15.7	0.250 ± 0.588	0.077 ± 0.180	0.029 ± 0.068	0.065 ± 0.153	4.39 ± 10.29
Day	7.6 ± 16.2	0.284 ± 0.601	0.208 ± 0.439	0.175 ± 0.371	0.199 ± 0.421	4.00 ± 8.47

TABLE 3.18 Coefficients of variation of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the force variables.

	MVC	RFD_{max}	RFD_{avg}	F_{30}	I_{100}
CV_{trial} (%)	3.8	13.2	10.9	59.0	26.2
CV_{day} (%)	7.4	25.0	20.8	44.6	21.0

TABLE 3.19 Coefficients of variation of the measurements A^1 and B^1, C^1 and D^1, and E^1 and F^1 for the electromyographical variables.

	EMD	RMS values 0-100 ms	0-500 ms	500-1500 ms	1500-2500 ms	MDF
CV_{trial} (%)	27.3	26.7	7.2	2.5	5.5	9.1
CV_{day} (%)	28.1	27.3	17.5	13.6	15.0	7.5

3.2.5 Discussion

The agreement between three or more trials can be examined using repeated measures analysis of variance (ANOVA) (Bland, 1995). By fitting the subject and trial main effects, the ANOVA identifies any significant trial bias and, at the same time, estimates the within-subject measurement error (Nevill and Atkinson, 1998). This can then be used to determine the random error component of the 95% 'limits of agreement' or the coefficient of variation between trials (reliability within the same session) or between-days. Even if the systematic bias is not statistically significant, the bias and random error can be quoted together. Expressed this way, the 'limits of agreement' provide a measurement of 'total error'.

One major assumption of repeated measures ANOVA is that the variance of the several repeated measures, or trials, is equal (homogeneity of variance), and the correlations among all combinations of trials (homogeniety of covariance) are equal. This is called the assumption of sphericity (Vincent, 1999). If the assumption of sphericity is not true, the probability of making a Type I error increases. In the present study, the Huynh-Feldt (HF) adjustment was used to correct for any violation of the assumption of sphericity. This adjustment was automatically provided by the SPSS statistical package. In the HF adjustment, df_C (degrees of freedom for columns which is used to represent variability between trials) and df_E (degrees of freedom for error which is used to measure within group variability) are multiplied by the value epsilon (ε) that ranges from 0.00 for maximum violation to 1.00 for no violation. For the purposes of the above analyses, if ε was ≥ 0.75, the violation was considered minimal and no adjustment was made. However if ε was < 0.75, then the p values were taken from the HF row produced from the SPSS output.

The overall reliability of the force and electromyographical variables (n = 5 trials) appears to be acceptable when assessed by the repeated measures design. There was no significant bias between trials for MVC and the coefficient of variation of 5.5 % could be used to indicate very good reliability. However this is unrealistic given that 4 out of the 8 subjects showed individual differences that could be calculated to be greater than 9% of the respective means. The limitation of using coefficients of variation to assess reliability is further evident when the more recent statistical method of 'limits of agreement' is used (Bland, 1995; Nevill and Atkinson, 1998). Although not statistically significant, the systematic bias between individual trials is 37.3 N. Furthermore the random error between trials is 70.1 N. As described previously the method used to calculate CV in the present study only represents approximately 68% of the error that is actually present in the repeated measurements for the average individual in the same sample, where 'limits of agreement' represent the test-retest differences for 95% of a population.

Despite this limitation, to provide comparisons with previous research the coefficients of variation for each variable will be described. The coefficients of variation (68% percentile) for 5 repetitions (CV_{trial}) for the amplitude of the EMG signal ranged from 4.7 to 32.2% and for the day-to-day measurements (CV_{day}) between 19.5 to 45.4%. However, the highest variation was for the RMS values expressed between 0-100 ms, the early contraction phase (Linnamo *et al.*, 1998), whereas the lowest variation was for the RMS values calculated in the peak force phase (500-1500 ms). Recently Vint and Hinrichs (1999) demonstrated that using integration intervals of 250 ms and longer, significantly reduced variability and improved reliability of average integrated EMG values during maximum effort isometric contractions. When considering the

time intervals 0-500, 500-1500 and 1500-2500 ms, CV_{trial} ranged from 4.7 to 8.8% and CV_{day} ranged from 19.5-26.9%.

When the means of two different trials were taken (first and third, second and fourth) (Viitasalo *et al.*, 1980), low coefficients of variation were produced for both within-session and between-day measurements. The CV_{trial} and CV_{day} for MVC were 2.5 and 7.4% respectively, whereas CV_{trial} and CV_{day} for RFD_{max} were 12.3 and 25.0%. The systematic bias between trials for maximum voluntary contraction force was also more acceptable reducing from 37.3 N to 13.7 N. It is clearly apparent that the coefficients of variation for rate of force development are higher than for maximum force, with values slightly greater for RFD_{max} compared to RFD_{avg}. Nevertheless all of the results analysed for RFD_{max} and RFD_{avg} compare favourably with previous studies.

For the force measurements, F_{30} and I_{100}, no significant main effects for trial or day were evident from the two-way ANOVA. However the coefficients of variation for these variables for both within-session and between-day measurements were considerably higher than for the other force parameters. Therefore for subsequent studies, F_{30} and I_{100} will not be considered.

For EMG measurements, low coefficients of variation were produced (omitting 0-100 ms), ranging from 3.0 to 4.3% for CV_{trial} and 13.6 to 17.5% for CV_{day}. These values again compare well with previous studies and provide the evidence for recording two trials for obtaining repeatable measurements. Notably, the coefficients of variation for the EMG data were determined from a single muscle, the vastus lateralis whereas in

the study completed by Viitasalo *et al.* (1980), the EMG signals were averaged for the rectus femoris, vastus lateralis and vastus medialis.

Nevertheless, it can be clearly seen that the coefficients of variation for between-day measurements are considerably higher than for within-session. Viitasalo and Komi (1975) reported that EMG measurements are repeatable when electrodes are not removed between tests, although this is not possible when studies are performed over several days. Reapplying electrodes may result in the measurements being inconsistent where the quality of the recorded signal can deteriorate (Komi and Buskirk, 1970). Indeed, Hering *et al.* (1988) suggested that the high variations from day to day of iEMG are more likely to be caused by changes in conductivity phenomena of body tissue rather than by physiological deviations, although in the present study the inter-electrode resistance was measured on each day of testing and was always found to be less than 2.0 kΩ. Equally, resistance did not change greatly from day to day for each subject. Interestingly, the coefficients of variation for between-day measurements for MDF were quite low. The frequency content of the signal is one variable that is most likely to be affected by changes in conductivity.

During the present study, several methodological issues were clarified. Firstly, with regards to the replacement of electrodes, Häkkinen and Komi (1983) stained the skin with small ink dots. This method has been frequently cited in the literature especially in training studies over several weeks duration (Häkkinen and Komi, 1985a; 1985b; Häkkinen *et al.*, 1985a; 1985b). For the present study, an outline of the electrodes was drawn on the muscles using a permanent marking pen as described by Keogh *et al.* (1999). The spacing of electrodes in the present study is shown in Plate 3.3. The

outsides of the electrodes are just touching to aid in the replacement of electrodes. When comparing electrode spacing in the literature, Viitasalo and Komi (1975) used an inter-electrode distance of 10 mm, whereas Viitasalo *et al.* (1980) and Vaz *et al.* (1996) used 20 and 30 mm respectively. The inter-electrode spacing in this study was 35 mm. Electrode distance has a significant influence on the measured amplitude, but not median frequency (Gerdle *et al.*, 1990).

Secondly, RMS values were obtained from the raw signal (Basmajian and DeLuca, 1985; Vaz *et al.*, 1996), whereas in the BASES guidelines (Bartlett, 1996), the use of a high-pass filter (e.g. 10 Hz) is sometimes recommended to stabilise the base-line and to remove low frequency noise generated by the electronics of the amplifier, thermal noise from electrode impedance, and movement artefacts (Acierno *et al.*, 1995). However, if the cut-off frequency is too high, significant components of the myoelectric signal will be lost. On the other hand, if the cut off frequency is too low, an unstable base-line and movement artefacts may appear. Visual inspection of the raw signal however revealed no unstable base-lines or movement artefacts. Therefore for the future studies, as the electromyographical signals are collected from isometric contractions (Vint and Hinrichs, 1999; Vaz *et al.* 1996), and standardised procedures for skin preparation and electrode placement are always adopted (Bartlett, 1996) the RMS values will be calculated from the raw signal.

Thirdly, the telemetry system used in the present study multiplexes at 250 Hz, however as (i) most of the EMG signal in the present study was below 200 Hz, (ii) other authors have reported similar findings (e.g. Bigland-Ritchie *et al.*, 1981), and (iii) when electromyographic signals were collected using a BIOPAC system which

mutliplexes at 500 Hz, and passed through a Fast Fourier Transform, the FFT output was visually similar to that produced by the telemetry system, then contamination from aliasing is not believed to be a problem for the future studies.

Although low coefficients of variation were produced as described above, maximum force was always greater for trial 2 than trial 1 on each day of testing (Table 3.1), indicating a possible learning effect or warm-up decrement effect (Ainscoe and Hardy, 1987). Bemben *et al.* (1992) have observed a gradual increase in the maximal forces produced over three successive trials, when examining the reliability of isometric force of the dorsiflexors and plantar flexors. The authors highlighted the need for more warm-up trials to increase the reliability of measurements. Whereas only a brief one-minute warm-up had been allowed in the study performed by Bemben and co-workers, 5 warm-up contractions at 75% of the maximum force were allowed in the present investigation. In addition, it can be observed that there is no real improvement in performance after trial 2.

Interestingly, the increase in force in trial 2 was not accompanied by an increase in neural activation. Furthermore, the learning or warm-up decrement effect was not evident for the rate of force development where maximum rate of force development usually occurred on trial 1. For the EMG data, significant trial effects were observed for the individual trials, illustrated by a decrease in neural drive from the first to the fifth trial. Bigland-Ritchie and Woods (1984) have stated that although integrated EMG and mean firing rate of individual motor units do decline during sustained MVC, this does not necessarily result in a loss of force. The authors suggest that the range of motor neuron firing rates elicited during a voluntary effort is regulated and

limited for each muscle to the minimum required for maximum force generation, thus preventing neuromuscular transmission failure and optimising motor control.

Bemben *et al.* (1992) also state that the reliability of fast force production data is dependent on the instructions given to the subjects. In an earlier study, Bemben *et al.* (1990) demonstrated that if both maximal force and maximal rate of force development are of interest, then instructions are necessary requiring forces to be produced as "hard and as fast" as possible. Indeed, more recently, Schlumberger *et al.* (1999) have found that in performing maximal isometric efforts, the instructions "hard and fast" induce optimal results.

As well as the pre-contraction instructions described previously, each subject was verbally encouraged with the words "Come on, you can do it", for the duration of each effort. McNair *et al.* (1996) found a 5% increase in peak force when subjects were encouraged with the same instructions. The power spectral analysis of EMG activity has been used to study the activation of muscle (Gerdle *et al.*, 1990), with the view that shifts in the median frequency are associated with changes in muscle fibre conduction velocities (Arendt-Nielsen and Mills, 1985; Komi and Tesch, 1979). Since muscle fibre conduction velocity is higher for fast twitch fibres (Andearssen and Arendt-Nielsen, 1987), which are normally activated in maximal effort contractions, McNair *et al.* (1996) thought that enhancements of strength as a result of verbal encouragement, might be reflected in a greater median frequency of the activated muscles, thus showing enhanced activation of type 2 fibres. However, no significant shifts in median frequency were observed between trials. It may be that the median frequency is more sensitive to changes in recruitment than firing rate (Gerdle *et al.*,

1991), and that maximum recruitment of motor units may already have occurred by 80% to 90% of maximum force (Milner-Brown *et al.*, 1973).

In relation to the effects of warm-up on maximum voluntary contraction force, Binkhorst *et al.* (1977) showed that changes in temperature within the physiological range affect the rate of force development but not the maximum isometric force. Increases in intramuscular temperature have been assumed to affect muscle fibre conduction velocity (Arendt-Nielsen and Mills, 1985). Everard (1997) found no significant differences between maximum isometric force after either active (cycle ergometer) or passive (massage) warm-ups, although differences were found for rate of force development. The warm-up should be related to the task being performed (Injer and Strømme, 1979; Shellock, 1986; Shellock and Prentice, 1985). Therefore it is reasonable to believe that 5 warm-up contractions are sufficient without the need for additional warm-up (e.g. on a cycle ergometer), since an extended warm-up may induce fatigue (Gutin *et al.*, 1976).

Mueller and Schmidtbleicher (1987) commented that repeatedly producing maximal rate of force development in isometric contractions can be difficult for some people, and it requires high motivation and full concentration. In order to achieve satisfactory levels of reliability the authors recommended that 3-5 trials should be performed. However the rate of force development and maximum voluntary neural activation tended to decrease after the second contraction. For further analysis, the means of trial 1 and 2 were compared to the means of trial 3 and 4, with no real effect on the within-session ' limits of agreement' or coefficients of variation. Further the within-session reliability for RFD_{avg} was better when trial 1 was combined with trial 2. It can

therefore be concluded that the mean of two different measurements (including the first maximum trial) for most of the neuromuscular performance variables was sufficient to obtain reliable within-session and between-day measurements. The reliability values for within-session measurements for EMD were noticeably higher when the mean of the first and second trials was taken compared to when the mean of the first and third trials was determined, although there was no real change in the F-value produced from the two-way ANOVA (trial effect). The reliability of this variable will therefore be closely examined in the next study.

3.1.6 Conclusions and recommendations

The average of two different measurements for most of the variables was sufficient to obtain acceptable repeatability for within-session and between-day measurements, and thus provide a comprehensive assessment of lower limb neuromuscular fatigue variables. However, the force variables F_{30} and I_{100} and the RMS values determined for the time period of 0-100 ms were not reliable enough to be considered for future studies.

3.3 Study 1B: Assessment of the systematic bias caused by successive measurements of maximum voluntary contraction force over the recovery period

3.3.1 Rationale of the study

In order to achieve the aim of this thesis, it is necessary to investigate the changes in maximum voluntary contraction force and the force produced by electrical stimulation over the immediate recovery period of 2 hours, as well as after rest for 24 and 48 hours following two forms of resistance exercise. It was determined in Study 1A, that the mean of two measurements of maximum voluntary isometric contraction force is sufficient to obtain reliable within-session and between-day measurements, and thus provide a comprehensive assessment of lower limb neuromuscular fatigue variables. However, the effect of taking two measurements of maximum voluntary contraction force at set time intervals over the immediate two hour recovery period on the measured variables has not been established.

3.3.2 Objective of the study

The objective of this study was to determine whether it would be possible to make two measurements at each time interval over the immediate recovery of 0, 15, 30, 60 and 120 min without some concomitant effect on the measured variable or significant trial bias.

3.3.3 Methodology

Eight male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. The mean age (± SD), height and body mass of the subjects were 24 ± 2 years, 1.79 ± 0.04 m, and 79.5 ± 7.39 kg, respectively. All the subjects were well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University.

Measures of maximal voluntary unilateral isometric force of the right leg extensor muscles were obtained using a strain gauge dynamometer attached to an adjustable chair as described in Study 1A. Surface electromyographic activity (EMG) was simultaneously recorded during the maximal isometric testing contractions from the vastus lateralis (VL) muscle of the right leg onto a second channel. Each subject was required to perform two maximal voluntary contractions at the time points of 0, 15, 30, 60 and 120 min and after 24 and 48 hours as shown in the protocol below (Figure 10).

	MVC	MVC	MVC	MVC	MVC
Day 1	0	15	30	60	120
Day 2 (after 24 hours)	0				
Day 3 (after 48 hours)	0				

Figure 3.4 Protocol to determine the degree of fatigue induced by taking successive measurements of maximum voluntary contraction force (MVC) at time points in minutes.

The subjects were instructed to exert their maximal force as *"hard and fast"* as possible (Bemben *et al.*, 1990; Schlumberger *et al.*, 1999), and maintain that force for 3 seconds. Verbal encouragement was given to each subject during the performance of each maximal contraction (McNair *et al.*, 1996). The words spoken were "Come on, you can do it", and they were repeated for the duration of the contraction. The time interval between maximal efforts was 1 minute.

Force data from the strain gauge were amplified and collected on-line by an Archimedes 310 Computer via a 12 bit analogue-to-digital converter. Both force and EMG data were sampled at 1000 Hz. The data obtained were stored on magnetic discs for later analysis. From the resultant force-time curve, data were recorded for peak force, maximal rate of force development (RFD_{max}) and the average rate of force development (RFD_{avg}) (Viitasalo *et al.*, 1980). Root mean square (RMS) and median frequency (MDF) values were determined from the raw myoelectrical signal (Bartlett, 1996; Basmajian and De Luca, 1985). RMS values were calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998). The electromechanical delay (EMD) and the MDF were determined as described in Study 1A.

Each subject was required to attend the laboratory on four occasions. The purpose of the first session was for familiarisation of the experimental techniques. A period of one week was allowed between familiarisation and the experimental session. Subjects were then required to attend on three successive occasions at the same time on each testing day to control for circadian variation (Atkinson and Reilly, 1996). A permanent marking pen was used to outline the position of the EMG electrodes on the

muscles. This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999). Additionally, no lower body strength training was allowed before (48 hours) and during the entire experimental period.

Data reduction and statistical methods

In order to evaluate the reliability of measurements, the averages of the two maximum isometric contractions recorded at each time interval were calculated for each neuromuscular performance variable (Viitasalo *et al.*, 1980) and compared across each time point using one-way ANOVA with repeated measures and also with a correction for 'sphericity' (Vincent, 1999). Tukey's post hoc test of honestly significant differences was used to assess the systematic bias between tests. The mean squared error term from ANOVA was used in the calculation of indicators of absolute reliability (Bland, 1995; Nevill and Atkinson, 1998). Statistical significance was set at $p<0.05$.

3.3.4 Results

The means and standard deviations of the averages of the two contractions for the neuromuscular performance variables are presented in Table 3.20. The one-way ANOVA with repeated measures shown in Table 3.21 revealed that when MVC and RFD_{avg} were compared across all time points, a significant trial effect was observed ($p<0.05$). This result reflects the increases in maximum force and rate of force development after 24 and 48 hours. It should be noted however, for MVC the systematic bias is 40.7 N, and therefore the force values after 24 and 48 hours are not significantly greater than base-line, rather the force value after 60 minutes. Similarly for RFD_{avg} the bias is 362.7 N, and therefore the significant difference is between the force value after 15 minutes on day 1 and the force value after 24 hours.

When data were analysed over the first two hours period, i.e. with the 24 and 48 hour data removed, no significant trial effects were observed. The coefficients of variation and limits of agreement (systematic bias $\pm$ random error) for MVC and RFD_{avg} were 4.8% and 30.94 $\pm$ 58.17 N and 10.9% and 304.8 $\pm$ 573.1 Ns^{-1} respectively.

TABLE 3.20 Mean (± SD) for the neuromuscular performance variables (average of two recorded over the time intervals of 0, 15, 30, 60 and 120 minutes, and after 24 and 48 hours for n = 8 subjects.

	0 min	15 min	30 min	60 min	120 min	24 hours	48 hours
Force variables							
MVC (N)	630.0 (25.19)	609.8 (50.67)	622.5 (47.54)	604.3 (43.82)	624.8 (35.01)	654.0 (42.05)	656.8 (53.08)
RFD_{max} ($N.s^{-1}$)	6082 (1336)	5523 (1033)	5667 (1129)	5435 (619.2)	6115 (1792)	7012 (2654)	5975 (1758)
RFD_{avg} ($N.s^{-1}$)	2816 (537.7)	2602 (405.2)	2638 (442.3)	2630 (362.6)	2721 (476.0)	2967 (580.1)	2895 (610.3)
EMG variables							
EMD (ms)	29.9 (9.07)	26.9 (7.74)	28.9 (6.03)	25.9 (8.69)	29.3 (8.60)	29.3 (7.60)	25.3 (6.32)
RMS values (Arbitrary Units)							
0-500 ms	1.361 (0.282)	1.348 (0.262)	1.385 (0.2400	1.353 (0.259)	1.423 (0.240)	1.421 (0.304)	1.408 (0.267)
500-1500 ms	1.503 (0.278)	1.448 (0.232)	1.488 (0.285)	1.462 (0.242)	1.542 (0.310)	1.496 (0.284)	1.548 (0.263)
1500-2500 ms	1.564 (0.312)	1.507 (0.253)	1.516 (0.272)	1.515 (0.294)	1.589 (0.329)	1.523 (0.286)	1.563 (0.282)
MDF (Hz)	59.26 (7.92)	58.83 (7.17)	59.14 (8.38)	57.91 (8.29)	56.51 (6.28)	58.28 (6.85)	57.30 (7.53)

TABLE 3.21 One-way ANOVA with repeated measures for the neuromuscular performance variables (from Table 3.20) over the time intervals of 0, 15, 30, 60 and 120 minutes, and after 24 and 48 hours for n = 8 subjects. The coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) are also presented.

	F-value	P-value	CV_{trial} (%)	Limits of Agreement
Force variables				
MVC (N)	4.79	0.006*	5.9	40.72 ± 72.72
RFD_{max} ($N.s^{-1}$)	2.29	0.120	24.4	1596 ± 2850
RFD_{avg} ($N.s^{-1}$)	2.94	0.017*	12.0	362.7 ± 647.7
EMG variables				
EMD (ms)	1.55	0.185	21.2	6.5 ± 11.6
RMS values (Arbitrary Units)				
0-500 ms	0.93	0.485	9.6	0.146 ± 0.261
500-1500 ms	1.22	0.319	9.0	0.148 ± 0.264
1500-2500 ms	1.03	0.421	8.2	0.139 ± 0.248
MDF (Hz)	1.33	0.266	6.0	3.83 ± 6.84

* $p<0.05$

3.3.5 Discussion

It has already been established from Study 1A that the average of two measurements is satisfactory for the within-session and between-day reliability of the selected neuromuscular performance variables analysed in the study above. In the present study, there was a trend for peak force and rate of force development to decline over the first hour of recovery although these differences were not significant.

However the systematic bias was significant when data after 24 and 48 hours of recovery were included in the analyses ($p<0.05$), although not in relation to base-line measurements as previously described. For MVC the significant difference was between the force value after 60 minutes and the force values after 24 and 48 hours, and for RFD_{avg} between the value after 15 minutes and the value recorded after 24 hours of recovery. It is therefore important that subjects are fully motivated to produce maximum force at each time point.

Although data after 24 and 48 hours are not significantly greater than base-line measurements, it appears there has been either a learning effect on day 2 and day 3 or a neuromuscular super-compensation training effect as described by Zatsiorsky (1995). Should it be a learning effect, then greater familiarisation of the subjects is required.

The co-efficient of variation for within-trial measurements for RFD_{avg} (12.0%) was just above the generally accepted limit of 10% variation. On the other hand, the co-efficients of variation for RFD_{max} and EMD were considerably greater than the

acceptable limit, most likely due to the methods of computation, and therefore these variables will not be considered for future studies.

3.3.6 Conclusions and recommendations

The results of this study proved that it is possible to make two measurements at each time interval over the immediate recovery of 0, 15, 30, 60 and 120 min without any significant trial bias. The systematic bias of 30.94 N and 304.8 Ns^{-1} for MVC and RFD_{avg} respectively, was deemed acceptable for future studies. For data to be compared over 24 and 48 hours of recovery, subjects must be adequately familiarised with performing maximum contractions prior to the first day of testing. The coefficients of variation for RFD_{max} and EMD were too large for these variables to be accepted within the test battery.

3.4 Study 1C: Assessment of the systematic bias caused by the successive measurements of the force elicited by electrical stimulation of the human quadriceps femoris muscles

3.4.1 Rationale for the study

Neuromuscular electrical stimulation has recently been used to assess changes in muscle contraction properties during (Beelen *et al.*, 1995; James *et al.*, 1995; Newham *et al.*, 1991) or following fatiguing dynamic exercise (Sale 1997; Strojnik and Komi, 1998; 1996a; 1996b; Skurvydas, 1998). Previously, researchers (Bergström and Hultman, 1988; Binder-Macleod and McDermond, 1992; McDonnel *et al.*, 1987; Stokes *et al.*, 1988; 1989) have more commonly used electrical stimulation to induce fatigue, and thus provide a clinical tool for assessing muscle performance. More specifically, the electrical stimulator is used to elicit repeated sub-maximal contractions while measuring the rate of decline of resultant isometric force levels (McDonnel *et al.*, 1987).

For the investigations reported in this thesis, neuromuscular electrical stimulation is to be used to differentiate experimentally between central and peripheral fatigue. Traditionally, two types of peripheral fatigue have been identified, namely high frequency fatigue (HFF) and low frequency fatigue (LFF) (Jones, 1981; 1996a; 1996b). High frequency fatigue reflects a selective loss of force at high stimulation frequencies and may occur as a result of impaired neuromuscular transmission or impaired propagation of the muscle action potential over the sarcolemma (Edwards, 1978; 1981). Conversely, low frequency fatigue is a specific failure of force generation at low frequencies of stimulation, whereas at high frequencies the tension is close to normal. This form of fatigue has been attributed to a failure of activation of

the muscle despite adequate excitation. Whilst high frequency fatigue can recover within minutes, low frequency fatigue may take several hours or days to recover (Edwards *et al.*, 1977a). A third form of peripheral fatigue has also been identified and is most likely to caused by a reduction in calcium release from the sarcoplasmic reticulum as a consequence of metabolic changes within in the fibre, which in turn has been attributed to the rise of intracellular inorganic phosphate (Allen and Westerblad, 2001; Lamb, 1999; Westerblad *et al.*, 2002). This form of fatigue recovers after a time course of tens of minutes (Allen *et al.*, 1995).

No definitive protocol has been cited in the literature for the assessment of forces elicited by electrical stimulation following dynamic exercise. Furthermore, the degree of fatigue induced by taking successive measurements of neuromuscular electrical stimulation over the immediate recovery period needs to be established. A second problem regarding the use of neuromuscular electrical stimulation is the method of presenting the force data produced at each frequency of stimulation. Traditionally, the force at each frequency has been expressed as a percentage of that generated by stimulation at 100 Hz in fresh muscle (Edwards *et al.*, 1977a). However, it is then not possible to use the 100% value within the statistical analyses, as the data have no variance. Nevertheless, "low frequency fatigue" has also been detected by a reduction in the ratio of forces at 20 and 50 Hz (20:50 Hz ratio) (Edwards *et al.*, 1977a) or 20 and 100 Hz (20:100 Hz ratio) (Brown *et al.*, 1996; Newham *et al.*, 1987; Strojnik and Komi, 1996b), although the reliability of this method has not been reported.

3.4.2 Objectives of the study

The objectives of this study were to determine (i) whether it would be possible to make successive measurements of electrical stimulation over the immediate recovery period of 0, 15, 30, 60 and 120 min without some concomitant effect on the measured variable or significant trial bias, and (ii) the most appropriate method for presenting neuromuscular electrical stimulation data.

3.4.3 Methodology

Four male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. The mean age (± SD), height and body mass of the subjects were 26 ± 2 years, 1.79 ± 0.05 m, and 84.8 ± 15.2 kg, respectively. All the subjects were well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University.

The force produced by neuromuscular electrical stimulation (NMES) of the quadriceps muscles was measured using a strain gauge dynamometer attached to an adjustable chair as previously described. The subjects were seated in the chair and firmly strapped across the chest and waist. In addition, subjects were requested to relax as much as possible and to keep their arms folded across the chest throughout the duration of the electrical stimulation. Subjects were assumed to be relaxed if their force records showed a flat base-line before stimulation, no apparent volitional activation during stimulation, and a smooth and complete return to baseline after stimulation (Binder-Macleod *et al.*, 1995). Force data from the strain gauge were

amplified and collected on-line by an Archimedes 310 Computer via a 12 bit analogue-to-digital converter. A sample frequency of 100 Hz was used for collection of force data produced by electrical stimulation. The data obtained were stored on magnetic discs for later analysis.

Neuromuscular electrical stimulation (NMES) of the quadriceps was evoked using a Digitimer high voltage stimulator (Hertfordshire, UK) (Plate 3.5). Self-adhering neurostimulation electrodes (Chattanooga, USA; 3" x 5") were placed over the vastus medialis muscle distally and the vastus lateralis muscle proximally (Plate 3.6) (McDonnel *et al.*, 1987).

Electrode pad placement was important both for comfort (lack of discomfort) and safety in electrically eliciting a muscle contraction at least 40% of the subject's maximum voluntary isometric contraction force (MVIC). McDonnel *et al.* (1987) have stated that the vastus medialis muscle electrode placement serves to provide medial patella stabilisation during an electrically elicited contraction. Equally, the proximal vastus lateralis muscle electrode placement has been shown to be the best for attaining the highest percentage of MVIC with the least amount of subjective discomfort.

Stimulation occurred with the voltage kept constant at 250 V. Initially, stimulated twitches (1 Hz) were used to locate the optimum site and current for electrical stimulation of the quadriceps (Cooper *et al.*, 1998; Stokes *et al.*, 1988). The current (mA) from the stimulator was then adjusted until at least 40% of the MVIC force was produced during stimulation using a 1 second, 100 Hz pulse.

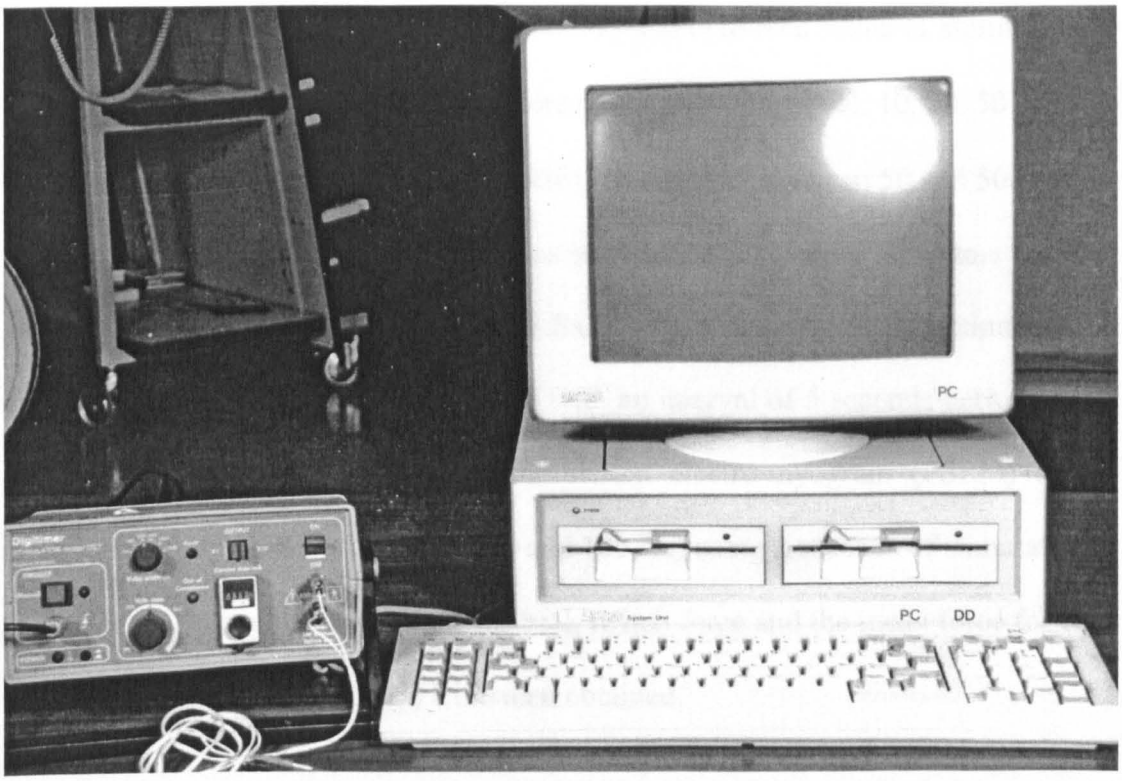


Plate 3.5 Digitimer high voltage stimulator driven by an Amstrad computer.

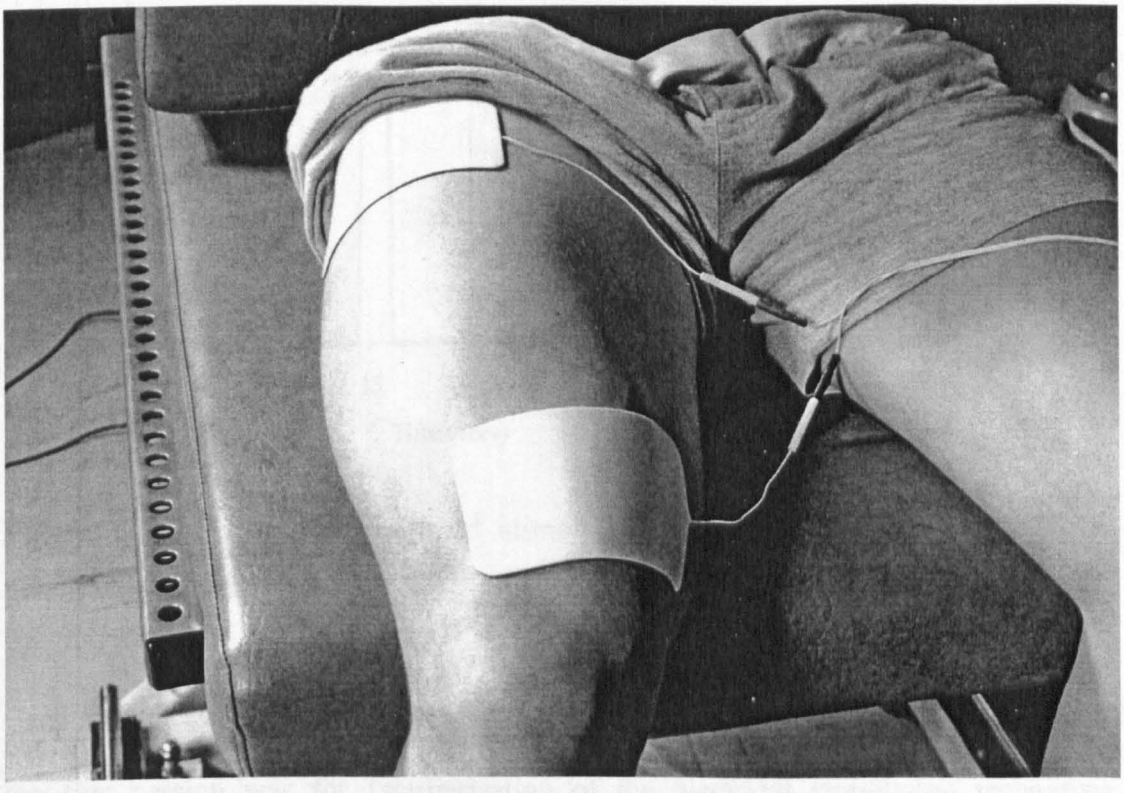


Plate 3.6 Placement of neurostimulation electrodes for measurement of electrically stimulated quadriceps force.

The stimulator was computer driven (Amstrad) and delivered trains of stimuli (pulse width 200μs) in a set pattern of frequencies of 1 Hz (twitch force), 10, 20, 50 and 100 Hz (Cooper *et al.*, 1998; Stokes *et al.*, 1988). A setting of between 50 and 500 micro-seconds is recommended for percutaneous stimulation (Digitimer Operators Manual, 1998). Using the protocol developed by Sale (1997), the muscle was stimulated at each frequency for a period of 2 seconds with an interval of 5 seconds between each stimulation. A typical programmed stimulation electro-myogram (PSEM) of the quadriceps (frequencies of 1, 10, 20, 50 and 100 Hz) using 2 seconds of stimulation is presented in Figure 3.5. The values for peak twitch force and the mean force for each frequency (F_{10}, F_{20}, F_{50}, and F_{100}) were then obtained.

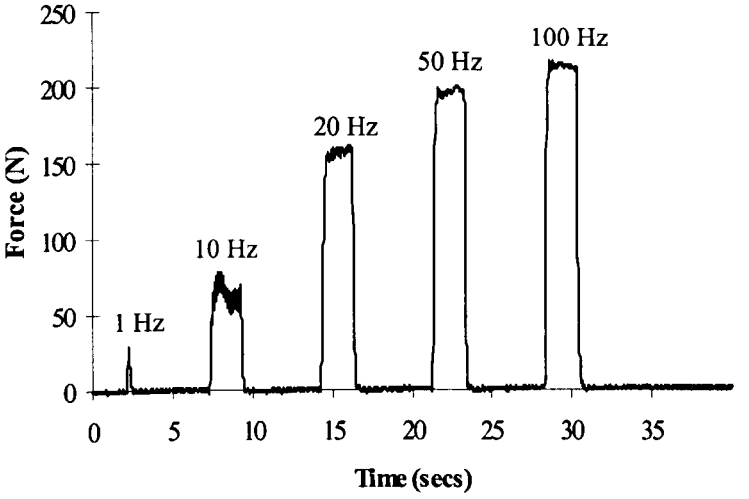


Figure 3.5 Typical programmed stimulation electro-myogram (PSEM) of the quadriceps.

Each subject was required to attend the laboratory on four occasions. The purpose of the first session was for familiarisation of the electrical stimulation techniques. Familiarisation was taken as the consistent production of a smooth plateaued trace recorded during electrical stimulation at each frequency (i.e. 10, 20, 50 and 100 Hz).

To assess the repeatability of the electrical stimulation techniques, subjects were then required to attend on three successive days at the same time of day in order to control for circadian variation (Atkinson and Reilly, 1996). The muscle was stimulated at the time points of 0, 15, 30, 60 and 120 min on day 1 and at 0 min on days 2 and 3 as shown in the design below (Figure 3.6). One week was allowed between familiarisation and the main testing session to ensure full recovery of function (Cooper *et al.*, 1988). A permanent marking pen was used to outline the position of the neuromuscular electrical stimulation electrodes on the muscles (Binder-Macleod and McDermond, 1992). This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999). Additionally, no lower body strength training was allowed before (48 hours) and during the entire experimental period.

	ES	ES	ES	ES	ES
Day 1	0'	15'	30'	60'	120'
Day 2 (after 24 hours)	0'				
Day 3 (after 48 hours)	0'				

Figure 3.6 Protocol to determine the degree of fatigue induced by taking successive measurements of electrical stimulation (ES) at time points in minutes.

Data reduction and statistical methods

Firstly, the force at each frequency was expressed as a percentage of that generated by stimulation at 100 Hz in fresh muscle at time = 0 ($1/100_{t=0}$, $10/100_{t=0}$, $20/100_{t=0}$, etc.) (Edwards *et al.*, 1977a). The percentage values (in relation to 100 Hz at 0 min) for 1 Hz (twitch), 10 Hz, 20 Hz and 50 Hz were compared across each time point

(including t = 0 min) using a one-way ANOVA with repeated measures and also with a correction for 'sphericity' (Vincent, 1999). Tukey's post hoc test of honestly significant differences was used to assess the systematic bias between tests. The mean squared error term from ANOVA was used in the calculation of indicators of absolute reliability (Bland, 1995; Nevill and Atkinson, 1998). Statistical significance was set at $p<0.05$.

The ratio of forces produced at 20 Hz and 50 Hz, and 20 Hz and 100 Hz stimulation frequencies (20:50 Hz and 20:100 Hz ratios respectively) were also calculated and compared across all time intervals using a one-way ANOVA with repeated measures to determine the within-trial error for each ratio. Both these ratios have commonly been used as an index of low-frequency fatigue (Brown *et al.*, 1996; Edwards *et al.*, 1977a; Newham *et al.*, 1987; Strojnik and Komi, 1996b).

The method of expressing data as percent changes to normalise the values and reduce inter-individual variability has commonly been used for both, force produced during a maximum voluntary contraction (Brown *et al.*, 1997), and force elicited by electrical stimulation (Cooper *et al.*, 1988; Skurvydas, 1998). However, inter-individual variability is not a consideration for repeated measures ANOVA designs, therefore all data were also compared as absolute values (Strojnik and Komi, 1998). Using the absolute values also negated the problem of not being able to put the control force value of 100% into the repeated measures ANOVA analyses. Therefore comparisons could be made across all times intervals for all force values.

3.4.4 Results

The absolute force values elicited by 2 seconds of electrical stimulation and the forces expressed as a percentage of that generated by stimulation at 100 Hz in fresh muscle (time = 0 min), are presented in Table 3.22 and Table 3.24 respectively. The mean percentage changes in force produced by electrical stimulation at each frequency are shown in Figure 3.7. The results from the one-way ANOVA with repeated measures for the absolute and relative force values are presented in Table 3.23 and Table 3.25 respectively. Statistical analyses of both sets of data reveal that it is sufficient to use the absolute force values produced by electrical stimulation in a repeated measures ANOVA design.

Although no significant changes were observed in the forces produced at each stimulation frequency (Table 3.23), it was evident that large decreases occurred in the twitch force and also the force produced by stimulation at 10 Hz, even though the subjects had not performed any exercise. The mean decline in force produced at 10 Hz after fifteen minutes was 16%, although there was a progressive recovery over the subsequent time intervals.

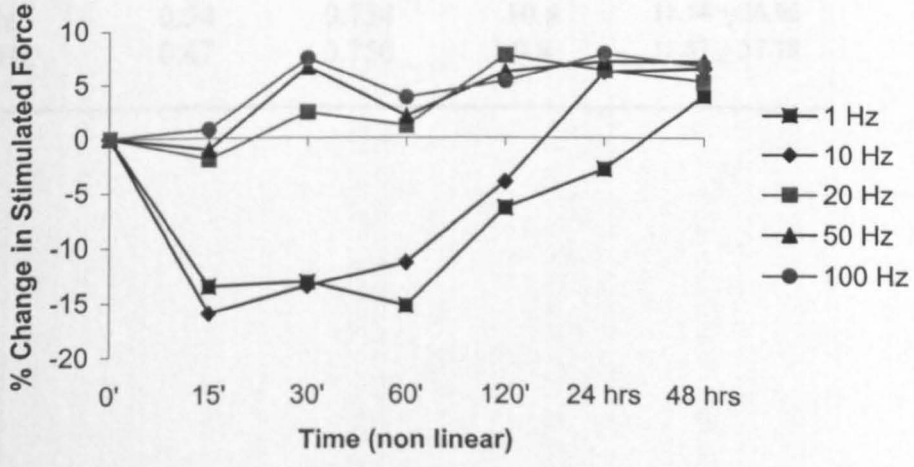


Figure 3.7 Mean percentage changes (n = 4) in stimulated quadriceps force using 2 seconds of stimulation.

TABLE 3.22 Mean (± SD) forces (N) produced by electrical stimulation for n = 4 subjects (absolute force values). The quadriceps muscles were stimulated for 2 seconds at each frequency.

	0 min	15 min	30 min	60 min	120 min	24 hours	48 hours
1 Hz	27.0	22.9	21.1	21.8	24.2	26.4	26.6
	(13.1)	(10.2)	(10.7)	(8.74)	(9.61)	(12.9)	(11.4)
10 Hz	61.2	51.4	52.3	50.3	57.1	63.5	60.3
	(34.1)	(28.1)	(28.0)	(21.4)	(31.5)	(35.6)	(29.6)
20 Hz	131.6	127.0	130.2	127.1	136.9	137.1	133.1
	(47.2)	(39.0)	(34.2)	(27.7)	(36.7)	(40.7)	(33.3)
50 Hz	176.8	173.2	183.0	173.6	183.6	184.6	182.4
	(60.9)	(53.9)	(49.2)	(34.5)	(53.6)	(46.3)	(40.2)
100 Hz	191.1	192.8	201.8	192.7	198.4	202.8	197.4
	(64.6)	(66.2)	(59.7)	(42.2)	(58.9)	(55.9)	(43.3)

TABLE 3.23 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for forces (absolute values) elicited by electrical stimulation.

	Absolute force values			
	F-value	P-value	CV_{trial} (%)	Limits of Agreement (N)
1 Hz	2.38	0.072	15.6	6.34 ± 7.52
10 Hz	1.13	0.383	25.0	14.14 ± 23.35
20 Hz	0.61	0.632	11.5	25.04 ± 29.73
50 Hz	0.54	0.734	10.5	31.14 ± 36.96
100 Hz	0.47	0.750	9.8	31.83 ± 37.78

TABLE 3.24 Mean (± SD) changes in electrically stimulated force (from Table 3.20). Values are expressed as a percentage of that generated by stimulation at 100 Hz in fresh muscle at time = 0.

	0 min	15 min	30 min	60 min	120 min	24 hours	48 hours
1 Hz	13.8	11.9	12.0	11.4	12.5	13.4	13.9
	(4.88)	(4.05)	(4.56)	(3.05)	(2.73)	(4.40)	(4.11)
10 Hz	30.4	25.7	26.2	25.8	28.3	31.4	31.4
	(10.6)	(9.73)	(9.44)	(5.51)	(7.29)	(8.74)	(12.4)
20 Hz	68.5	67.2	69.9	69.0	73.0	72.5	71.9
	(8.68)	(10.8)	(12.4)	(13.1)	(8.07)	(7.40)	(14.4)
50 Hz	92.2	91.2	97.9	93.9	97.5	98.5	98.4
	(3.59)	(3.89)	(15.0)	(13.7)	(10.2)	(8.85)	(15.6)
100 Hz	**100%**	100.8	107.4	103.7	105.2	107.8	106.7
		(2.37)	(15.3)	(13.0)	(10.2)	(7.85)	(17.7)

TABLE 3.25 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for forces (values / 100 $Hz_{t=0}$) elicited by electrical stimulation.

	Force values / 100 $Hz_{t=0}$			
	F-value	P-value	CV_{trial} (%)	Limits of Agreement (%)
1 Hz	2.16	0.096	15.2	3.19 ± 3.78
10 Hz	1.34	0.327	22.5	10.57 ± 12.55
20 Hz	0.67	0.673	10.8	12.53 ± 14.88
50 Hz	0.73	0.596	11.0	17.38 ± 20.63

The ratio of forces produced at 20 Hz and 50 Hz, and 20 Hz and 100 Hz stimulation frequencies are shown in Figure 3.8. No significant changes were observed in the stimulation force ratios over the measured time intervals. The results for the one way ANOVA with repeated measures, the coefficients of variation and the limits of agreement for the 20:50 Hz and 20:100 Hz ratios are presented in Table 3.26.

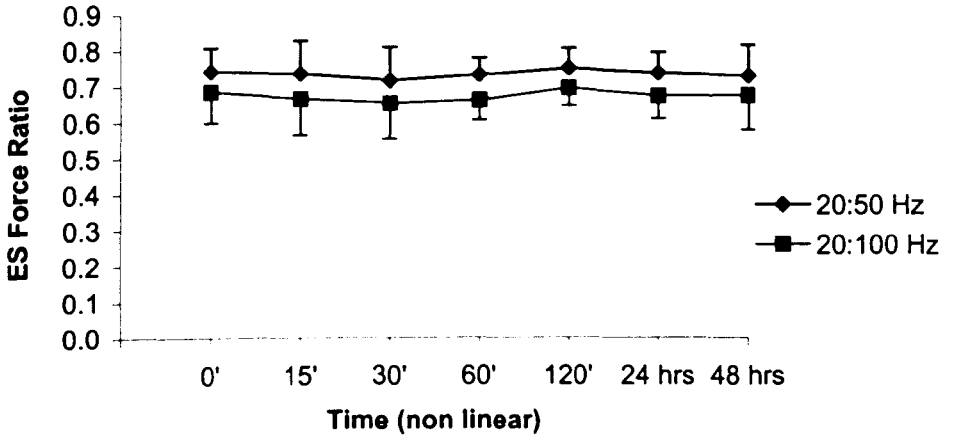


Figure 3.8 20:50 Hz and 20:100 Hz Ratios (mean and SD) following no exercise (n = 4) using 2 seconds of stimulation.

TABLE 3.26 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for 20:50 Hz and 20:100 Hz ratios over the time intervals of 0, 15, 30, 60 and 120 minutes, and after 24 and 48 hours.

	F-value	P-value	CV_{trial} (%)	Limits of Agreement
20:50 Hz	0.55	0.717	5.5	0.067 ± 0.079
20:100 Hz	0.82	0.568	6.5	0.072 ± 0.086

3.4.5 Discussion

It has previously been shown that results obtained by sub-maximal stimulation give a reliable estimate of the function of the whole muscle (Edwards *et al.*, 1977a). Considering the day-to-day variation, the control of muscle temperature is not a problem when studying a large muscle groups such as the quadriceps (Edwards *et al.*, 1977b). The objectives of this study were to determine (i) whether it would be possible to make successive measurements of electrical stimulation over the immediate recovery period of 0, 15, 30, 60 and 120 min without some concomitant effect on the measured variable or significant trial bias, and (ii) the most appropriate method for presenting neuromuscular electrical stimulation data. Using this information to establish the reliability of the neuromuscular electrical stimulation technique means that the recovery in force at the different stimulation frequencies following resistance exercise, can be assessed over the immediate 2 hour recovery period as well as after 24 and 48 hours. The decrements in force are then attributable to the exercise model.

Although there were no significant trial effects for any of the frequencies of stimulation, the coefficients of variation for the twitch force and the force produced at 10 Hz, were notably larger than for the other frequencies of stimulation. Edwards *et al.* (1977a) definitively stated that the twitch force is an unreliable measure of the state of fatigue. The authors explained that as the peak force in a twitch is only about one tenth of the tetanic force, the mechanical response is critically sensitive to a change in the amount of activation per pulse. Even in fresh muscle, the activation per pulse can vary over a wide range.

Nevertheless, an isometric twitch (1 Hz) has frequently been used as an indicator of muscle fatigue, providing information about the number of active cross-bridges. Bigland-Ritchie *et al.* (1983), Hainaut and Duchateau (1989) and Strojnik and Komi (1998) all clearly demonstrated a decrease in twitch force in humans, although the recovery of twitch tension can be very rapid, taking approximately 2 minutes (Thompson *et al.*, 1992). Therefore as muscle function in the present study will be assessed 5 minutes after the exercise session, the twitch force immediately after the workout might be lower than the twitch force which will be measured. Two other common variables of the twitch force are maximum twitch rate of force development and twitch half force relaxation time (Strojnik and Komi, 1998; Skurvydas, 1998), although due to the low sampling frequency (100 Hz) used in the present study, and the high variability of the single twitch force, these variables will not be analysed.

The coefficient of variation for the force produced at 10 Hz (where complete tetanus does not occur), was 25.0% when calculated from the absolute force values and 22.5% when expressed as the percentage of the force generated by 100 Hz at time t = 0. This may possibly explain why data are not often published for force produced at this frequency (Brown *et al.*, 1996; Jereb and Strojnik, 1995, Strojnik and Komi, 1998). Therefore this frequency of stimulation will not be considered for future studies. The coefficients of variation for the other frequencies of stimulation were more in keeping with the deemed acceptable limit of 10% variation.

When comparing recovery of the forces produced at the different stimulation frequencies, Edwards *et al.*, (1977a) reported that following fatiguing activity, that the ensuing muscle weakness recovered rapidly (within 30 minutes) when the muscle was

tested at high frequencies of stimulation (e.g. 50 Hz), but if the muscle was tested at low frequencies of stimulation (e.g. 20 Hz), then the developed force was reduced substantially, and this deficit took several days to recover. The authors added that this "low-frequency fatigue" may be detected by a reduction in the ratio of forces at 20 and 50 Hz (20:50 Hz ratio). Similarly, Newham *et al.* (1987) measured the ratio of forces produced using 20 Hz and 100 Hz stimulation frequencies post eccentric exercise, demonstrating a progressive recovery following the exercise. Brown *et al.* (1996) following stimulated eccentric exercise, and Strojnik and Komi (1996b) during prolonged stretch-shortening cycle exercise have also used the 20:100 Hz ratio as an assessment for low-frequency fatigue. The results from the present study indicate that the calculation of these ratios is a reliable method of assessing peripheral fatigue.

Edwards *et al.* (1977a) state that the ratio of the forces obtained at the two test frequencies not only emphasises the difference between high and low frequencies, but also avoids the complication of not knowing what value to use for the control force. However the statistical analyses from the present study clearly indicate that it is not a problem in using the absolute force values produced by electrical stimulation in a repeated measures ANOVA design. By comparing the absolute changes in forces elicited by electrical stimulation with the maximum voluntary contraction force and their time-course can identify whether there is any central limitation of the contraction process (Bigland-Ritchie and Woods, 1984).

3.4.6 Conclusions and recommendations

With regards objective (i), the results of this study proved that it is possible to make successive measurements of electrical stimulation over the immediate recovery period of 0, 15, 30, 60 and 120 min without any significant trial bias. Furthermore, the reliability of measurements was sufficient to allow peripheral fatigue to be assessed after 24 and 48 hours. Although not statistically significant, the measurement error for the forces produced from a single twitch and 10 Hz was very large and therefore these variables will not be considered for future studies.

Further, subjective responses from each subject suggested that 2 seconds of stimulation at each frequency was too long as they began to feel some discomfort under the medial electrode after the initial 2 hour period. It is therefore recommended for future studies that the duration of stimulation should be reduced to 1 second at each frequency. The interval between each stimulation will be maintained at 5 seconds.

With regards objective (ii), it is also possible to use the absolute force values in the repeated measures ANOVA design, rather than expressing the values as a percentage of the force produced in fresh muscle at 100 Hz. This therefore eliminates the problem of not being able to analyse the forces produced at 100 Hz across all time intervals.

3.5 Study 1D: Assessment of the systematic bias caused by the successive measurements of maximum voluntary contraction force and the force elicited by electrical stimulation

3.5.1 Rationale for the study

The first step in the investigation of neuromuscular fatigue is to establish whether the reduction in the expected or required force output is due to a failure of neural drive (central fatigue or fatigue 'in the mind') rather than in the muscle (peripheral fatigue) (Edwards, 1978). Central fatigue has commonly been detected by comparing the decreases in voluntary force with that developed by neuromuscular electrical stimulation of the same muscle (Bigland-Ritchie and Woods, 1984).

From Study 1A, it was established that the average of two measurements of maximum voluntary isometric contraction force is sufficient to obtain within-session and between-day reliability, and thus provide a comprehensive assessment of lower limb neuromuscular fatigue variables. Study 1B established that performing two maximal voluntary contractions at the time intervals of 0, 15, 30, 60 and 120 minutes does not have a concomitant influence on selected neuromuscular performance variables. In Study 1C, it was determined that stimulating the muscle at the time intervals of 0, 15, 30, 60 and 120 minutes allows sufficient recovery to prevent significant fatigue effects. Furthermore, the reliability of the force elicited by electrical stimulation is sufficient to allow peripheral fatigue to be assessed after 24 and 48 hours. For the final study it is therefore necessary to establish that it is possible to take both sets of measurements together.

3.5.2 Objective of the study

The objective of this study was to determine whether it would be possible to make successive measurements of maximum voluntary contraction and electrical stimulation over the immediate recovery period of 0, 15, 30, 60 and 120 min without some concomitant effect on the measured variables or significant trial bias.

3.5.3 Methodology

Seven male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. The mean ($\pm$ SD) age, height and body mass of the subjects were 25 $\pm$ 3 years, 1.78 $\pm$ 0.05 m, and 77.7 $\pm$ 5.74 kg, respectively. All the subjects were well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University.

The force generated by the quadriceps femoris muscles of the right leg was measured using the strain gauge dynamometer as described in detail above. A sample frequency of 1000 Hz was used for the collection of force and electromyographical data from the maximal voluntary contractions and a sample frequency of 100 Hz was used for collection of force data elicited by electrical stimulation. All data obtained were stored on magnetic discs and stored for later analysis.

Subjects were initially required to perform two maximal voluntary contractions with surface electromyographic (EMG) activity being simultaneously recorded from the vastus lateralis (VL) muscle of the right leg as described previously. Data were

recorded for peak force and the average rate of force development (RFD_{avg}) (Viitasalo *et al.*, 1980). Root mean square (RMS) and median frequency (MDF) values were determined from the raw myoelectrical signal (Bartlett, 1996; Basmajian and De Luca, 1985). RMS values were calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998). The MDF was determined as described in Study 1A.

A 15 minutes recovery period was allowed prior to electrical stimulation, designated as time = 0 min. Neuromuscular electrical stimulation (NMES) of the quadriceps was evoked using a Digitimer high voltage stimulator (Hertfordshire, UK) as described in Study 1C. The Programmed Stimulation Electro-Myogram test protocol involved electrically stimulating the muscle in a set pattern of frequencies of 20, 50 and 100 Hz. The muscle was stimulated at each frequency for a period of 1 second with an interval of 5 seconds between each stimulation. The mean force for each frequency (F_{20}, F_{50}, and F_{100}) was then obtained. Electrical stimulation was followed by the measurement of maximal voluntary neural activation and force production after a 1 minute recovery. The subjects were required to perform two maximal contractions and the time interval between maximal efforts was 1 minute. The test protocol is illustrated in Figure 3.9.

Each subject was required to attend the laboratory on four occasions. The purpose of the first session was for familiarisation of the experimental techniques. A period of one week was allowed between familiarisation and the experimental session. Subjects were then required to attend on three successive occasions at the same time on each testing day to control for circadian variation (Atkinson and Reilly, 1996). A

permanent marking pen was used to outline the position of the EMG and electrical stimulation electrodes on the muscles. This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999). Additionally, no lower body strength training was allowed before (48 hours) and during the entire experimental period.

TIME	ACTIVITY/MEASURE
- 15 min	MVC with simultaneous recording of surface EMG (Base-line)
0 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 15 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 30 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 60 min	NMES followed by MVC with simultaneous recording of surface EMG
+120 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 24 hrs	NMES followed by MVC with simultaneous recording of surface EMG
+ 48 hrs	NMES followed by MVC with simultaneous recording of surface EMG

Figure 3.9 Protocol to determine the degree of fatigue induced by taking successive measurements of both maximum voluntary isometric force and the force elicited by electrical stimulation.

Data reduction and statistical methods

With regards to the voluntary efforts, the averages of the two maximum isometric contractions at each time interval were calculated for each neuromuscular performance variable (Viitasalo *et al.*, 1980) and compared across each time point using one-way ANOVA with repeated measures and also with a correction for 'sphericity' (Vincent, 1999). Tukey's post hoc test of honestly significant differences was used to assess the systematic bias between tests. The mean squared error term from ANOVA was used in the calculation of indicators of absolute reliability (Bland, 1995; Nevill and Atkinson, 1998). The absolute mean force values produced at 20, 50 and 100 Hz (F_{20}, F_{50}, and F_{100}) were analysed using one-way ANOVA with repeated measures across all time intervals (including 0 min) as described for the voluntary contractions. Statistical significance was set at $p<0.05$.

3.5.4 Results

The means (± SD) of the averages of the two contractions for the neuromuscular performance variables are presented in Table 3.27. The one-way ANOVA with repeated measures revealed a significant trial effect for the amplitude of the EMG signal, determined between 1500-2500 ms (Table 3.28). However, when data were analysed over the first two hour period (and not after 24 and 48 hours), no significant trial effect was observed.

The coefficients of variation for within-trial measurements for maximum isometric force (4.5%) and average rate of force development (8.6%) were below the acceptable limit of 10%. Interestingly, these coefficients of variation and the values for systematic bias are lower than those determined when maximum voluntary contraction was measured separately in Study 1B. The coefficients of variation for EMG values expressed between 500-1500 ms and 1500-2500 ms (even including data for 24 and 48 hours) were also within the acceptable limit, 9.5% and 7.1% respectively. On the other hand, the coefficient of variation for the amplitude of the signal calculated between 0-500 ms was 13.2%, whereas in Study 1B, it was only 9.6%.

TABLE 3.27 Mean (± SD) of the neuromuscular performance variables recorded over the time intervals of base-line, 0, 15, 30, 60 and 120 minutes, and after 24 and 48 hours for n = 7 subjects.

	Base-line	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs
Force variables								
MVC (N)	620.9	613.9	608.5	604.3	606.7	602.3	620.0	628.7
	(67.64)	(68.67)	(65.06)	(63.01)	(59.03)	(72.60)	(64.31)	(61.31)
RFD_{avg} ($N.s^{-1}$)	3041	2850	2934	2858	2882	2856	2952	3089
	(679.9)	(659.4)	(452.5)	(611.6)	(521.1)	(629.3)	(563.1)	(502.1)
EMG variables								
RMS values								
(Arbitrary Units)								
0-500 ms	1.353	1.372	1.345	1.368	1.423	1.425	1.330	1.394
	(0.266)	(0.195)	(0.189)	(0.267)	(0.246)	(0.210)	(0.197)	(0.314)
500-1500 ms	1.492	1.501	1.456	1.486	1.464	1.474	1.406	1.531
	(0.260)	(0.188)	(0.170)	(0.216)	(0.205)	(0.232)	(0.194)	(0.279)
1500-2500 ms	1.530	1.488	1.464	1.456	1.506	1.497	1.407	1.576
	(0.247)	(0.205)	(0.214)	(0.217)	(0.214)	(0.216)	(0.204)	(0.230)
MDF (Hz)	58.15	57.59	57.59	57.73	57.38	56.05	57.17	56.05
	(5.54)	(3.68)	(2.52)	(4.56)	(5.03)	(3.91)	(3.76)	(4.99)

TABLE 3.28 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for the neuromuscular performance variables (from Table 3.28) when combined with electrical stimulation.

	F-value	P-value	CV_{trial} (%)	Limits of Agreement
Force variables				
MVC (N)	1.57	0.206	4.5	33.48 ± 54.08
RFD_{avg} ($N.s^{-1}$)	1.82	0.150	8.6	306.0 ± 494.3
EMG variables				
RMS values				
(Arbitrary Units)				
0-500 ms	0.53	0.624	13.2	0.220 ± 0.356
500-1500 ms	0.96	0.448	9.5	0.170 ± 0.275
1500-2500 ms	3.22	0.025*	7.1	0.128 ± 0.207
MDF (Hz)	0.61	0.651	6.4	4.44 ± 7.18

* $p<0.05$

The mean absolute force values produced at 20 Hz, 50 Hz and 100 Hz are presented in Table 3.29. The mean percentage changes in force elicited by electrical stimulation at each frequency are shown in Figure 3.10. Progressive decreases in the forces elicited at each frequency occurred over the first thirty minutes of recovery. For stimulation at 20 Hz (i.e. low frequency of stimulation), a 10.8% decrease in force output was observed. For the high stimulation frequencies (50 Hz and 100 Hz), the decreases were approximately 5%. The forces elicited at each stimulation frequency then recovered whereby for stimulation at 20 Hz, the mean increase in force after 48 hours was 15.3% greater than at time = 0 min. The one-way ANOVA with repeated measures established that there were significant trial effects when data were compared across all 7 time points (Table 3.30) and even when data after 24 and 48 hours were excluded from the analysis (Table 3.31).

When analysing the data over the immediate recovery period (the first five time points), post hoc analysis revealed that the decline in 20 Hz force after 30 minutes compared to base-line was significant ($p<0.05$; $HSD_{0.05} = 15.45$ N). For the simulation frequency of 50 Hz, the force produced at 30 minutes was significantly less than the forces produced at 60 and 120 minutes respectively ($HSD_{0.05} = 22.17$). Similarly, for the stimulation frequency of 100 Hz, the force produced at 30 minutes was significantly less than the forces produced at 60 and 120 minutes respectively ($HSD_{0.05} = 20.13$).

TABLE 3.29 Mean (± SD) forces (N) produced by electrical stimulation for n = 7 subjects (absolute values). The quadriceps muscles were stimulated for 1 second at each frequency.

	0 min	15 min	30 min	60 min	120 min	24 hours	48 hours
20 Hz	185.1	173.3	164.6	175.7	178.6	199.4	210.7
	(39.0)	(37.2)	(35.0)	(28.5)	(42.0)	(49.0)	(34.8)
50 Hz	265.3	257.6	250.9	273.3	278.8	269.4	285.9
	(57.5)	(56.0)	(49.9)	(45.5)	(59.4)	(61.9)	(55.9)
100 Hz	288.0	281.4	271.0	294.7	298.5	288.3	308.2
	(57.0)	(57.1)	(50.0)	(46.6)	(60.0)	(62.6)	(61.1)

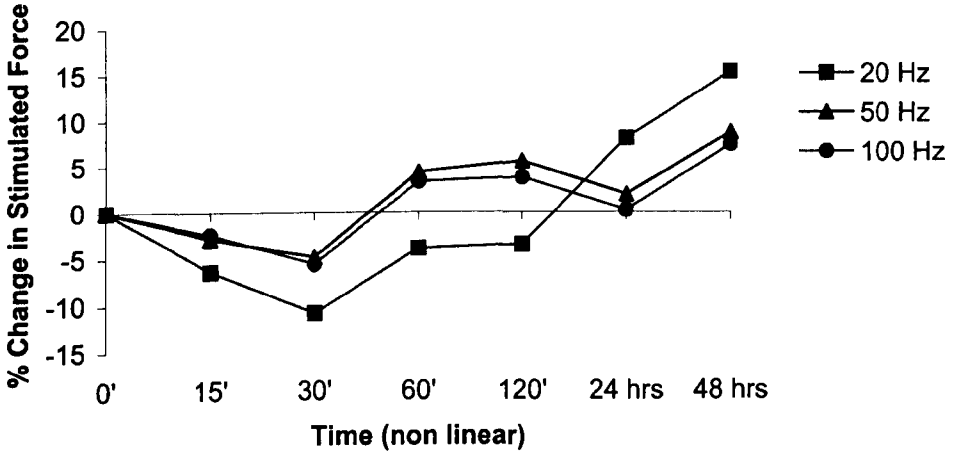


Figure 3.10 Mean percentage changes (n = 7) in stimulated quadriceps force when combined with subsequent measurements of maximum voluntary isometric force.

TABLE 3.30 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for force produced by electrical stimulation at 20, 50 and 100 Hz (from Table 3.29) over the time intervals of 0, 15, 30, 60 and 120 minutes, and after 24 and 48 hours.

	F-value	P-value	CV_{trial} (%)	Limits of Agreement
20 Hz	8.03	0.000*	11.5	25.21 ± 41.45
50 Hz	3.40	0.009*	8.2	26.26 ± 43.19
100 Hz	3.25	0.012*	8.6	29.73 ± 48.88

* $p<0.05$

TABLE 3.31 One-way ANOVA with repeated measures, coefficients of variation and 95% 'limits of agreement' (systematic bias ± random error) for force produced by electrical stimulation at 20, 50 and 100 Hz (from Table 3.29) over the time intervals of 0, 15, 30, 60 and 120 minutes.

	F-value	P-value	CV_{trial} (%)	Limits of Agreement
20 Hz	4.09	0.011*	7.9	15.45 ± 27.17
50 Hz	4.50	0.007*	7.5	22.17 ± 38.98
100 Hz	5.11	0.004*	6.3	20.13 ± 35.40

3.5.5 Discussion

The results from the present study show that there is no significant trial bias (due to leaning or fatigue) for either MVC or RFD_{avg} when measurements are taken over the immediate recovery period, at the time intervals of 0, 15, 30, 60, 120 min, and after 24 and 48 hours. Furthermore the values calculated for systematic bias (Table 3.28) are actually smaller for both MVC and RFD_{avg} than the respective values calculated in Study 1B. The absence of any learning effect or super-compensation training effect (Zatsiorsky, 1995) for data produced after 24 or 48 hours should also be noted.

On the other hand, close examination of the data, suggests that taking successive measurements of two voluntary contractions at each time interval (over the immediate recovery period) has a small concomitant influence on the measured neuromuscular performance variables. Indeed the data reflect a trend of a gradual decrease in maximum voluntary isometric force and rate of force development. The decrements in neuromuscular performance can possibly be explained by the phenomena of 'post-lunch' or midday dip. The subjects in the present study were tested between 1300 and 1500 hours. Wit (1980) has demonstrated that when isometric strength of the knee extensors is measured consecutively during the waking hours of the solar day, 2 diurnal peaks are evident; one at the end of the morning, and another in the late afternoon/evening. Performance transiently declines between these times of the day. Atkinson and Reilly (1996) however, have stated that it is difficult to separate a true time of day effect from influences arising from the experimental protocol. The decline in performance in Study 1B and Study 1D may be a consequence of a fall in motivation arising from the high number of serial measurements that have been performed, which could occur at any time of day. For example, measurements are

taken at five time points in the protocol described above in the two hour recovery period. Nevertheless, Atkinson (1994) has demonstrated that when isometric strength measures are recorded under an optimal experimental protocol (Atkinson and Reilly, 1996), which allows sufficient recovery between test sessions without disturbing sleep, post midday decrements in performance are still evident.

Similarly, in the investigation completed above, when measurements of maximum voluntary isometric force are combined with measurements of force elicited by electrical stimulation, large decreases in electrically stimulated force are observed. This is especially evident for the force produced at the low frequency of stimulation, 20 Hz where a decrease of 15% occurred within the first 30 minutes period, although then recovered. This trend was similar for the forces elicited at the high frequencies of stimulation, 50 Hz and 100 Hz.

The mechanisms of central fatigue and therefore motivation are eliminated by the use of electrical stimulation (Bigland-Ritchie and Woods, 1984), therefore decreases in force production are likely to be explained by mechanisms of peripheral fatigue or time of day effects (Atkinson, 1994; Atkinson and Reilly, 1996). Although it may be difficult to distinguish between time of day and fatigue effects, it is important to note that no significant decreases in electrical stimulation force were observed when the muscle was stimulated in Study 1C without the measurement of maximum voluntary contractions. It therefore seems more likely that the decreases in force are explained by the experimental protocol causing fatigue.

3.5.6 Conclusions and recommendations

Taking measurements of both maximal force and force elicited by electrical stimulation at the time intervals of 0, 15 and 30 minutes is too frequent as the experimental protocol appears to be inducing fatigue. This is particularly evident for the forces elicited by electrical stimulation, and in particular at low frequencies of stimulation. Consequently, for future study, it is recommended that measurements are not taken 15 minutes after the exercise session. It can also been seen that the curves for 50 Hz and 100 Hz are very similar and therefore the forces produced at 50 Hz will not be measured in the future studies.

3.6 General discussion

Considering maximum voluntary contraction force, the average of two contractions is sufficient to obtain within-session and between-day reliability. Equally performing two contractions at each time interval does not have any significant trial effect on either peak force, average rate of force development, amplitude of the EMG signal calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms, and MDF. On the other hand, the variability of the measurements, RFD_{max}, F_{30} and I_{100}, electromechanical delay, and the amplitude of the EMG signal calculated for the time period of 0-100 ms was too high for these variables to be considered for future studies.

It is also important to remember that at each time interval the pre-contraction instructions must be reinforced clearly and concisely in addition to the verbal encouragement given during the contraction. It was noticeable on several occasions that some subjects were lifting in the chair, gaining extra leverage and extra force production from the use of the hip extensor muscles. It is therefore recommended that a third strap should be tightly fastened at the top of the thighs to prevent the subject gaining any mechanical advantage.

Regarding the forces elicited by electrical stimulation, it was demonstrated in Study 1C, that the measurement error for the twitch force and the force produced at the stimulation frequency of 10 Hz was too high for these variables to be considered for future studies. From Study 1D, due to the evidence of significant trial bias, it may be more appropriate that measurements are taken 0, 30, 60 and 120 minutes post exercise. From Study 1C, subjects expressed some discomfort when stimulating the

muscle for 2 seconds at each frequency of stimulation. For Study 1D, the duration of stimulation was reduced to 1 second, although the interval between was maintained at 5 seconds.

Also discussed in Study 1C was the problem of presenting the force data elicited by electrical stimulation. Traditionally, the force at each frequency has been expressed as a percentage of that generated by stimulation at 100 Hz in fresh muscle (Edwards *et al.*, 1977a). However this method does not allow for the control force value of 100% to be entered into the repeated measures ANOVA analyses. However the results from Study 1C clearly indicate that it is not a problem to use the absolute force values produced by electrical stimulation in a repeated measures ANOVA design. "Low frequency fatigue" assessments have also been made by using either the 20:50 Hz (Edwards *et al.*, 1977a) or 20:100 Hz ratios (Brown *et al.*, 1996; Newham *et al.*, 1987). These ratios are believed to not only emphasise the difference between high and low frequencies, but also avoid the complication of not knowing quite what value to use for the control force. However if similar decreases in force were to be observed at both the low and high frequency following the exercise session, then the nature of the fatigue mechanisms would not be revealed by either of the 20:50 Hz or 20:100 Hz ratios. Therefore changes in the forces elicited by electrical stimulation will be compared using the absolute force values. As data are similar for 50 Hz and 100 Hz, 50 Hz will not be used for future studies.

3.7 Recommendations for future studies

(i) To assess the decreases in maximum voluntary neural activation and force production, the average of two contractions will be taken at each time interval.

(ii) Measures of maximal force will be taken 1 minute after electrical stimulation.

(iii) For electrical stimulation, trains of stimuli will be delivered in a set pattern of frequencies of 20 Hz and 100 Hz. The muscle will be stimulated at each frequency for a period of 1 second with an interval of 5 seconds between each stimulation.

(iv) Muscle responses will be assessed at the time intervals of 0, 30, 60 and 120 min and also after 24 and 48 hours following the exercise session.

CHAPTER 4

NEUROMUSCULAR AND METABOLIC CHARACTERISTICS OF FATIGUE IN RESPONSE TO HEAVY RESISTANCE AND DYNAMIC STRENGTH EXERCISE IN SUBJECTS ENGAGED IN TEAM SPORTS

4.1 Background to the study

The ability of the muscles to develop high force in short periods of time and hence produce high limb acceleration is critical for success in many sports, and may even be more important than maximum force production capability (Wilson, 1992). It has been discussed that both heavy resistance exercise and dynamic strength exercise can develop intra-muscular coordination and therefore enhance speed-strength characteristics. However it has been suggested that heavy loads are superior (Schmidtbleicher and Buehrle, 1987) due to the significantly longer time under tension (Keogh *et al.*, 1999).

Whilst the acute neuromuscular fatigue and short-term recovery characteristics from fatigue has received particular attention after heavy resistance exercise (Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1988), less information is available after explosive type strength loading (e.g. Linnamo *et al.*, 1998), although fatigue after this type of loading does tend to recover quicker. Further no data are apparent for dynamic strength exercise, a form of resistance exercise commonly used by players engaged in team sports.

It would therefore be of interest to examine whether the fatigue and recovery characteristics would be the same following dynamic strength exercise compared to heavy resistance exercise. The results of such an investigation will have implications for players engaged in team sports as to the optimal recovery required before a subsequent training session and the choice of resistance exercise session preceding a game.

4.2 Introduction

Neuromuscular fatigue is defined as a failure to generate the required or expected force or power output during sustained or repeated contractions (Edwards, 1981). This failure becomes apparent quite quickly after the onset of intense activity (Häkkinen, 1993; 1994a). Following the activity, a sustained weakness may persist for several days, which will consequently have an effect on subsequent training or competitive performance. Two types of fatigue are identified, namely central fatigue, an impairment in the central nervous system, and peripheral fatigue, an impairment beyond the neuromuscular junction (Edwards, 1981).

Players engaged in team sports (e.g. rugby) regularly use forms of resistance training for the development of maximal peak force (strength) and rate of force development. Establishing the nature of fatigue after a particular type of resistance exercise, as well as its time course of recovery, is of vital importance for the training optimisation of an individual player. Indicators of the mechanisms involved in the fatigue process may be identified by changes in any of the neuromuscular parameters measured after a workout (Strojnik and Mesesnel, 1994).

4.2.1 Objective of the study

The objective of this study was to quantify the acute neuromuscular and metabolic responses to heavy resistance and dynamic strength exercise in subjects engaged in team sports over the immediate recovery period of 0-2 hours as well as after rest for 24 and 48 hours.

4.3 Methodology

4.3.1 Subjects

Eight male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. All subjects engaged regularly in sports such as rugby league, rugby union and soccer, and had over one year's experience of weight training. Each subject was well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University. However, during the course of the study, one subject withdrew as he found the technique of electrical stimulation caused too much discomfort, whereas the other subject withdrew because of the commitment required to complete the extensive experimental design. The mean ($\pm$ SD) age, height and body mass of the six remaining subjects were 22 $\pm$ 3 years, 1.76 $\pm$ 0.04 m, and 78.8 $\pm$ 12.3 kg, respectively.

4.3.2 Experimental design

The experimental design comprised of two different loading sessions: (1) heavy resistance exercise (HRE) and (2) dynamic strength exercise (DSE). Measurements of neuromuscular electrical stimulation (NMES) of the quadriceps muscle were recorded before the exercise session and immediately (5 minutes) after the session. The same measurements were also repeated during the recovery period at intervals of 30, 60 and 120 minutes as well as after 24 and 48 hours. Measurements of maximal voluntary neural activation and force production were also recorded at the same time intervals, 1 minute after electrical stimulation in each case. The testing session always took place

at the same time of day from either 9.00 to 12.00h or 14.00 to 1700h to control for circadian variation (Atkinson and Reilly, 1996). The test protocol followed the format as illustrated in Figure 4.1.

TIME	ACTIVITY/MEASURE
BEFORE EXERCISE	
+ 0 min	Base-line blood sample and muscle soreness
+ 15 min	NMES followed by MVC with simultaneous recording of surface EMG
	Exercise session, either HRE, DSE or No Exercise. Rating of perceived exertion (RPE) recorded after each set
AFTER EXERCISE	
+ 3 min	Muscle soreness and blood sample
+ 5 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 30 min	Blood sample
	NMES followed by MVC with simultaneous recording of surface EMG
+ 60 min	NMES followed by MVC with simultaneous recording of surface EMG
+ 120 min	Muscle soreness and blood sample
	NMES followed by MVC with simultaneous recording of surface EMG
+ 24 hrs	Muscle soreness, blood sample, NMES and MVC (EMG)
+ 48 hrs	Muscle soreness, blood sample, NMES and MVC (EMG)
+ 72 hrs	Muscle soreness
+ 96 hrs	Muscle soreness
+ 120 hrs	Muscle soreness

Figure 4.1 Protocol to determine the fatigue and recovery characteristics in response to heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

4.3.3 Experimental procedures

4.3.3.1 Strength training sessions

The exercises used in the present study were a back squat lift for HRE, and a loaded counter-movement vertical jump for DSE. For the back squat lift illustrated in Plate 4.1, the subject holds the loaded barbell on the shoulders and bends the knees to a low squat position and thereafter stands up with the loaded barbell back to the standing position. The range of motion about the knee joint was 2.1 rad (120^{o}) to 3.14 rad (180^{o}) (Wilson *et al.*, 1993). The loads were monitored such that fatigue always occurred on the last repetition. Although the loads lifted were heavy and the actual movement velocity was low, each subject was instructed to move the bar as quickly as possible, such that the intended movement velocity was high (Behm and Sale, 1993b).

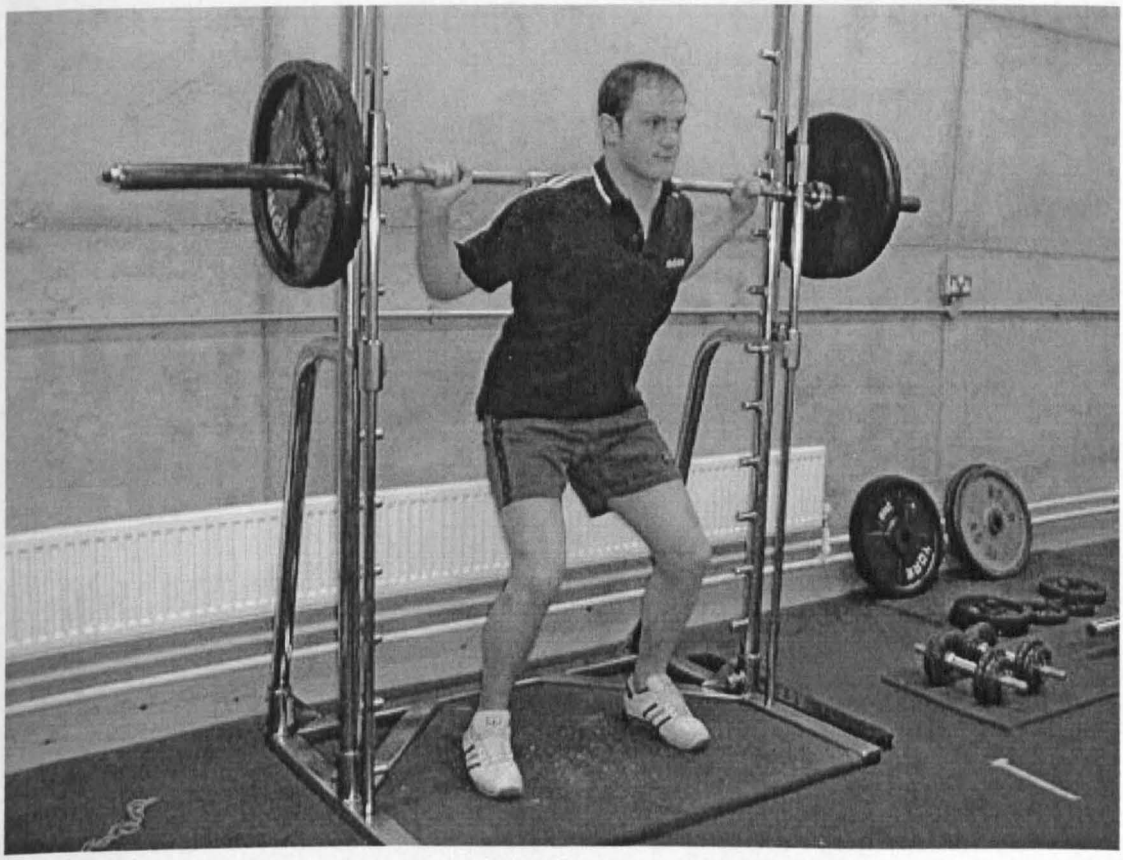


Plate 4.1 Subject performing Heavy Resistance Exercise in a Smith Machine.

For the loaded counter-movement vertical jumps illustrated in Plate 4.2, subjects were instructed to execute a downward movement at a self-selected speed and depth and immediately jump upward for maximum height. These instructions encouraged subjects to find their own optimum jumping conditions (Young *et al.*, 1995). Subjects were also encouraged to bend the knees upon landing to absorb the impact, then pause briefly to mentally prepare for the next repetition. This resulted in a pause between jump repetitions of approximately 2-4 seconds. For both conditions, subjects performed warm-up lifts with light loads before the actual exercise sessions.

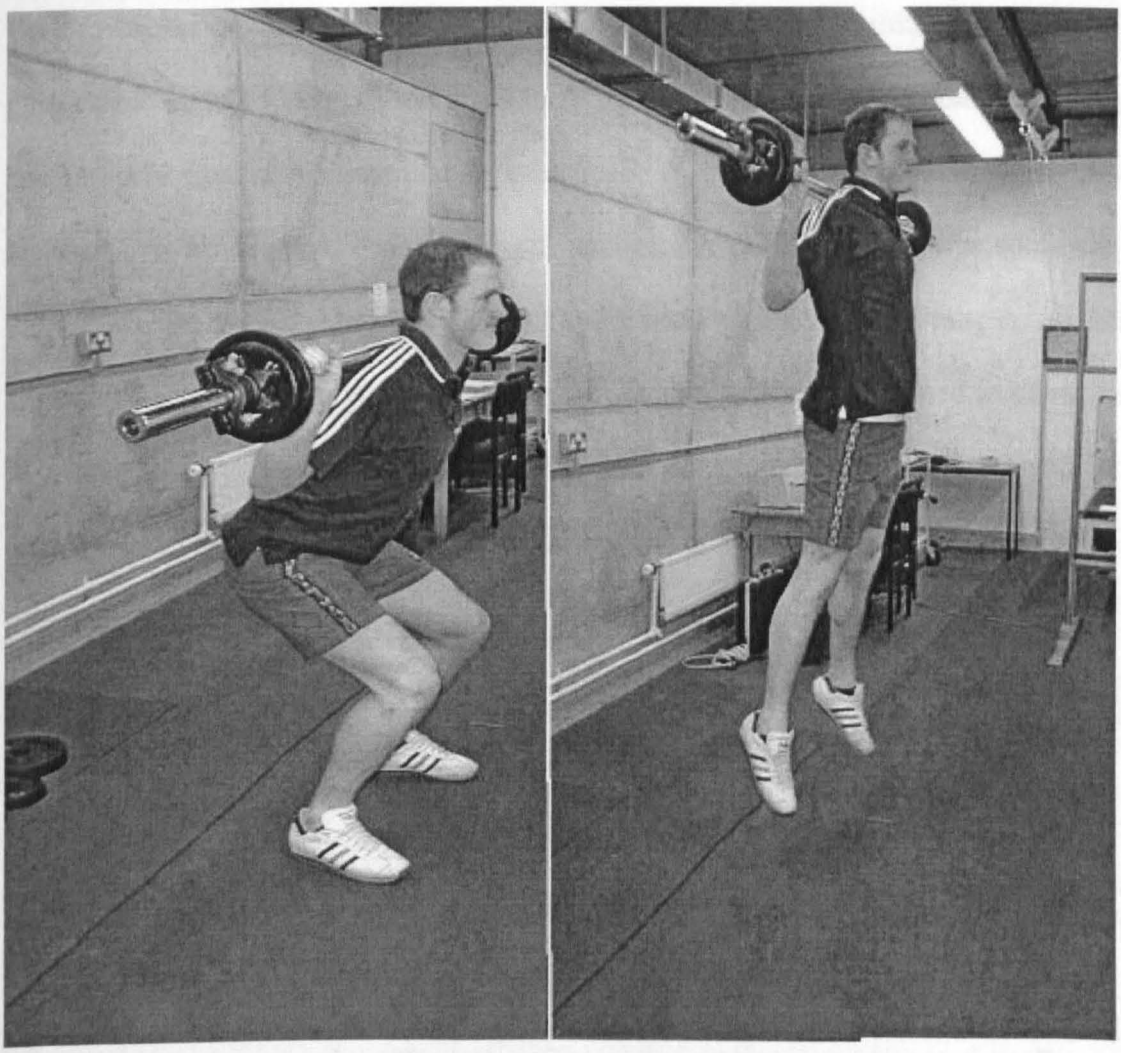


Plate 4.2 Subject performing Dynamic Strength Exercise.

The HRE session was comprised of 5 sets of 6 RM back squat lifts. The loads lifted were approximately 85% to 90% of the one repetition maximum (1 RM). In DSE, the subjects performed 5 sets of 10 loaded counter-movement vertical jumps at a load of 30% of maximum (1 RM). Three minutes recovery was allowed between sets. Subjects were therefore required to attend the laboratory prior to testing to determine their individual workload and to familiarise themselves with the experimental techniques.

On the occasion when the one repetition maximum was determined, each subject performed warm-up lifts with a light load. The load was then increased and each subject performed one repetition at each load. A rest interval of 3 minutes was allowed between trials to ensure adequate recuperation. This process was continued until a weight was reached that was deemed maximum by the researcher. In all subjects, the process was supervised such that the 1 RM was determined in no more than five trials to eliminate the possible effects of fatigue. This was achieved by starting the subject's single repetition attempts at 50% of subjective predictive maximum, then 75%, 90% and finally 100% and above if successful (Semenick, 1994). Each subject was capable of squatting at least 1.5 times, their own body mass for one repetition.

No additional lower body strength training was allowed during the entire experimental period. Subjects were also required to perform the same series of tests but with no exercise session. The order of exercise session was selected according to a controlled counter-balanced design in order to eliminate sequence bias (as shown below), but also to minimise any training effects. Therefore each testing session was

separated by a two-week period, although the "no exercise" condition (control) always took place in week 5 respectively. Each subject was required to record his food and fluid intake 24 hours prior to the test and also on the three test days. Subjects were instructed to follow the same diet for the subsequent test sessions. For the "no exercise" condition, the time period between measurements was kept constant at 30 minutes for each subject. This was the average time taken to perform the heavy resistance exercise session including warm-up sets.

	Week 1	Week 3	Week 5	Week 7
Subject 1	Familiarisation	HRE	Control	DSE
Subject 2	Familiarisation	DSE	Control	HRE
Subject 3	Familiarisation	HRE	Control	DSE
Subject 4	Familiarisation	DSE	Control	HRE
Subject 5	Familiarisation	HRE	Control	DSE
Subject 6	Familiarisation	DSE	Control	HRE

Figure 4.2 Experimental design to investigate the neuromuscular and metabolic characteristics of fatigue and recovery in response to heavy resistance and dynamic strength exercise.

4.3.3.2 Neuromuscular measurements

The force generated by the quadriceps femoris muscle of the right leg was measured using a strain gauge dynamometer attached to an adapted Lido Isokinetic Dynamometer chair (Loredan, Davis, CA) as illustrated in Plate 4.3. The strain gauge dynamometer was calibrated each week, by applying a series of known weights and converting the resulting voltage into force.

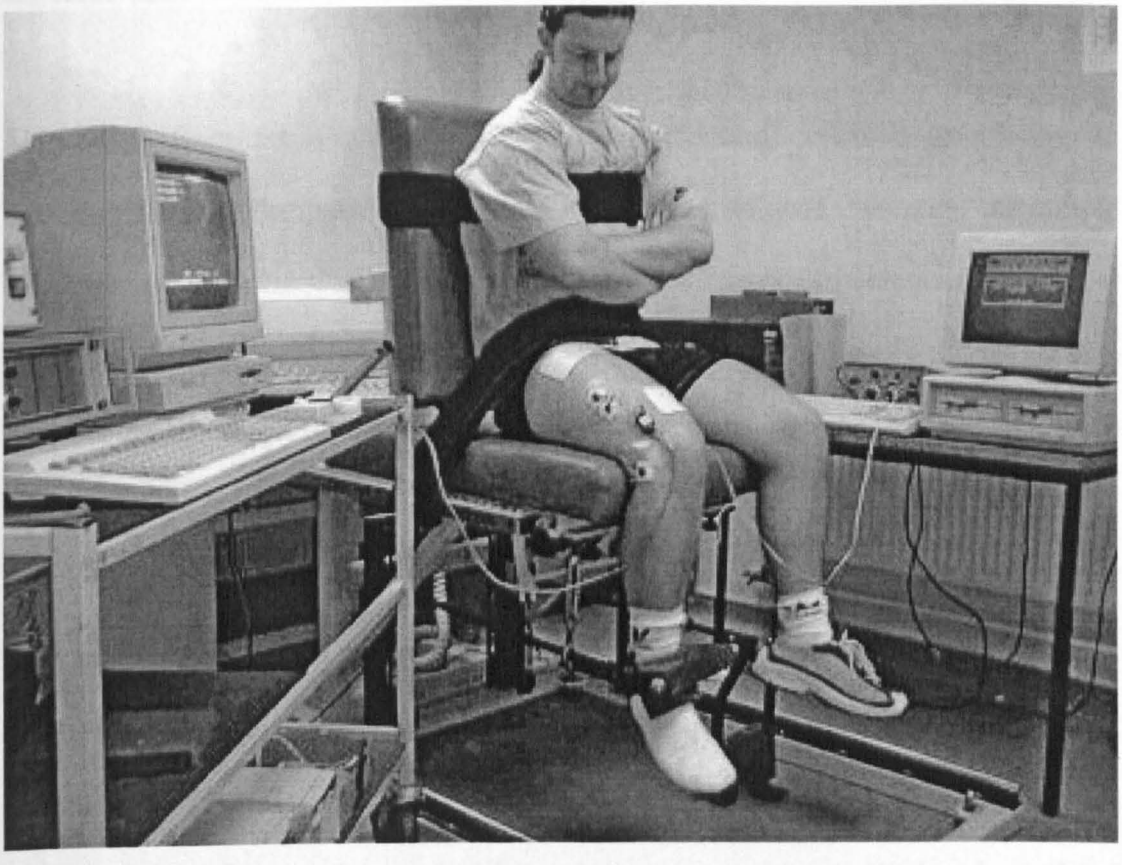


Plate 4.3 Experimental set-up for the measurement of maximum voluntary unilateral isometric force and neural activation and the force elicited by electrical stimulation of the leg extensor muscles.

For the assessment of neuromuscular function, the subject sat in the test chair with a knee joint angle of 90° (Zhou *et al.*, 1996) with the attachment from the strain gauge securely anchored just above the malleolus (Tornvall, 1963). The ankle cuff was attached to the strain gauge via a metal bar, fed through a bottleneck arrangement.

The ankle cuff and strain gauge could be moved vertically and horizontally to account for differences in subjects' physical characteristics. The subjects were seated in the adjustable, straight-backed chair and firmly strapped across the chest, waist and pelvis. In addition, subjects were requested to keep their arms in a folded position with hands clasping the opposite shoulder throughout the duration of the contraction. The uninvolved leg was allowed to hang freely. Thus, the position of the subjects in the force chair was standardised.

Force data from the strain gauge were amplified and collected on-line by an Archimedes 310 Computer via a 12 bit analogue-to-digital converter. A sample frequency of 1000 Hz was used for the collection of force and electromyographical data from the maximal voluntary contractions and a sample frequency of 100 Hz was used for collection of force data produced by electrical stimulation. All data were stored on magnetic discs for later analysis.

For maximum voluntary unilateral isometric force, the subjects were instructed to exert their maximal force as *"hard and fast"* as possible (Bemben *et al.*, 1990; Schlumberger *et al.*, 1999), and maintain that force for 3 seconds. Verbal encouragement was given to each subject during the performance of each maximal contraction (McNair *et al.*, 1996). The words spoken were "Come on, you can do it", and they were repeated for the duration of the contraction. The time interval between maximal efforts was one minute. From the resultant force-time curve, data were recorded for peak force, and the average rate of force development (RFD_{avg}) (Viitasalo *et al.*, 1980).

Surface electromyographic activity (EMG) was simultaneously recorded during the maximal isometric testing contractions from the vastus lateralis (VL) muscle of the right leg onto a second channel. The EMG signals were recorded telemetrically (MTR8 Biomedical Telemetry Receiver, I.M.I.E. LTD., Leeds, U.K.) and passed through pre-amplifiers, located no further than 10 cm from the electrodes. The technical specifications of the telemetry system conformed to both the British Association of Sport and Exercise Sciences (BASES) (Bartlett, 1996), and the International Society of Electrophysiology and Kinesiology (ISEK) (Merletti, 1999) standards and recommendations for collecting EMG data. The gain of the pre-amplifiers was 4000. The pre-amplifiers possessed a balanced input impedance of > 10M , and a common mode rejection ratio of > 110 dB.

Two disposable silver-silver chloride pre-gelled surface electrodes of 10 mm diameter (Vermont Medical, USA) were applied, with a centre-to-centre distance of 35 mm, longitudinally to the belly of the vastus lateralis. The electrodes were placed over the area of greatest muscle bulk just lateral to the rectus femoris on the distal half of the thigh, approximately one hand's breadth above the patella (Winter, 1988). The reference electrode was located on the lateral side of the knee of the tested thigh. Slight pressure was applied to improve contact between the electrodes and the skin, by fixing the electrodes with adhesive tape (Herzog *et al.*, 1994).

The skin was carefully prepared by shaving the required area to remove unwanted body hair. The surface was then cleaned and degreased using a clean tissue moistened with warm soapy water until no grease was evident on the tissue (Bartlett, 1997). This ensured that the inter-electrode resistance was always below 2.0 kΩ (Viitasalo *et al.*,

1980). The skin resistance was recorded on each day of testing using a moving coil meter. It was also recorded before and after the exercise session.

Root mean square (RMS) and median frequency (MDF) values were determined from the raw myoelectrical signal (Basmajian and De Luca, 1985) as previously described. RMS values were calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998).

Neuromuscular electrical stimulation (NMES) of the quadriceps was evoked using a Digitimer high voltage stimulator (Hertfordshire, UK). Self-adhering neurostimulation electrodes (Chattanooga, USA; 3" x 5") were placed over the vastus medialis muscle distally (just above the knee) and the vastus lateralis muscle proximally (McDonnel *et al.*, 1987). Stimulation occurred with the voltage kept constant at 250 V. Initially, stimulated twitches (1 Hz) were used to locate the optimum site and current for electrical stimulation of the quadriceps (Cooper *et al.*, 1998; Stokes *et al.*, 1988). The current (mA) from the stimulator was then adjusted until at least 40% of the MVC force was produced during stimulation using a 1 second, 100 Hz pulse. This current was then used throughout the experiment.

The stimulator was computer driven (Amstrad) and delivered trains of stimuli (pulse width 200μs) in a set pattern of frequencies of 20 Hz and 100 Hz. The muscle was stimulated at each frequency for a period of 1 second with an interval of 5 seconds between each stimulation. The mean force for each frequency (F_{20} and F_{100}) was then obtained. A permanent marking pen was used to outline the position of the EMG and electrical stimulation electrodes on the muscles. This ensured placement of the

electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999).

4.3.3.3 Blood measurements

Initially due to ethical considerations, it was recommended that blood measurements should be obtained from the earlobe, as finger prick samples may lead to blood contamination of the barbell. However, even after several practice sessions, it was not always possible to obtain sufficient quantities of blood from the earlobe site. Consideration was also given to the collection of blood from the antecubital vein as observed in previous studies (Brown *et al.*, 1996; Pullinen and Komi, 1995; Strojnik and Komi, 1998), although as subjects were required to perform the squat exercise, the position of the arm holding the bar after puncture may have been uncomfortable and even lead to bruising. For each subject only one blood sample was required before the exercise session to provide a base-line sample. It was therefore concluded that a finger prick sample would be more suitable. This was taken prior to warm-up, 15 minutes before the start of the strength exercise session. Consequently the blood measurement site was dry before the subject handled the bar. For extra precaution, a water-proof plaster was placed over the wound. All remaining blood samples were taken after exercise, when the subject was no longer required to handle the bar. Prior to each measurement, the non-dominant hand was warmed in a water bath at 45^{o}C for two minutes.

Finger prick blood samples were therefore taken before the exercise session, 3 minutes and 30 minutes after the session, and 120 minutes after the exercise session. Blood samples were also collected 24 and 48 hours post exercise. All samples were

taken from the non-dominant hand of the subject. After warming, the skin was cleaned with an alcohol wipe and subsequently left for 10 seconds for the alcohol to evaporate. The skin was broken with an Autoclix lancette (Boehringer Mannhein, Germany). The first droplet of blood was wiped away with a clean tissue.

Blood was immediately drawn into a heparinised (lithium nitrite) tube to prevent further production of lactic acid. Two 50 µl portions were then drawn from the heparinised tube and each added to 100 µl of cold 8% perchloric acid. These samples were then centrifuged for 10 minutes at 1500 rpm (Eppendorph Centrifuge, Model 5412). The supernatant was pipetted into 5 ml plain tubes and stored at -80^{0}C for later analysis. On the day of analysis, the samples were thawed at room temperature and analysed for plasma lactate using photoenzymatic methods on a Monarch centrifugal analyser (Model 761, Lexington, MA).

To determine the haematocrit, arterialised blood was drawn into two plain microhaematocrit capillary tubes, avoiding the introduction of air bubbles. The tubes were filled to approximately two thirds of their length and plugged with critoseal (Gelman-Hawksley Ltd, England), a clay type sealant at the blood-free end of the capillary tube. The tubes were placed with the sealant end outermost in opposite channels of a rotor in a micro-capillary centrifuge and spun for 5 minutes at 5000 rpm. The tubes were then placed on a Hawksley micro-haematocrit reader (Gelman-Hawksley Ltd., England) and the average percentage Haematocrit value obtained.

The haemoglobin concentration (g/dl) was determined using a Haemocue met-Hb system (Haemocue Ltd., Sheffield). Arterialised blood was drawn into two Haemocue

cuvettes, again avoiding the introduction of air bubbles. The cuvettes were then placed into a ß-Haemoglobin photometer for analysis. The average of the two samples was subsequently recorded. The combined data (haemoglobin and haematocrit) were then used to calculate the plasma volume changes following the exercise sessions according to the method used by Dill and Costill (1974).

A further blood sample was drawn into a 5ml tube coated in lithium heparin anti-coagulant (L. I. P. Equipment & Services, West Yorkshire, England). The tube was gently shaken to mix the anticoagulant. This was then centrifuged for 10 minutes at 1500 rpm (Eppendorph Centrifuge, Model 5412). The plasma was pipetted into 5 ml plain tubes and again stored at -80^{0}C for later analysis of potassium and creatine kinase. Blood collected 24 and 48 hours post exercise was analysed for creatine kinase only. The potassium and creatine kinase concentrations of the plasma samples were analysed at the Department of Clinical Chemistry, Royal Liverpool Hospital (Appendix 3).

4.3.3.4 Upper leg muscle soreness

Immediate-onset muscle pain and delayed onset muscle soreness (DOMS) were assessed after the exercise bout and on days 1, 2, 3, 4 and 5 of recovery respectively. Before taking a blood sample, each subject was required to rate the soreness of the quadriceps femoris muscles of both the stimulated and non stimulated leg using a graphic rating scale (Figure 4.3). The subjects were instructed to indicate the soreness of the entire muscle area in two ways: firstly in a relaxed state (general soreness, GS), and then while performing knee-flexion exercise (leg soreness, LS) (Thompson *et al.*, 1997). On the occasion when no exercise session was performed the level of

discomfort of the stimulated leg was used to indicate the degree of soreness initiated by electrical stimulation.

Graphic pain rating scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

No Pain — DA — SP — MSP — P — VP — Unbearable Pain

Figure 4.3 Graphic pain rating scale (adapted from Denegar and Perrin, 1992).

Following data collection the perceived pain was quantified by measuring the distance (to the nearest 0.5 cm) from the extreme left of the graphic pain rating scale to the mark made on the 10 cm line to describe the pain. The measured distance was multiplied by 2 to yield perceived pain scores from 0 to 20. Any vertical line falling on a dividing value was recorded as the higher value.

4.3.3.5 Ratings of perceived exertion

As different magnitudes of training load were used to simulate actual training sessions performed by games players, ratings of perceived exertion (Borg, 1970) were measured during the course of the exercise session. A copy of the scale is presented in Appendix 4). The scale consists of 15 grades from 6 to 20, where a rating of perceived exertion (RPE) score of 7 indicates the subject feels the workload to be very, very light, whereas a RPE of 20 indicates the subject feels the workload to be very, very hard. Subjects were instructed to rate the degree of exertion as accurately

and honestly as possible. After each exercise set, the subject was asked to state a number or to point with a finger at a suitable scale value of how difficult the exercise had felt during that particular set of lifts.

4.3.4 Statistical Analyses

In order to evaluate the fatigue and recovery characteristics in response to the three loading conditions all data (including upper leg muscle soreness and ratings of perceived exertion) were analysed using a two-way ANOVA (Condition x Time) with repeated measures on both factors: Condition (Heavy, Control and Dynamic) and Time (the changes over time after each loading condition). If a significant main effect for Condition or significant Condition x Time interaction was observed, the two-way ANOVA was repeated between the heavy resistance exercise and dynamic strength exercise conditions only. Statistical significance was set at $p<0.05$. Data were analysed using the SPSS statistical package.

4.4 Results

A one-way ANOVA with repeated measures established that there were no significant differences between base-line values for all of the neuromuscular and metabolic parameters. Therefore all data, except plasma volume changes were compared as absolute values.

4.4.1 NMES force-frequency characteristics

The relative changes (mean $\pm$ SD) in force elicited by electrical stimulation at each frequency of stimulation (20 Hz and 100 Hz), after each loading condition (HRE, Control and DSE) are presented in Figure 4.4. For the forces produced at 20 Hz, the 3 x 7 analysis of variance with repeated measures (ANOVA; Condition x Time) established that there were significant main effects for Condition ($F = 30.55$, $p < 0.05$) and Time ($F = 13.88$, $p < 0.05$), and also a significant effect for Condition x Time interaction ($F = 9.22$, $p < 0.05$). Similarly for the forces produced at 100 Hz, there were significant main effects for Condition ($F = 7.90$, $p < 0.05$) and Time ($F = 15.75$, $p < 0.05$), and a significant effect for Condition x Time interaction ($F = 3.92$, $p < 0.05$). A 2 x 7 analysis of variance with repeated measures (ANOVA; Condition x Time) was therefore used to compare differences between the HRE and DSE conditions only. The results from this analysis showed that for each frequency of stimulation, there was a significant main effect for Time (20 Hz, $F = 21.44$ $p < 0.05$; 100 Hz, $F = 15.53$ $p < 0.05$), but not Condition. Equally, there was no Condition x Time interaction between the HRE and DSE conditions for either frequency of stimulation.

The relative decreases (mean ± SD) in force produced by electrical stimulation at frequencies of 20 Hz and 100 Hz after HRE and DSE are presented in Figure 4.5. With regards the forces elicited at 20 Hz, relative decreases of 40.0 ± 17.2% and 39.1 ± 8.8 % were observed after HRE and DSE respectively. Although there was no significant effect for Condition x Time interaction, there was a trend for force to recover more quickly after DSE. For the force elicited at 100 Hz, relative decreases of –30.9 ± 16.5 % and –32.6 ± 5.3 % were evident after HRE and DSE respectively. After 60 minutes these values had recovered to within –20.7 ± 12.9 % and –16.5 ± 9.3 % of their corresponding force values recorded before the loading. Force then recovered more quickly after DSE during the second hour of rest –6.1 ± 8.0 % compared to –13.4 ± 7.3 % after HRE.

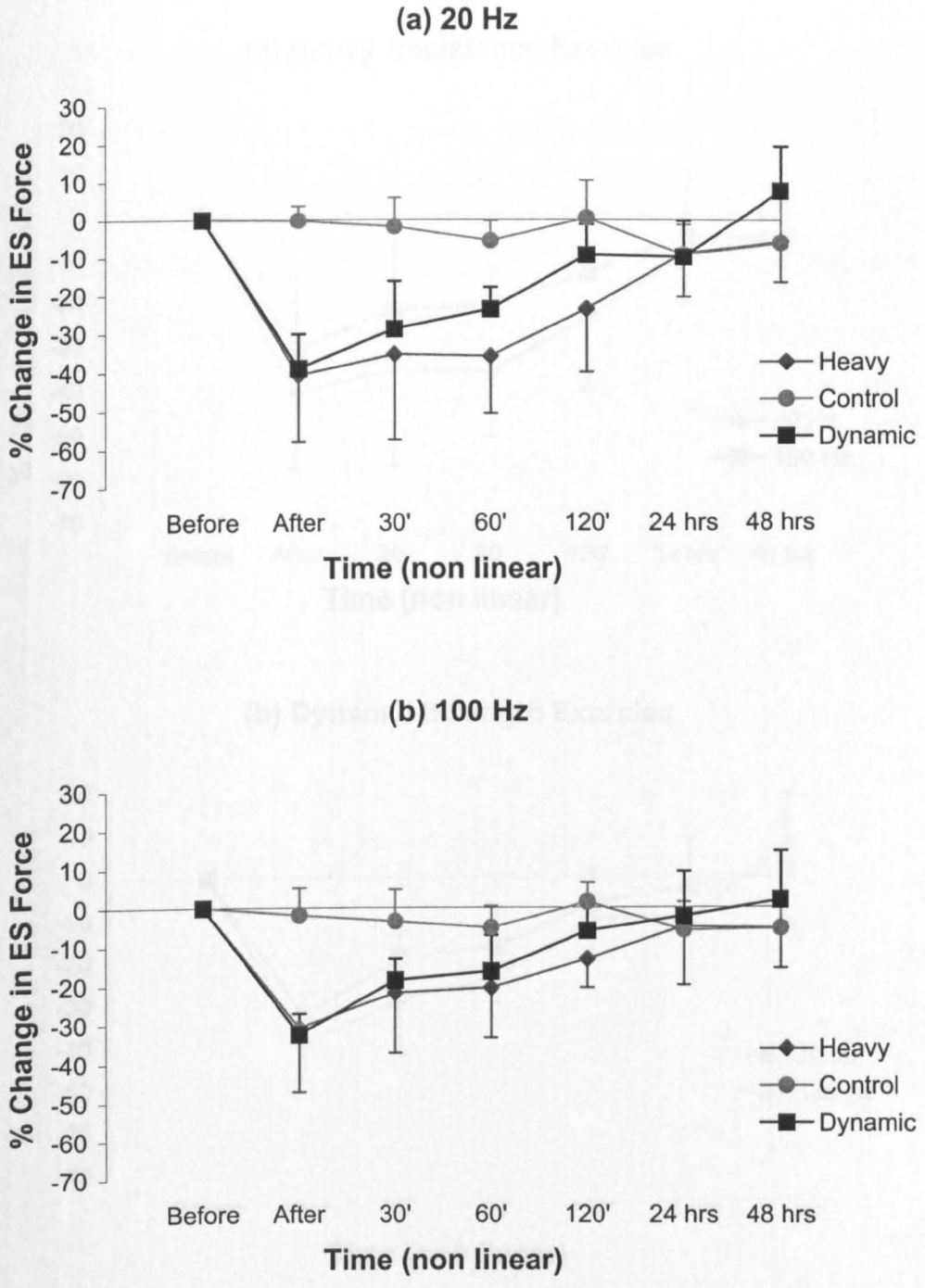


Figure 4.4 Percentage change (mean ± SD) in force elicited by electrical stimulation at frequencies of (a) 20 Hz and (b) 100 Hz, after heavy resistance exercise (HRE), no exercise condition and dynamic strength exercise (DSE).

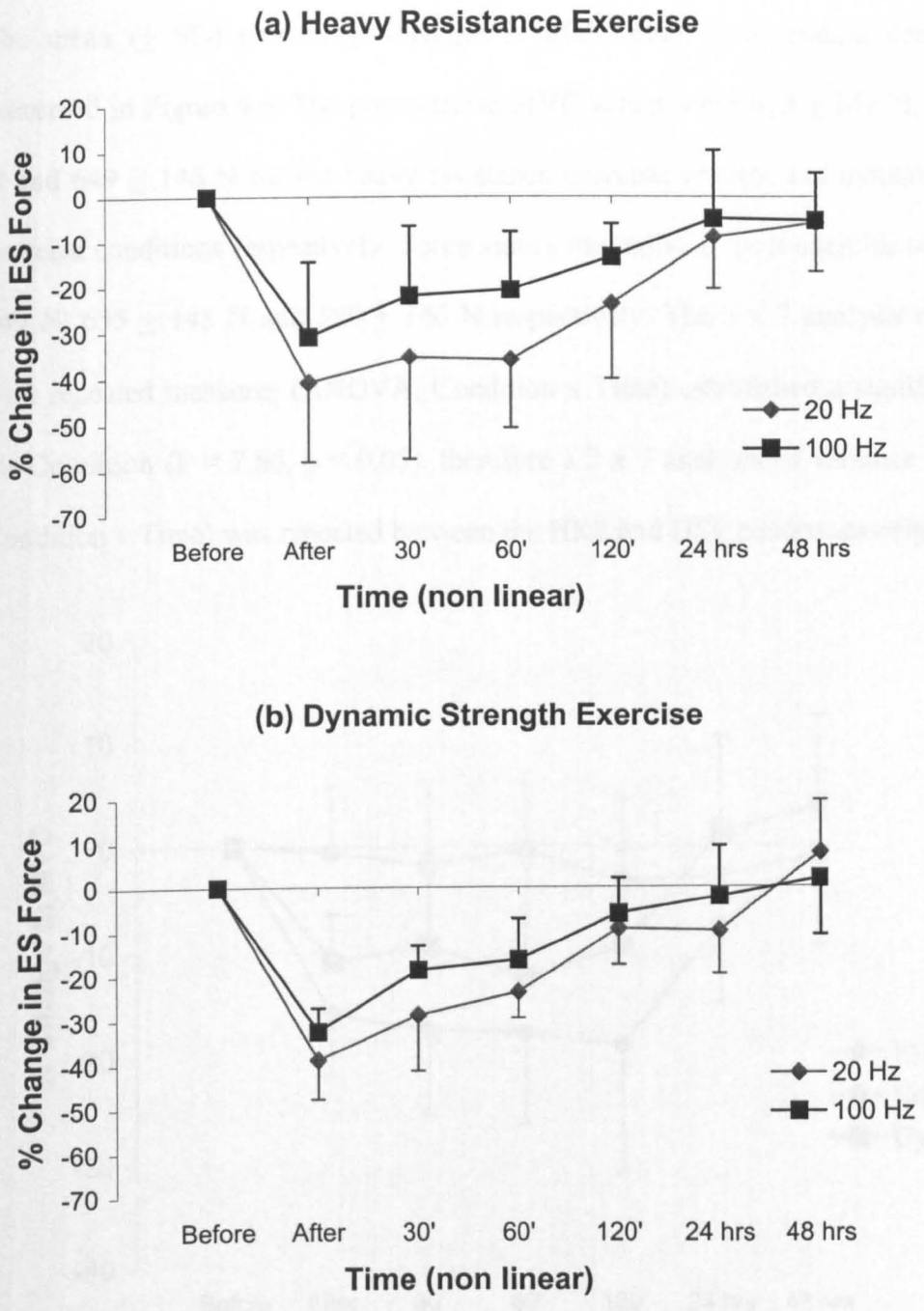


Figure 4.5 Percentage change (mean ± SD) in force elicited by electrical stimulation (ES) after (a) heavy resistance exercise (HRE) and (b) dynamic strength exercise (DSE).

4.4.2 Maximum voluntary contraction force (MVC)

The mean (± SD) percentage changes in MVC after each loading condition are presented in Figure 4.6. The pre-exercise MVC values were 658 ± 142 N, 658 ± 134 N and 649 ± 146 N for the heavy resistance exercise, control and dynamic strength exercise conditions respectively. Force values immediately post exercise were: 558 ± 149 N, 655 ± 143 N and 580 ± 146 N respectively. The 3 x 7 analysis of variance with repeated measures (ANOVA; Condition x Time) established a significant main for Condition ($F = 7.66$, $p < 0.05$), therefore a 2 x 7 analysis of variance (ANOVA; Condition x Time) was repeated between the HRE and DSE conditions only.

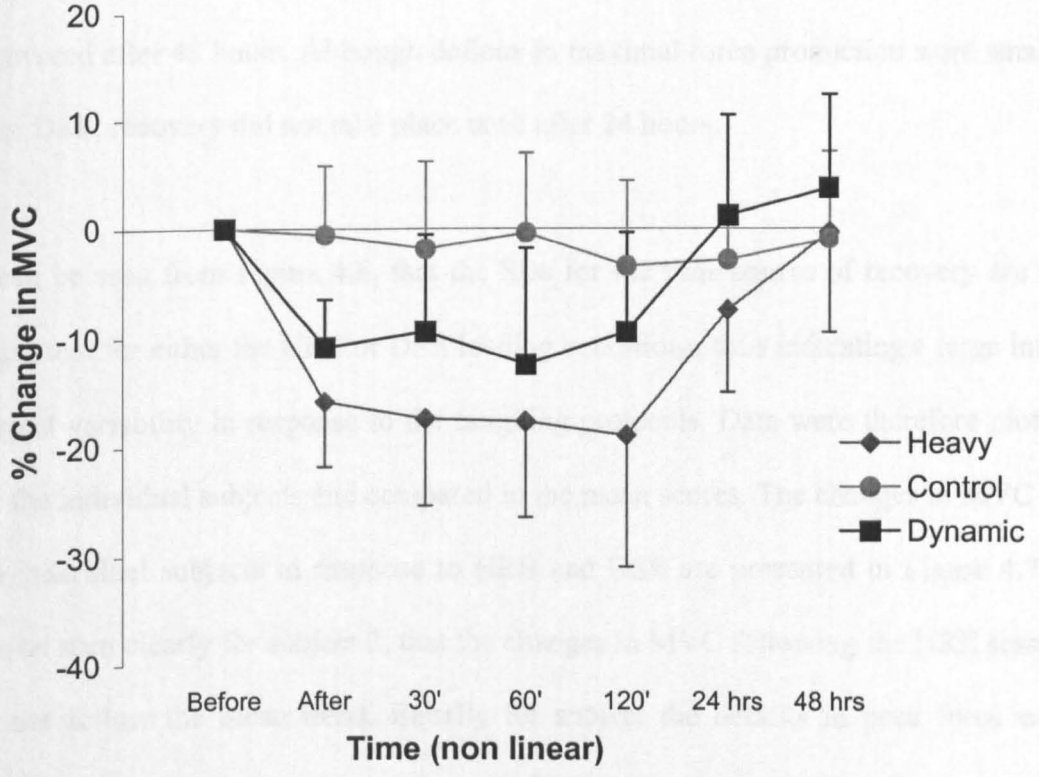


Figure 4.6 Percentage change (mean ± SD) in maximum voluntary contraction (MVC) force after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

No significant main effects for Condition or Condition x Time interaction were observed between the HRE and DSE loading conditions, although the force production was less after heavy resistance exercise for the duration of the recovery period. A significant main effect for Time ($F = 13.79$, $p < 0.05$) was observed. Therefore acute heavy resistance exercise and dynamic strength exercise resulted in significant decreases in maximal force production. The relative decreases in force for HRE and DSE immediately after exercise were -15.8 ± 5.9 % and -10.9 ± 4.4 % respectively. For the HRE condition maximal force gradually decreased over the first two hours of recovery, peaking at a deficit of -18.9 ± 12.0 %. A deficit in force production was still evident after 24 hours over recovery (-7.5 ± 7.5 %), although recovered after 48 hours. Although deficits in maximal force production were smaller after DSE, recovery did not take place until after 24 hours.

It can be seen from Figure 4.6, that the SDs for the time course of recovery are not consistent for either the HRE or DSE loading conditions, thus indicating a large intra-subject variability in response to the fatiguing protocols. Data were therefore plotted for the individual subjects and compared to the mean scores. The changes in MVC for the individual subjects in response to HRE and DSE are presented in Figure 4.7. It can be seen clearly for subject 2, that the changes in MVC following the HRE session do not follow the mean trend. Equally for subject the deficits in peak force were considerably greater than the mean scores. These data highlight the individual nature of responses to different types of loading conditions.

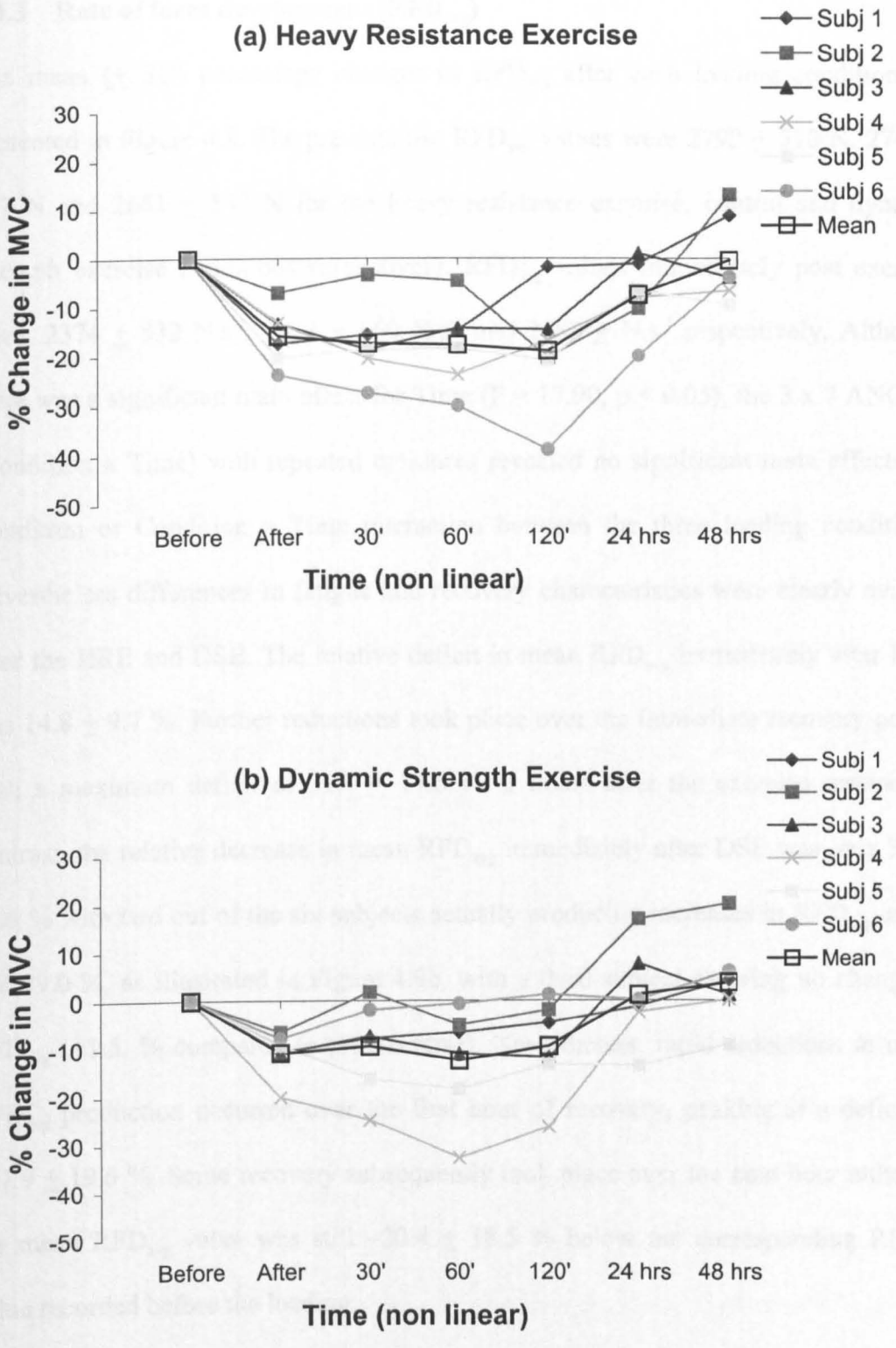


Figure 4.7 Percentage change in maximum voluntary contraction (MVC) force after (a) heavy resistance exercise (HRE) and (b) dynamic strength exercise (DSE) for individual subjects. Mean data are also presented.

4.4.3 Rate of force development (RFD_{avg})

The mean (± SD) percentage changes in RFD_{avg} after each loading condition are presented in Figure 4.8. The pre-exercise RFD_{avg} values were 2792 ± 510 N, 2740 ± 687 N and 2661 ± 547 N for the heavy resistance exercise, control and dynamic strength exercise conditions respectively. RFD_{avg} values immediately post exercise were: 2374 ± 532 $N.s^{-1}$, 2471 ± 660 $N.s^{-1}$ and 2488 ± $N.s^{-1}$ respectively. Although there was a significant main effect for Time ($F = 17.90$, $p < 0.05$), the 3 x 7 ANOVA (Condition x Time) with repeated measures revealed no significant main effects for Condition or Condition x Time interaction between the three loading conditions. Nevertheless differences in fatigue and recovery characteristics were clearly evident after the HRE and DSE. The relative deficit in mean RFD_{avg} immediately after HRE was 14.8 ± 9.7 %. Further reductions took place over the immediate recovery period with a maximum deficit of 31.1 ± 14.6 %, 2 hours after the exercise session. In contrast, the relative decrease in mean RFD_{avg} immediately after DSE was only 3.7 ± 20.6 % with two out of the six subjects actually producing increases in RFD_{avg} of 7.9 and 29.0 %, as illustrated in Figure 4.9b, with a third subject showing no change in RFD_{avg} (+1.5. % compared to pre-exercise). Nevertheless, rapid reductions in mean RFD_{avg} production occurred over the first hour of recovery, peaking at a deficit of –27.9 ± 19.6 %. Some recovery subsequently took place over the next hour although the mean RFD_{avg} value was still –20.4 ± 18.5 % below the corresponding RFD_{avg} value recorded before the loading.

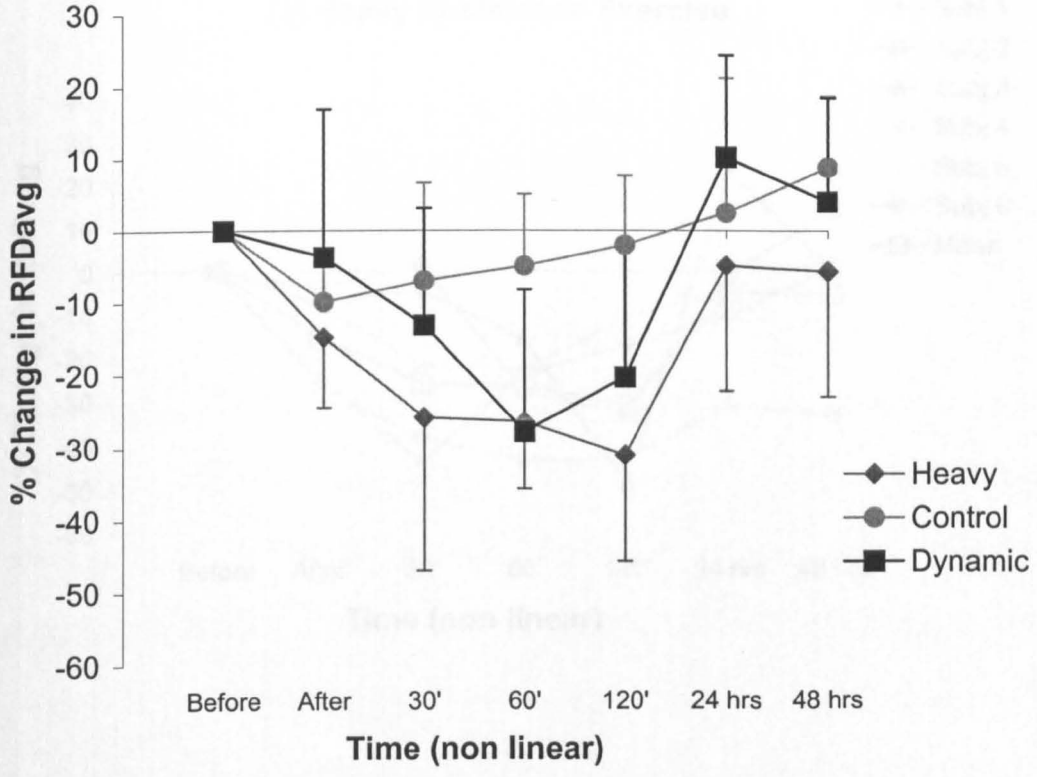
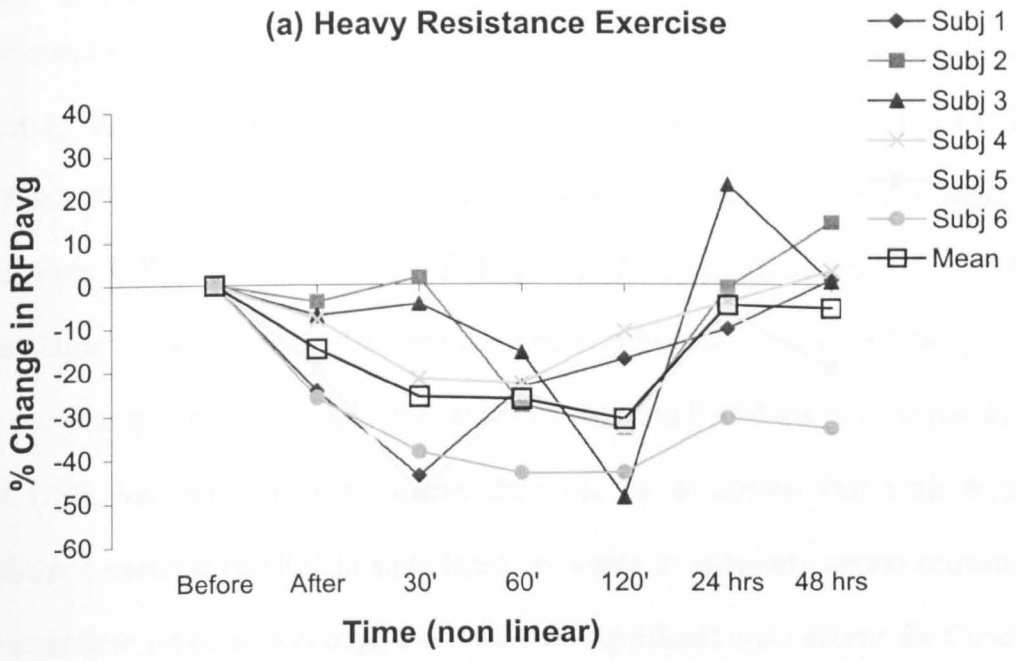


Figure 4.8 Percentage change (mean ± SD) in average rate of force development (RFD_{avg}) after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

After 24 and 48 hours of recovery mean values for RFD_{avg} were still 4.9 ± 17.4 and 5.7 ± 17.5 % below pre-exercise values respectively following HRE. Large intra-individual variability was again evident (Figure 4.9a) with two subjects showing deficits in RFD_{avg} after 24 hours recovery of 10.4 and 30.9 % respectively, whereas one subject produced a relative increase of 23.3 % compared to the pre-exercise values. For DSE, mean RFD_{avg} had fully recovered after 24 hours with a relative increase of 10.2 ± 14.1% compared to the pre-exercise values, although it can be seen from 4.9b, that this trend was not consistent for all six subjects.



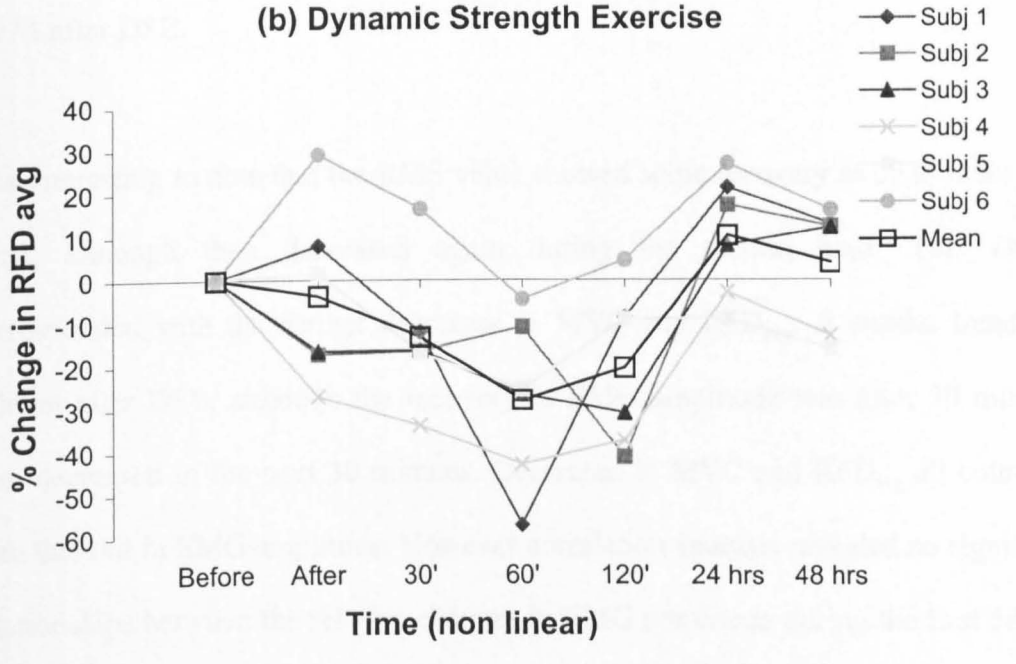


Figure 4.9 Percentage change in average rate of force development (RFD_{avg}) after (a) heavy resistance exercise (HRE) and (b) dynamic strength exercise (DSE) for individual subjects. Mean data are also presented.

4.4.4 Surface electromyographic activity (EMG)

The mean (± SD) absolute changes in EMG data are presented in Table 4.1 and the mean (± SD) relative changes in the same variables are presented in Table 4.2. The 3 x 7 ANOVA (Condition x Time) with repeated measures revealed a significant Condition x Time interaction ($F = 3.78$, $p < 0.05$). The subsequent 2 x 7 ANOVA (Condition x Time) produced a significant main effect for Time ($F = 3.56$, $p < 0.05$) for the changes in EMG amplitude expressed between 0-500 ms in response to HRE and DSE, but not Condition. It can therefore be concluded that both forms of resistance exercise resulted in significant decreases in voluntary neural activation of the exercised muscles. Although there were no significant main effects for Condition, it can be seen from Table 4.2, that the decreases in EMG amplitude during the early part of the force-time curve were greater after HRE –14.7 ± 6.1 % compared to –6.2 ± 7.9 % after DSE.

It is interesting to note that the RMS value showed some recovery at 60 minutes after HRE, although then decreased again during the second hour. This change corresponded with the further decreases in MVC and RFD_{avg}. A similar trend was evident after DSE, although the recovery in EMG amplitude was after 30 minutes, then decreased in the next 30 minutes. Decreases in MVC and RFD_{avg} all coincided with this fall in EMG amplitude. However correlation analysis revealed no significant relationships between the relative changes in EMG amplitude during the first 500 ms and the relative changes in peak force and average rate of force development after HRE or DSE.

No significant differences were observed for the amplitude of the EMG signal expressed between 500-1500 ms. A significant ($F= 3.34$, $p < 0.05$) main effect for

Time, was evident for the RMS value calculated between 1500-2500 ms, although there was no significant Condition effect. Relative decreases of –8.8 ± 4.6 % and –9.8 ± 5.8 % were evident immediately after HRE and DSE respectively.

Median frequency of the vastus lateralis muscle increased after both HRE and DSE. Although no significant differences were evident between contraction types, the shift to higher frequencies was prolonged after HRE, remaining 11.7 ± 12.5 % higher than base-line 30 minutes after the end of the exercise session. After 60 minutes, the median frequency was showing a clear leftward shift back to lower frequencies and was even -5.4 ± 5.6 % lower then pre-exercise values after 2 hours of recovery. This leftward shift to lower then base-line frequencies was not as evident after DSE. Further, after 24 and 48 hours of recovery the median frequency after HRE was 4.6 ± 8.8 % and 7.0 ± 13.1 % higher than pre-exercise values respectively.

Table 4.1 Mean (± SD) changes in EMG amplitude (RMS values) and Median Frequency (MDF) after heavy resistance exercise (HRE) and dynamic strength exercise (DSE). RMS values are expressed as arbitrary units.

	Before	After	30 min	60 min	120 min	24 hrs	48 hrs
Heavy							
RMS values							
0-500 ms	1.516	1.294	1.348	1.423	1.358	1.467	1.438
	(0.284)	(0.273)	(0.333)	(0.301)	(0.345)	(0.241)	(0.336)
500-1500 ms	1.640	1.502	1.525	1.575	1.557	1.615	1.573
	(0.242)	(0.256)	(0.290)	(0.241)	(0.268)	(0.207)	(0.267)
1500-2500 ms	1.672	1.525	1.562	1.592	1.597	1.666	1.635
	(0.221)	(0.222)	(0.242)	(0.196)	(0.246)	(0.163)	(0.255)
MDF (Hz)	57.00	62.38	63.36	59.28	54.14	59.20	60.26
	(6.972)	(8.132)	(8.278)	(7.909)	(9.035)	(4.548)	(2.070)
Control							
RMS values							
0-500 ms	1.538	1.525	1.480	1.532	1.582	1.347	1.423
	(0.281)	(0.279)	(0.279)	(0.297)	(0.233)	(0.354)	(0.307)
500-1500 ms	1.676	1.644	1.638	1.698	1.695	1.481	1.520
	(0.212)	(0.214)	(0.197)	(0.126)	(0.140)	(0.255)	(0.295)
1500-2500 ms	1.699	1.700	1.699	1.727	1.739	1.547	1.569
	(0.172)	(0.197)	(0.140)	(0.114)	(0.119)	(0.235)	(0.270)
MDF (Hz)	60.26	60.75	61.56	61.89	60.18	60.31	63.90
	(4.225)	(3.680)	(4.413)	(5.194)	(4.011)	(9.131)	(11.48)
Dynamic							
RMS values							
0-500 ms	1.509	1.417	1.451	1.404	1.480	1.544	1.510
	(0.219)	(0.259)	(0.246)	(0.211)	(0.180)	(0.146)	(0.209)
500-1500 ms	1.663	1.593	1.600	1.607	1.646	1.653	1.650
	(0.155)	(0.189)	(0.175)	(0.171)	(0.158)	(0.115)	(0.094)
1500-2500 ms	1.760	1.591	1.629	1.654	1.676	1.702	1.707
	(0.145)	(0.202)	(0.202)	(0.194)	(0.152)	(0.134)	(0.103)
MDF (Hz)	59.85	64.99	62.79	60.26	59.03	60.01	59.69
	(5.156)	(11.14)	(6.494)	(7.052)	(3.523)	(7.571)	(7.573)

Table 4.2 Mean (± SD) percentage changes in EMG amplitude (RMS values) and Median Frequency (MDF) after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Before	After	30 min	60 min	120 min	24 hrs	48 hrs
Heavy							
RMS values							
0-500 ms	0.0	-14.7	-12.2	-6.5	-11.1	-2.6	-5.7
	(0.0)	(6.1)	(8.0)	(4.7)	(10.4)	(6.7)	(10.5)
500-1500 ms	0.0	-8.6	-7.6	-4.0	-4.7	-1.2	-4.1
	(0.0)	(4.6)	(5.2)	(1.8)	(11.1)	(3.6)	(7.1)
1500-2500 ms	0.0	-8.8	-6.8	-4.5	-4.2	0.3	-2.2
	(0.0)	(4.6)	(4.1)	(5.2)	(10.3)	(6.8)	(6.6)
MDF	0.0	10.0	11.7	4.3	-5.4	4.6	7.0
	(0.0)	(13.3)	(12.5)	(9.1)	(5.6)	(8.8)	(13.1)
Control							
RMS values							
0-500 ms	0.0	-0.9	-3.8	-0.5	3.5	-13.3	-7.5
	(0.0)	(3.3)	(4.0)	(2.4)	(5.0)	(9.8)	(10.3)
500-1500 ms	0.0	-1.8	-2.1	1.9	1.6	-12.0	-9.4
	(0.0)	(6.8)	(4.7)	(5.3)	(5.5)	(6.8)	(13.6)
1500-2500 ms	0.0	0.1	0.2	2.0	2.7	-9.1	-7.3
	(0.0)	(5.5)	(4.4)	(6.3)	(6.0)	(8.7)	(15.9)
MDF	0.0	0.9	2.3	2.8	-0.1	-0.1	5.5
	(0.0)	(1.8)	(5.8)	(6.5)	(2.8)	(10.9)	(11.5)
Dynamic							
RMS values							
0-500 ms	0.0	-6.2	-3.6	-6.6	-1.1	3.2	0.2
	(0.0)	(7.9)	(9.6)	(8.2)	(10.2)	(7.7)	(4.2)
500-1500 ms	0.0	-4.3	-3.7	-3.3	-0.7	-0.3	-0.4
	(0.0)	(4.6)	(5.9)	(6.5)	(9.0)	(4.7)	(4.6)
1500-2500 ms	0.0	-9.8	-7.5	-6.1	-4.5	-2.9	-2.8
	(0.0)	(5.8)	(6.2)	(6.2)	(8.0)	(7.6)	(4.0)
MDF	0.0	8.4	5.1	1.1	-1.1	0.1	-0.4
	(0.0)	(11.8)	(7.9)	(11.1)	(4.8)	(5.2)	(6.8)

4.4.5 Plasma lactate concentrations

The mean (± SD) changes in plasma lactate concentration are presented in Table 4.3. A 3 x 4 ANOVA (Condition x Time) with repeated measures established significant main effects for Condition ($F = 7.58$, $p < 0.05$), Time ($F = 33.87$, $p < 0.05$) and a significant Condition x Time interaction ($F = 11.41$, $p < 0.05$). The subsequent 2 x 4 ANOVA (Condition x Time) with repeated measures established a significant main effect for Time ($F = 34.27$, $p < 0.05$) but not Condition. Therefore lactate levels increased significantly after HRE and DSE to very similar concentrations, with similar rates of recovery. The actual experimental techniques in the control condition caused no changes in plasma lactate concentration.

Table 4.3 Mean (± SD) changes in blood lactate values after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Unit	Before	After	30 min	120 min
Heavy	$mmol.l^{-1}$	0.8 (0.3)	6.1 (3.1)	1.5 (1.1)	0.7 (0.2)
Control	$mmol.l^{-1}$	0.9 (0.3)	0.7 (0.2)	0.7 (0.2)	0.7 (0.2)
Dynamic	$mmol.l^{-1}$	0.8 (0.4)	6.0 (3.0)	1.4 (0.8)	0.6 (0.2)

4.4.6 Creatine kinase activity and upper leg muscle soreness

As some of the base-line data were outside the adult reference range (33-194 IU l^{-1}) plasma creatine kinase activity was subjected to logarithmic transformation. This meant that positively skewed distributions tended towards symmetry, and since relatively large mean CK values have a large standard deviation and smaller CK values have a smaller standard deviation, logarithmic transformation reduced the standard deviation of the values with a high activity more than it reduced the standard deviation of the values with the lower activity (Howell, 1992). Even before the logarithmic transformation, there was no significant difference between base-line values due to the large variance range. No significant main effects for Condition or Time were observed after either HRE or DSE, although CK did peak after 24 hours in response to both loading conditions.

General soreness and leg soreness were analysed using a three-factor analysis of variance (ANOVA) (Condition x Leg x Time), with repeated measures on the last factor; Time (i.e. the changes over time after each exercise session). The factor Condition represents the difference between the heavy resistance exercise and dynamic strength exercise sessions, and the factor Leg represents the difference in muscle soreness between right and left legs. For general soreness there were no significant main effects for Condition or Leg, although there was a significant main effect for Time ($F = 2.87$, $p < 0.05$). Similar for leg soreness, although soreness values tended to be higher after HRE, there were significant main effects for Condition or Leg, although again there was a significant main effect for Time ($F = 8.35$, $p < 0.05$).

It is interesting to note that there was some immediate muscle pain, which tended to be a dull ache particularly after HRE. The DOMS increased the day after exercise and peaked 48 hours after HRE and 24 hours after DSE. Soreness remained slightly elevated even up to 120 hours after HRE.

Table 4.4 Mean (± SD) changes in creatine kinase activity after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Before	After	30 min	120 min	24 hrs	48 hrs
Heavy						
CK activity	382	498	439	434	488	358
IU l^{-1}	(595)	(778)	(648)	(625)	(511)	(355)
LOG CK activity	2.297	2.412	2.389	2.399	2.526	2.409
IU l^{-1}	(0.472)	(0.474)	(0.448)	(0.431)	(0.396)	(0.375)
% change in CK	0.0	33.4	27.1	29.7	79.9	40.5
activity	(0.0)	(35.1)	(37.6)	(34.0)	(69.2)	(63.6)
Control						
CK activity	253	253	256	251	272	330
IU l^{-1}	(90)	(89)	(91)	(92)	(136)	(236)
LOG CK activity	2.375	2.376	2.381	2.374	2.389	2.431
IU l^{-1}	(0.177)	(0.174)	(0.175)	(0.171)	(0.218)	(0.295)
% change in CK	0.0	0.4	1.5	-0.2	9.8	29.5
activity	(0.0)	(1.4)	(1.3)	(5.6)	(42.5)	(70.2)
Dynamic						
CK activity	958	1021	954	920	889	462
IU l^{-1}	(1705)	(1784)	(1675)	(1576)	(1001)	(469)
LOG CK activity	2.537	2.579	2.555	2.555	2.679	2.467
IU l^{-1}	(0.631)	(0.624)	(0.616)	(0.608)	(0.538)	(0.450)
% change in CK	0.0	10.3	4.3	4.3	72.9	7.6
activity	(0.0)	(6.7)	(6.7)	(7.3)	(127.4)	(68.7)

Table 4.5 Upper leg muscle soreness (DOMS), after heavy resistance exercise and dynamic strength exercise (Mean ± SD).

	Before	After	2 hrs	24 hrs	48 hrs	72 hrs	96 hrs	120 hrs
Heavy Resistance Exercise								
Right Quadriceps	0.0	0.0	1.2	2.7	2.0	0.3	0.0	0.0
General Soreness	(0.0)	(0.0)	(2.0)	(2.9)	(3.2)	(0.5)	(0.0)	(0.0)
Left Quadriceps	0.0	0.0	1.0	2.2	2.0	0.5	0.0	0.0
General Soreness	(0.0)	(0.0)	(1.7)	(1.7)	(3.2)	(0.8)	(0.0)	(0.0)
Right Quadriceps	0.0	0.0	1.5	5.8	6.5	1.8	0.7	0.2
Leg Soreness	(0.0)	(0.0)	(1.8)	(4.2)	(5.6)	(2.1)	(1.2)	(0.4)
Left Quadriceps	0.0	0.0	1.5	5.2	6.5	2.0	0.7	0.2
Leg Soreness	(0.0)	(0.0)	(1.8)	(4.1)	(5.6)	(2.3)	(1.2)	(0.4)
Dynamic Strength Exercise								
Right Quadriceps	0.0	0.0	0.7	1.5	0.7	0.7	0.0	0.0
General Soreness	(0.0)	(0.0)	(1.2)	(1.8)	(1.2)	(1.2)	(0.0)	(0.0)
Left Quadriceps	0.0	0.0	0.3	1.7	0.5	0.8	0.0	0.0
General Soreness	(0.0)	(0.0)	(0.5)	(1.9)	(1.2)	(1.3)	(0.0)	(0.0)
Right Quadriceps	0.0	0.0	1.3	3.5	2.8	1.0	0.7	0.0
Leg Soreness	(0.0)	(0.0)	(1.5)	(2.3)	(2.9)	(2.0)	(1.2)	(0.0)
Left Quadriceps	0.0	0.0	0.5	3.7	2.7	1.0	0.7	0.0
Leg Soreness	(0.0)	(0.0)	(0.8)	(2.3)	(3.1)	(2.0)	(1.2)	(0.0)

4.4.7 Potassium concentrations and plasma volume changes

The changes in potassium concentration (Mean ± SD) and plasma volume (Mean ± SD) after HRE and DSE are presented in Table 4.6 and 4.7 respectively. With regards changes in potassium concentration, no significant main effects for Condition or Time were observed although there was a –9.0 ± 5.7 % decrease in potassium concentration immediately after DSE. Significant decreases in plasma volume were evident after HRE and DSE ($F = 5.98$, $p < 0.05$), although the decrease was not significantly greater after HRE.

Table 4.6 Mean values (± SD) of potassium (K^+) concentration at rest, and after 3 and 30 minutes of recovery following heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Unit	Before	+ 3min	+ 30 min
Potassium	mmol l^{-1}			
Heavy		4.5 (0.4)	4.4 (0.2)	4.6 (0.3)
Control		4.5 (0.5)	4.7 (0.5)	4.6 (0.4)
Dynamic		4.5 (0.3)	4.1 (0.4)	4.4 (0.2)

Table 4.7 Percentage plasma volume changes (Mean ± SD) following heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Before	After	30 min	120 min	24 hrs	48 hrs
Heavy	0.0 (0.0)	-8.4 (6.6)	-1.8 (4.9)	-3.8 (5.1)	-0.7 (7.1)	2.6 (7.7)
Control	0.0 (0.0)	-1.8 (4.7)	-2.7 (3.1)	-2.0 (4.7)	1.4 (5.8)	-1.4 (5.5)
Dynamic	0.0 (0.0)	-4.8 (7.8)	-0.2 (3.5)	0.2 (7.4)	0.9 (5.5)	-2.0 (2.6)

4.4.8 Ratings of perceived exertion

No significant differences were observed in RPE between HRE and DSE although the ratings were consistently higher after HRE for each subject. A significant main effect for Set was observed ($F = 12.58$, $p < 0.05$) for both groups.

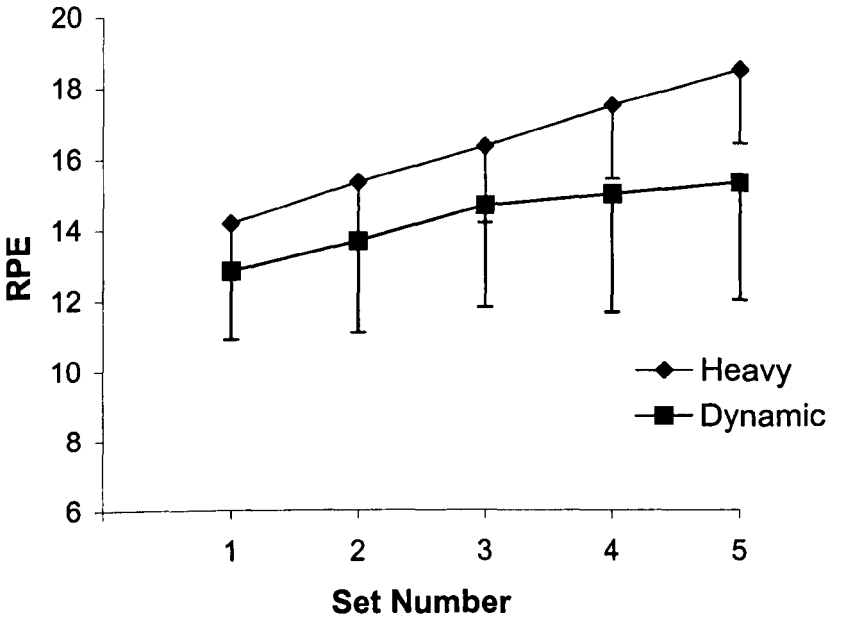


Figure 4.10 The response of rating of perceived exertion (RPE) to heavy resistance exercise (HRE) and dynamic strength exercise (DSE). Values are expressed as the mean $\pm$ SD.

4.5 Discussion

The present findings demonstrated that heavy resistance exercise and dynamic strength exercise led to considerable acute fatigue in the neuromuscular system. As could be expected, both high intensity-training sessions resulted in significant decreases in peak force (maximal strength, MVC) of the exercised muscles (Figure 4.6). Although there was no significant main effect for Condition, a clear trend was apparent in that the deficits in peak force were greater and recovery was slower after HRE compared to DSE. This lack of significance may be due to the sample number (n = 6) used in the present study. As illustrated in Appendix 2, a minimum number of 8 subjects were required to achieve a power of 80% at $p = 0.05$, with six subjects producing a statistical power of 65%. Although eight subjects were initially recruited, due to the demanding nature of the experimental design, two subjects dropped out during the course of the study. It can also be seen from Appendix 2 that 10 subjects would be required to achieve a statistical power over 90%.

Studies with similar experimental techniques are also characterised by low to moderate subject numbers. For example Brown *et al.*, (1996) used 9 subjects when measurements were recorded up to 9 days post exercise. When comparisons have been made between athletes of different training backgrounds, moderate sample sizes are also evident and with unequal numbers between groups (e.g. Häkkinen and Myllylä, 1990: endurance, n = 9; power, n = 6; strength, n = 9). In the present study, however, each subject was tested under each experimental condition, consequently data were analysed using a repeated measures ANOVA design, which controls for inter-subject variability and thus provides a strong statistical model. However

differences between the means as well as being due to the 'treatment' and measurement error, can also be due to the variability within a person's scores (intra-individual variability). This variability can be observed by comparing the SDs for each time point (Figure 4.6). When individual data are plotted, clear differences in response to the two different loading conditions can be observed. It may therefore be considered that even with a larger number of subjects, the large variability in response to the fatiguing protocols may prevent the determination of a significant statistical result.

The training volumes of 5 sets of 6 RM for HRE and 5 sets of 10 loaded counter-movement vertical jumps at a load of 30% of maximum (1 RM) were chosen to represent typical sessions used by players engaged in team sports. In the present study, very similar increases in lactate were observed after HRE and DSE. Although the increase in lactate of 6.1 $\pm$ 3.1 mmol.l^{-1} was lower compared to other heavy resistance exercise protocols (e.g. Linnamo *et al.*, 1998: 5 sets of 10 RM, La = 11.9 mmol.l^{-1}; Hakkinen, 1994a: 10 sets of 10 RM: La = 15.0 mmol.l^{-1}), the increase in lactate 6.0 $\pm$ 3.0 mmol.l^{-1} after DSE was greater than Linnamo *et al.* (1998) observed after ESL. Statistical analysis confirmed that there was no significant difference between HRE and DSE. This would possibly indicate that the physiological stress imposed by both loading conditions were approximately equal despite the greater perceived stress as indicated by the RPE values (although not significant) during the heavy resistance exercise session.

It has been suggested that heavy loads are superior for developing speed-strength characteristics due to the longer time under tension. Consequently the differences in

duration of motor unit activation between HRE and DSE may have an effect on the fatigue and recovery characteristics. The present decreases in peak force and average rate of force development were associated with a decrease in maximal voluntary neural activation of the exercised muscles (Table 4.1 and Table 4.2) which may have resulted from decreased central drive and hence central fatigue. However correlation analysis revealed no significant relationship between the relative changes in EMG amplitude expressed between 0-500 ms and the decreases in peak force and average rate of force development immediately after HRE and DSE. Nevertheless, the decreases in EMG amplitude during the early part of the force-time curve (0-500 ms) were greater after HRE -14.7 ± 6.1 % compared to -6.2 ± 7.9 % after DSE, although again this difference was not significant. This larger reduction in central drive observed after HRE also corresponded to the greater perceived stress and greater muscle soreness recorded for this loading condition. The latter variables may have some bearing on the motivation of subjects to produce maximal neural drive.

Interestingly the larger decrease in EMG amplitude after HRE during the first 500 ms is in contrast to the study by Linnamo *et al.* (1998) where deficits in integrated EMG calculated over the first 100 ms were 36.4 ± 13.6 % after explosive strength loading and only 16.2 ± 26.6 % after maximal strength loading respectively. The authors concluded that explosive strength loading especially in men appeared to lead primarily to central fatigue with less involvement of peripheral fatigue than MSL. The results of the present study on the other hand do not support this conclusion. The difference in EMG responses may however be explained by the fact that the critical time for the development of high firing frequencies required to generate high rates of force development, is in the first 100 ms of the contraction, and therefore differences

in EMG may not be as apparent when expressed between 0-500 ms. The calculation of RMS values over the first 100 ms in the previous methodological studies was found to have very high variability and therefore was not considered for the present study.

With regards the changes in RFD_{avg}, large differences were evident between the two loading conditions, but were not significant. Forty-eight hours was not sufficient to allow full recovery of RFD_{avg} after HRE providing a good indication of the strenuous nature of this type of training. On the other hand, recovery of mean RFD_{avg} after DSE was complete after 24 hours with evidence of a super-compensation training effect (Zatsiosky, 1995). Closer examination of the data again revealed a large variability between subjects in response to the DSE session as illustrated in Figure 4.9b. Immediately after DSE (+ 5mins), two out of the six subjects actually produced values for RFD_{avg} greater than pre-exercise values, which may be explained by a potentiation effect. Potentiation effects have been shown to peak approximately 5-8 minutes after maximal exercise protocols depending on the training status of the athlete (Güllich and Schmidtbleicher, 1996) and then decay to control levels after about 8-12 minutes. Güllich and Schmidtbleicher (1996) concluded that the positive potentiation effects on performance express themselves mainly in the steepness of the rise in force (i.e. in explosive force) and can occur despite decreases in maximal force production, as was the case in the present study. This is illustrated in Figure 4.7b for subjects 1 and 6 respectively. With regards to the mechanisms underlying these potentiation processes, these may involve an alteration in calcium kinetics (Duchateau and Hainaut, 1986), although the phosporylation of myosin light chains (Grange *et al.*, 1993; Sweeney *et al.*, 1993) is thought to be the more likely explanation. The

study of post-tetanic twitch potentiation has also emphasised that the process of potentiation and fatigue occur concurrently (Enoka, 1994). Thus it may be considered that the speed-strength performance as measured by the average rate of force developed immediately after exercise is the net result of potentiation and muscular fatigue (Güllich and Schmidtbleicher, 1996).

It has also been reported that frequencies of the EMG power spectrum are related to the average conduction velocity of the active muscle fibres (Arendt-Nielsen and Mills, 1985). Normally a shift to the left is observed with fatigue. However, since muscle fibre conduction velocity is higher for fast twitch fibres (Andearssen and Arendt-Nielsen, 1987), a shift of the power spectrum to high frequencies would represent an increase in the average conduction velocity and therefore a greater use of fast twitch fibres. The shift towards higher frequencies after HRE and DSE in the present study suggests that more fast units would have been recruited towards the end of the exercise sessions. Another explanation however could be an increase in muscle temperature, which has been shown to cause a shift of MPF to higher frequencies (Petrofsky and Lind, 1980b).

Significant decreases in the forces elicited by neuromuscular electrical stimulation were observed immediately after HRE and DSE. Although there were no significant differences between conditions, there was a trend for the forces to recover quicker after DSE. It was very noticeable however that the force produced at 100 Hz recovered within the first two hours of recovery whereas, the maximum voluntary contraction force did not show any evidence of recovery, thus providing further evidence of central inhibition of the contraction processes.

Low frequency or long lasting fatigue is evident when force has recovered at high frequencies of stimulation, but the force at low frequencies of stimulation are still reduced. In the present study, there is no evidence to suggest that this form of fatigue was evident in response to the two loading conditions. Evidence to support the presence of traditional 'high frequency fatigue' during the performance of the fatiguing protocols is possibly provided however by the changes in plasma potassium concentration.

Skeletal muscle is the main source of extra cellular potassium (K^+) released during exercise (Clausen, 1986; Juel *et al.*, 1990; Sjøgaard, 1990; 1991; Sjøgaard *et al.*, 1985). Changes in plasma K^+ although often biased by water displacement during exercise, are a good reflection of the accumulation-depletion balance of K^+ in the interstitial space (Sjøgaard and Saltin, 1982). It has been shown that the accumulation of extra-cellular K^+ in isolated ventricular fibres is proportional to the frequency and duration of the applied stimulus. Following the stimulus, it has also been shown there is a depletion of extra-cellular K^+ below resting concentrations. Marcos and Ribas (1995) examined the kinetics of plasma potassium concentrations during exhausting cycling exercise in trained and untrained men and found a linear relationship between the magnitude of the increase in plasma K^+ concentration during exercise and the magnitude of the decrease immediately after cessation of exercise. Marcos and Ribas (1995) also stated that as decreases in plasma volume in all cases were less than 10%, the increases in K^+ concentration were not due to haemoconcentration. It has been reported that increased K^+ depolarises muscle cells and subsequently inactivates voltage dependent sodium channels responsible for the muscle action potential (Hodgkin and Huxley, 1952). Since inactivation of sodium channels reduces

sarcolemmal excitability, an increased extacellular K^+ concentration may be expected to cause the lack of responsiveness to neural stimuli, which underlies fatigue and more specifically high frequency fatigue (Jones, 1981).

The major efflux of K^+ from muscle occurs during the repolarisation phase of the muscle action potential, and thus it is proportional to the frequency of the muscle action potentials. Marcos and Ribas have shown that plasma K^+ concentration was higher in a sprint compared to a progressive exercise test when the pedalling frequency was higher. In the present study, the largest decrease in plasma K^+ concentration was after DSE, which according to the work of Marcos and Ribas, would indicate that the largest increase in plasma K^+ concentration would occur during the DSE session. This in turn could possibly reflect the requirement for higher frequency action potentials required to generate the high forces and accelerations during the execution of a loaded counter-movement vertical jump. However it should be noted that plasma potassium concentrations were not measured during the course of each loading condition, i.e. after each set and therefore this statement should be interpreted with caution.

4.6 Conclusions

In summary, the present findings demonstrated that subjects found HRE harder than DSE as indicated by the RPE values, although both forms of exercise produced similar levels of plasma lactate concentration. Fatigue after HRE also tended to have a greater central component with a greater reduction in neural activation, whereas DSE appeared to lead primarily to peripheral fatigue. Further evidence to support the presence of a central limitation to the contraction process was provided by the recovery in 100 Hz force in the first two hours after the exercise session, whereas MVC did not recover until after 48 hours.

There were no significant differences between the two distinct loading conditions, however there was a trend for the decreases in maximal peak force and rate of force development to be less and recover quicker after DSE compared to HRE. Furthermore the results also suggested that performing a DSE session only 24 hours before a game may have a beneficial effect on performance as indicated by the enhancement of RFD_{avg} by 10% after 24 hours of recovery. Training after HRE would not be recommended until after at least 48 hours.

CHAPTER 5

NEUROMUSCULAR FATIGUE AND RECOVERY FOLLOWING HEAVY RESISTANCE AND DYNAMIC STRENGTH TRAINING PROGRAMMES IN SUBJECTS ENGAGED IN TEAM SPORTS

5.1 Background to the study

Muscular fatigue is one of the contributing factors to decrements in athletic performance. Physical conditioning programmes are designed to delay the effects of muscular fatigue, and enable the athlete develop a higher functional capacity for competition. However given the intense nature of heavy resistance exercise and dynamic strength exercise, and the need for extensive high frequency recruitment of muscle fibres and motor units in a range of synergistic muscles, there would appear to be limited opportunity for compensatory strategies, to enable performance to be sustained. Increased fatigue resistance would appear to depend on carefully planned designed training programmes designed to adapt the excitation and contraction processes, the cytoskeleton and the metabolic systems, not only to tolerate but also to minimise the changes in the intracellular environment that are caused by the intense activity.

It was also identified in Study 2, that fatigue after HRE tended to have a greater central fatigue component with a greater reduction in neural activation, whereas DSE appeared to lead primarily to peripheral fatigue. Further evidence to support the central inhibition was the failed recovery of MVC compared to the recovery of 100 Hz force in the first two hours after exercise. Central activation failure can be identified, by superimposing a 100 Hz pulse during the performance of a MVC, and the feasibility of using such a method will be assessed in the following pilot study.

5.2 Pilot Study: Assessment of quadriceps activation by superimposing electrical stimulation during the performance of a maximum voluntary contraction

5.2.1 Rationale for the study

Central fatigue has commonly been detected (as in the present study) by comparing the decreases in voluntary force with that developed by neuromuscular electrical stimulation of the same muscle (Bigland-Ritchie and Woods, 1984), as well as by observing the decreases in the voluntary neural activation of the exercised muscles (Häkkinen, 1993; 1994a; Häkkinen and Komi, 1986b; Komi and Rusko, 1974; Komi and Viitasalo, 1977; Linnamo *et al.*, 1998).

A third and very simple method to determine whether central fatigue is present during a voluntary contraction is to superimpose a maximal electrical stimulus into the nerve or contracting muscle and to look for a twitch superimposed on the recording of the voluntary force (Bélanger and McComas, 1981; Merton, 1954). If a twitch is observed, then either not all motorneurons have been recruited or else some are not firing impulses at the optimal frequency for force generation (Gandevia, 1992). The sensitivity of the technique can be improved by applying two or more stimuli close together, rather than a single one, so as to make the twitch force larger (Enoka, 1994; McComas, 1996).

The twitch interpolation technique has been used to indicate any possible unconscious inhibition of fibre recruitment following fatiguing exercise using static (Strojnik and Komi, 1998) and dynamic (Newham *et al.*, 1991) contractions. Strojnik and Komi (1998) assessed the activation level of the quadriceps by superimposing a double

twitch during the performance of a maximum voluntary isometric contraction after maximal stretch-shortening cycle exercise. In contrast, Newham *et al.* (1991) wished to superimpose electrical stimulation on a voluntary isokinetic contraction. These authors found that single twitches were too small and brief to be reliably detected and measured when superimposed on a dynamic contraction because of the shape of the force curve and the lack of a plateau. They found that more force was generated over a longer period of time by a short train of high frequency stimulation. During the dynamic isokinetic contractions, a train of stimuli at 100 Hz was subsequently delivered for 250 ms.

More recently, Brown *et al.* (1996) applied a 1 second pulse of a 100 Hz stimuli during a 3 seconds maximal voluntary isometric contraction before and after, 70 electrically stimulated single leg knee extensor eccentric muscle actions. Both maximum voluntary contraction force (MVC) and maximum voluntary contraction with superimposed percutaneous electrical myostimulation stimulation (MVS) were reduced after exercise, with maximal force loss occurring 3 days after exercise. However the consistent 10% increase in force using the MVS compared to the MVC technique, suggested that it was not a problem in motivation, or a problem associated with delayed onset muscle soreness. The MVS contraction was still greater than the MVC contraction even when soreness was back to base-line 9 days after the exercise session. Brown *et al.* (1996) concluded that since the force increases when using the MVS technique were only observed after the exercise, this may indicate the presence of a central limiting mechanism which may have restricted recruitment of partially damaged or vulnerable fibres.

5.2.2 Objective of the study

The objective of this study was to assess the technique of superimposed percutaneous myoelectrical stimulation following heavy resistance exercise in two subjects, to determine its feasibility of use for the training study described later in this chapter.

5.2.3 Methodology

Subjects

Two male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study and subject data are given in Table 5.1. Both subjects engaged regularly in team sports and had over one year's experience of weight training. In addition, each subject was very familiar with the experimental techniques of neuromuscular electrical stimulation and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University.

TABLE 5.1 Subject data

	Age (yr)	Height (m)	Mass (kg)
Subject A	27	1.77	78.0
Subject B	21	1.78	76.0

Experimental design

Measurements of neuromuscular electrical stimulation (NMES) of the quadriceps femoris muscle were recorded before a heavy resistance exercise (HRE) session and immediately (5 minutes) after the session. The same measurements were also

repeated during the recovery period at intervals of 30, 60 and 120 minutes as well as for 24 and 48 hours afterwards. Measurements of maximal voluntary neural activation and force production were also recorded at the same time intervals, 1 minute after electrical stimulation in each case. A maximum voluntary contraction with superimposed percutaneous electrical myostimulation (MVS) was then recorded, 1 minute after the second MVC trial. Both testing sessions took place between 14.00 and 1700h to control for circadian variation (Atkinson and Reilly, 1996). The test protocol followed the format as illustrated in Figure 5.1.

For the heavy resistance exercise sessions, both subjects performed 5 sets of 6 repetitions of the back squat exercise at a load approximating to 85% to 90% of the subject's 1RM. Although the loads lifted were heavy and the actual movement velocity was low, each subject was instructed to move the bar as quickly as possible, such that the intended movement velocity was high (Behm and Sale, 1993b).

The force generated by the quadriceps femoris muscles of the right leg and the simultaneous recording of surface electromyographic activity were measured using the experimental techniques described in Study 2. From the resultant force-time curve, data were recorded for peak force and the average rate of force development (RFD_{avg}) (Viitasalo *et al.*, 1980). Root mean square (RMS) and median frequency (MDF) values were determined from the raw myoelectrical signal (Basmajian and De Luca, 1985). RMS values were calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998).

TIME	ACTIVITY/MEASURE
BEFORE EXERCISE	
+ 0 min	Base-line muscle soreness
+ 15 min	NMES followed by MVC with simultaneous recording of surface EMG and MVS technique
	Heavy resistance exercise session. Rating of perceived exertion (RPE) recorded after each set
AFTER EXERCISE	
+ 3 min	Muscle soreness
+ 5 min	NMES, MVC (EMG), MVS
+ 30 min	NMES, MVC (EMG), MVS
+ 60 min	NMES, MVC (EMG), MVS
+ 120 min	Muscle soreness, NMES, MVC (EMG), MVS
+ 24 hrs	Muscle soreness, NMES, MVC (EMG), MVS
+ 48 hrs	Muscle soreness, NMES, MVC (EMG), MVS
+ 72 hrs	Muscle soreness
+ 96 hrs	Muscle soreness
+ 120 hrs	Muscle soreness

Figure 5.1 Protocol to investigate the technique of using superimposed electrical stimulation to assess motor unit activation of the quadriceps muscle following heavy resistance exercise.

Neuromuscular electrical stimulation (NMES) of the quadriceps was evoked using a Digitimer high voltage stimulator (Hertfordshire, UK). Self-adhering neurostimulation electrodes (Chattanooga, USA; 3" x 5") were placed over the vastus

medialis muscle distally (just above the knee) and the vastus lateralis muscle proximally (McDonnel *et al.*, 1987). Stimulation occurred with the voltage kept constant at 250 V. Initially, stimulated twitches (1 Hz) were used to locate the optimum site and current for electrical stimulation of the quadriceps (Cooper *et al.*, 1998; Stokes *et al.*, 1988). The current (mA) from the stimulator was then adjusted until at least 40% of the MVC force was produced during stimulation using a 1 second, 100 Hz pulse. This current was then used throughout the experiment.

The stimulator was computer driven (Amstrad) and delivered trains of stimuli (pulse width 200ms) in a set pattern of frequencies of 20 Hz and 100 Hz. The muscle was stimulated at each frequency for a period of 1 second with an interval of 5 seconds between each stimulation. The mean force for each frequency (F_{20} and F_{100}) was then calculated. A maximum voluntary contraction with superimposed percutaneous electrical myostimulation (MVS) was also obtained by applying a 1 second pulse of a 100 Hz stimuli during a 3 seconds voluntary contraction at the conditions established above. The pulse was applied once the maximum force level had been attained (Strojnik and Komi, 1996). Verbal encouragement was also given during the MVS trial. A permanent marking pen, was used to outline the position of the EMG electrodes on the muscles. This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999).

In addition, immediate-onset muscle pain and delayed onset muscle soreness were assessed after the exercise bout and on days 1, 2, 3, 4 and 5 of recovery respectively as previously described. Ratings of perceived exertion were also recorded after each set.

5.2.4 Results

Examples of the force-time curves produced from a maximum voluntary contraction with superimposed percutaneous electrical myostimulation are given in Figure 5.2a and Figure 5.2b. Figure 5.2a shows a force recording with complete motor unit activation, whereas Figure 5.2b clearly illustrates a deficit in motor unit activation.

For Subject A, the pre-exercise MVC and MVS values were 539 N and 551 N respectively, a difference of only 2.2%. Immediately following exercise, the decline in MVC was 6.9 %. Values recorded over the immediate recovery period were consistently lower at each measured time point with a maximal force loss of 17 % occurring two hours after exercise (Figure 3). Over the immediate recovery period, the MVS technique consistently increased the force generation, but only to a maximum of 6.7%. It can be seen that 24 hours post exercise, full recovery of MVC has almost taken place although the MVS was 8.2% higher than the MVC. After 48 hours of recovery, a supercompensation effect has taken place with the MVC 10.0 % higher than the pre-exercise value. This finding corresponds to the large (10.7 %) increase in voluntary neural activation over the time period of 500-1500 ms (maximal force production phase), despite the very high rating of upper leg muscle soreness. The MVS is only 4.5 % higher than the MVC.

For subject A, RFD_{avg} was also reduced after exercise. Immediately and 30 minutes post exercise the decline in RFD_{avg} was 9.9 % and 7.8 % respectively. Maximal reduction in RFD (18.3%) was observed 60 minutes after exercise, but then recovered to within 9.6 % of base-line over the next hour. The maximal reduction in RFD_{avg} is

supported by the large decrease in neural drive over the early part of the force-time curve (0-500 ms).

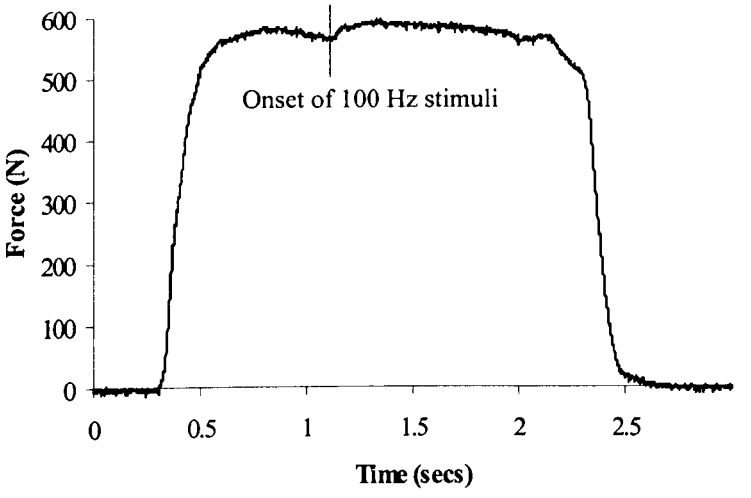


Figure 5.2a Typical isometric force-time curve for leg extensor muscles with superimposed percutaneous electrical myostimulation recorded prior to a heavy resistance exercise session.

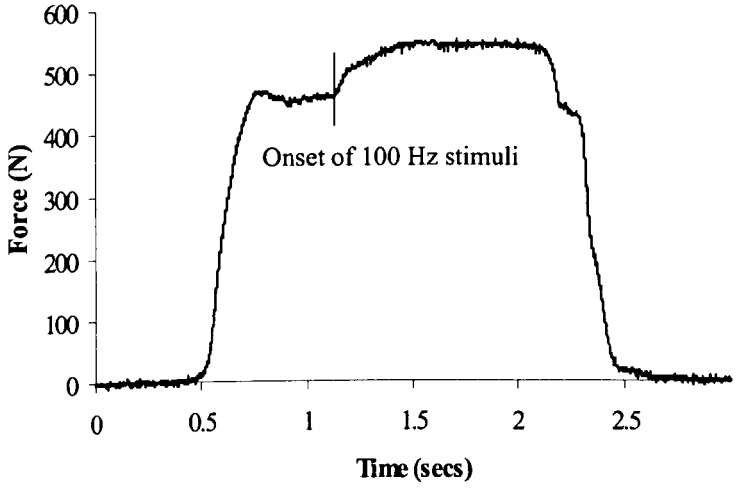


Figure 5.2b Typical isometric force-time curve for leg extensor muscles with superimposed percutaneous electrical myostimulation recorded immediately after a heavy resistance exercise session.

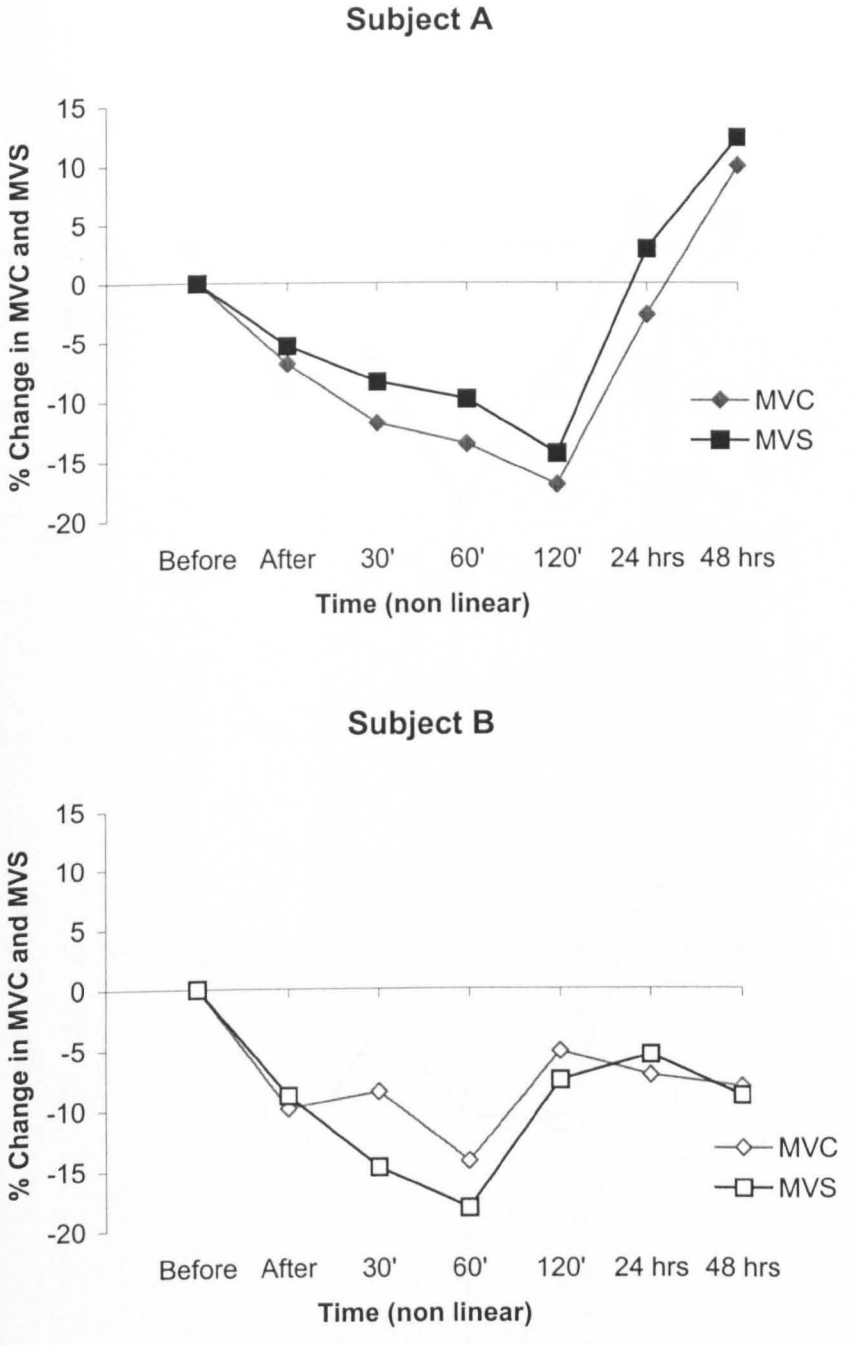


Figure 5.3 Percentage change in maximum voluntary contraction (MVC) force and MVC with superimposed percutaneous electrical myostimulation (MVS) following a single bout of heavy resistance exercise.

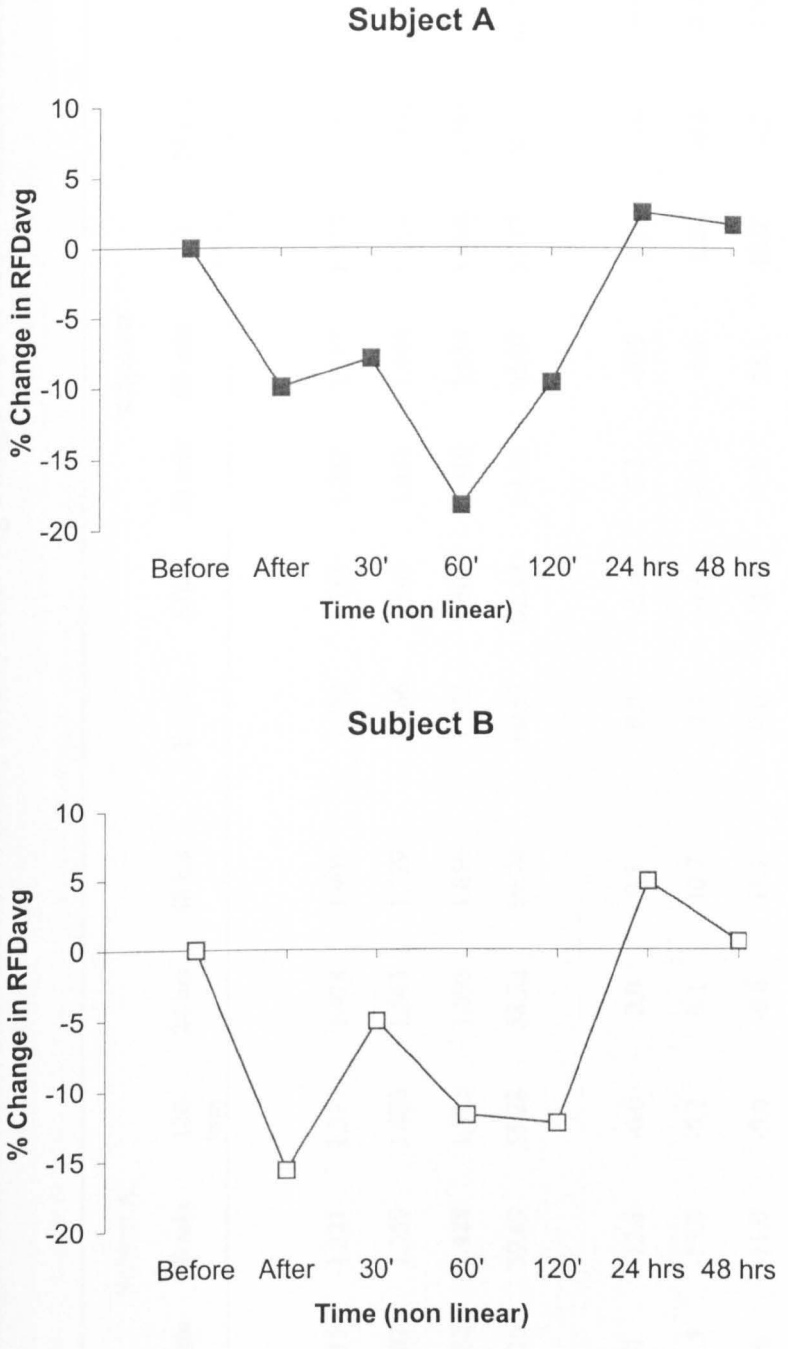


Figure 5.4 Percentage change in average rate of force development (RFD_{avg}) following a single bout of heavy resistance exercise.

TABLE 5.2 Absolute and relative changes in RMS values and Median Frequency (MDF) following a single bout of heavy resistance exercise (HRE).

	Subject A							Subject B						
	Before	After	30 min	60 min	120 min	24 hrs	48 hrs	Before	After	30 min	60 min	120 min	24 hrs	48 hrs
Δ Absolute RMS values (Arbitrary Units)														
0-500 ms	1.401	1.343	1.315	1.221	1.317	1.428	1.405	1.253	1.185	1.212	1.117	1.377	1.183	1.133
500-1500 ms	1.562	1.523	1.397	1.359	1.480	1.563	1.729	1.466	1.443	1.418	1.444	1.584	1.461	1.346
1500-2500 ms	1.604	1.517	1.482	1.428	1.525	1.595	1.856	1.352	1.508	1.410	1.534	1.568	1.395	1.456
MDF (Hz)	60.67	62.62	56.26	59.69	55.28	58.22	59.70	60.67	62.13	64.58	65.07	55.77	60.18	61.15
Δ Relative (%) RMS														
0-500 ms	0.0	-4.1	-6.1	-12.8	-6.0	2.0	0.3	0.0	-5.4	-3.3	-10.9	9.9	-5.6	-9.6
500-1500 ms	0.0	-2.5	-10.5	-13.0	-5.2	0.1	10.7	0.0	-1.6	-3.3	-1.5	8.0	-0.3	-8.2
1500-2500 ms	0.0	-5.5	-7.6	-11.0	-5.0	-0.6	15.7	0.0	11.5	4.3	13.4	16.0	3.2	7.7
MDF	0.0	3.2	-7.3	-1.6	-8.9	-4.0	-1.6	0.0	2.4	6.5	7.3	-8.1	-0.8	0.8

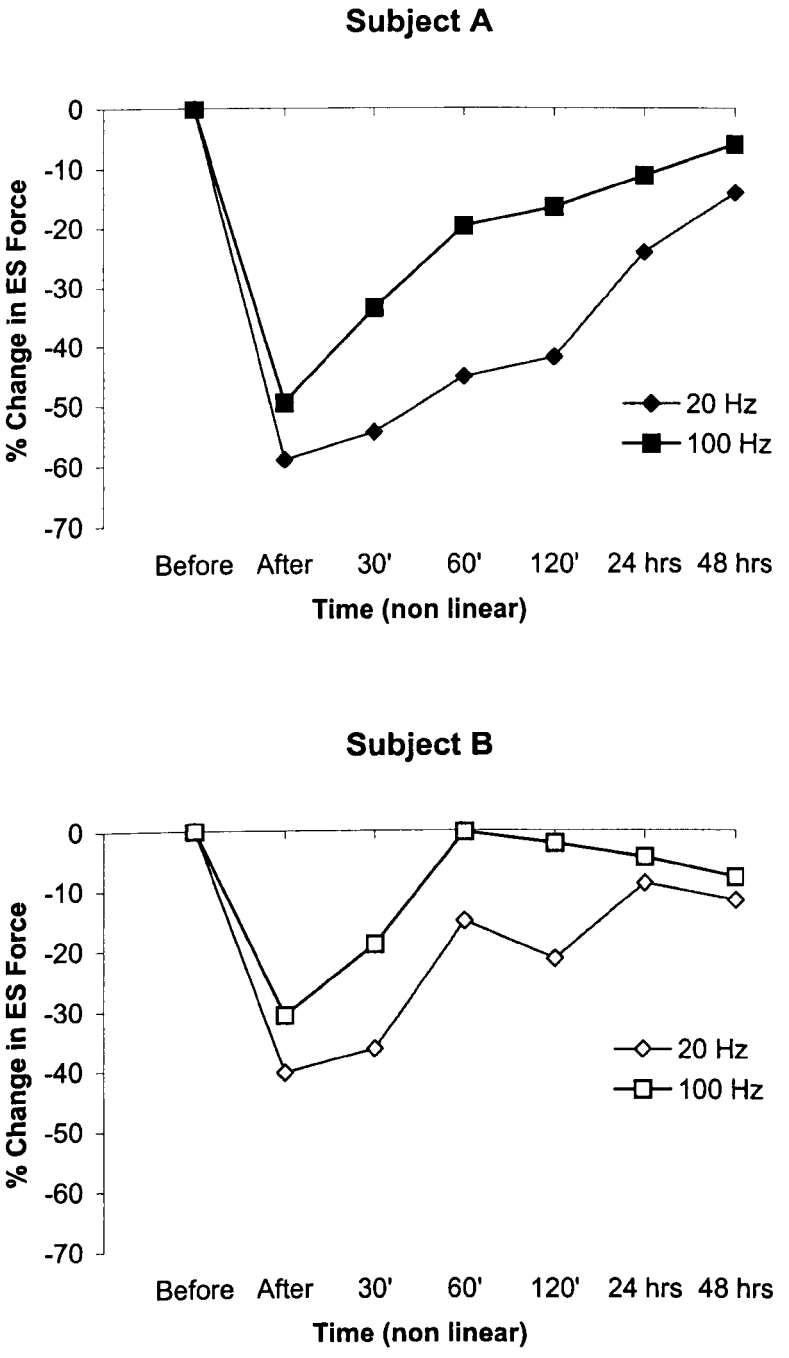


Figure 5.5 Percentage change in force elicited by electrical stimulation following a single bout of heavy resistance exercise HRE).

TABLE 5.3 Upper leg muscle soreness (DOMS), following a single bout of heavy resistance exercise (HRE).

		Before	After	2 hrs	24 hrs	48 hrs	72 hrs	96 hrs	120 hrs
Subject A Right Quadriceps	GS	0	1	3	7	8	1	0	0
Left Quadriceps	GS	0	1	3	7	8	1	0	0
Right Quadriceps	LS	0	3	7	16	18	11	7	5
Left Quadriceps	LS	0	3	7	16	18	11	7	5
Subject B Right Quadriceps	GS	0	0	0	3	3	0	0	0
Left Quadriceps	GS	0	0	0	3	3	0	0	0
Right Quadriceps	LS	0	0	0	3	3	0	0	0
Left Quadriceps	LS	0	0	0	3	3	0	0	0

GS = General Soreness

LS = Leg Soreness

Ratings of perceived exertion

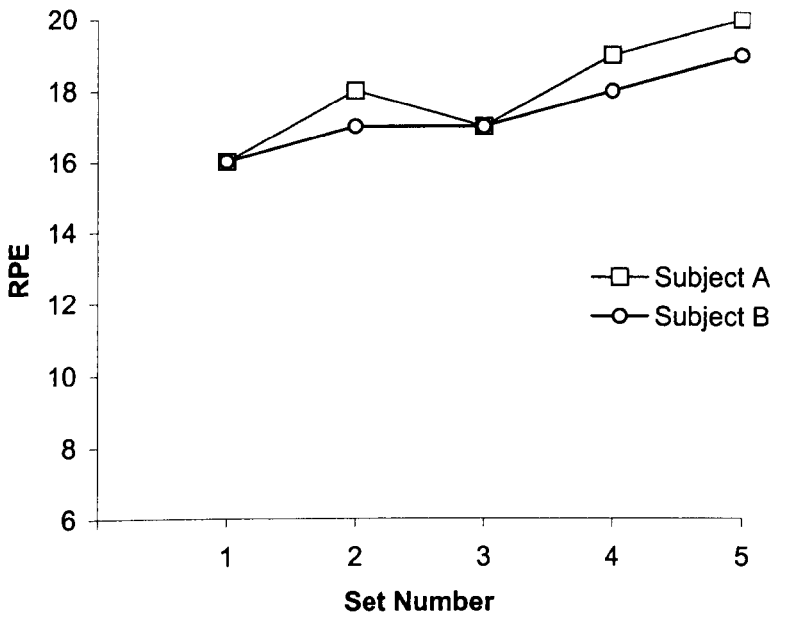


Figure 5.6 The response of rating of perceived exertion (RPE) to the heavy resistance exercise (HRE) session.

5.2.5 Discussion

The technique of superimposing single electrical impulses on a voluntary contraction has been shown to be reliable in detecting incomplete muscle activation during isometric contractions, with the use of either motor nerve or percutaneous stimulation (Bélanger and McComas, 1981; Merton, 1954). However more recently, it has been shown that applying short trains of high frequency stimulation has been more successful in assessing voluntary activation of the human quadriceps following fatiguing exercise (Brown *et al.*, 1996; Newham *et al.*, 1991). In the present study, a 1 second pulse of a 100 Hz stimuli was superimposed during the performance of a 3 seconds maximum voluntary isometric contraction at a level sufficient to induce at least 40% of the subject's MVC as described by Brown *et al.* (1996). Further, the MVS values may more clearly demonstrate the force generating capability of the exercised muscles.

For subject A, large reductions in MVC were observed in the initial two hours recovery period. The MVS technique consistently increased the force generation by approximately 6% at the time points of 30, 60 and 120 minutes post exercise. After 24 hours of recovery, MVC had returned to within 3% of pre-exercise levels, although the MVS technique increased this value by 8%. It is also interesting to note that 24 hours post exercise, RFD_{avg} and maximal voluntary neural activation had returned to within pre-exercise values. From approximately 30 to 90 % of MVC, tension is largely increased by recruitment, thereafter an increased firing rate of motor units effects 100 % MVC (DeLuca *et al.*, 1982; Kulkulka and Clamann, 1981; Milner-Brown *et al*, 1973). Therefore it is possible that after 24 hours of recovery some

motorneurons were not firing impulses at the optimal frequency for maximum force generation.

On the other hand during the first two hours of recovery, large decreases in RFD_{avg} and maximal voluntary neural activation were observed. As RMS values are considered to provide a measure of the number of recruited motor units during voluntary contractions (Basmajian and De Luca, 1985), it is more likely that the differences in force between MVS and MVC are because of an inability to recruit damaged or vulnerable muscle units, rather than a lack of optimisation of firing frequency. Although serum CK was not measured for this pilot study, the very high ratings of upper leg muscle soreness suggest that a substantial amount of structural damage could have occurred as a result of the heavy resistance exercise session.

For subject B, very different results were observed, as the MVC values were consistently higher than the MVS values. It is therefore reasonable to accept that due to the large number of measurements, this subject lacked motivation on the third trial to generate maximum force even with the superimposed 1-second pulse of electrical stimulation. It is also interesting to note the failure for both MVS and MVC to recover from 24 to 48 hours. Decrements in force elicited by electrical stimulation were also observed over this period. Such loss of force may again be possibly explained by structural damage although subject B reported no muscle soreness (Table 5.2).

5.2.6 Conclusions and recommendations

It appears that the technique of superimposing a 1 second pulse at 100 Hz during the performance of a maximum voluntary contraction may demonstrate more clearly the force generating capacity of the exercised muscle. However due to the large number of measurements that are to be recorded at each time interval it is important that subjects are fully motivated to complete the experimental protocol.

5.3 Introduction

The mechanisms of neuromuscular fatigue in human skeletal muscles can be divided into those of central and peripheral origin, depending on whether the site is proximal or distal to the neuromuscular junction (Edwards, 1981; 1983). A multitude of publications describe the neural and muscular mechanisms of fatigue (e.g. Bigland-Ritchie, 1984; Bigland-Ritchie and Woods, 1984; Bigland-Ritchie *et al.*, 1986a; 1986b) while others have explored the biochemical changes with fatigue (e.g. McKenna, 1992; Clausen, 1986; Clausen and Nielson, 1984). However the neuromuscular changes whereby a trained muscle offers a better resistance to fatigue has not been clearly defined.

5.3.1 Objective of the study

The objective of this study was to examine the effects of a six-weeks heavy resistance and dynamic strength training programme on the acute neuromuscular and metabolic responses to a single heavy resistance and dynamic strength exercise session in subjects engaged in team sports.

5.4 Methodology

5.4.1 Subjects

Twelve male students from the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, volunteered for the study. All subjects were from a team sport background although were not regularly competing during the experimental period. Each subject was well informed about the possible risks associated with the experiment and gave their written informed consent prior to participation. Approval was obtained for this study from the Ethics Committee of Liverpool John Moores University. The subject details are presented in Table 5.4.

Table 5.4 Subject details (mean ± SD) for the heavy resistance and dynamic strength training groups

	Count (f)	Age (yr)	Height (m)	Mass (kg)	
				Pre-training	Post-training
HRE group	6	25 (5)	1.73 (0.04)	81.5 (7.57)	81.5 (7.71)
DSE group	6	22 (4)	1.77 (0.05)	84.0 (14.5)	84.1 (14.6)

5.4.2 Experimental design

Subjects followed either a heavy resistance or dynamic strength training programme, and trained 2 times per week under supervision. Subjects were assigned to either the heavy resistance or dynamic strength training groups, matched in terms of pre-training strength scores (Wilson and Murphy, 1995). The length of the training programme was 6 weeks. This is normally the maximum length of a mesocycle designed for increasing strength or power (Sale, 1988). It was not deemed necessary to include a control group, as the training load was much greater than the subject's normal habitual level of activity.

The acute neuromuscular and metabolic responses to a single exercise session (either HRE or DSE) were measured after the first training session (Figure 5.7). Tests of muscle function were performed up to 48 hours post exercise. Following the 6 weeks of training, measurements of maximum voluntary isometric contraction force, average rate of force development and squat 1RM were taken +3 days after the last training session. One week full recovery was then allowed before assessing the acute responses to a subsequent training session +10 days after the last training session. The absolute load (repetitions x weight) was the same for the pre- and post- test conditions for both training groups (Pierce *et al.*, 1993).

In assessing muscular function, measurements of neuromuscular electrical stimulation (NMES) of the quadriceps muscle were recorded before the exercise session and immediately (5 minutes) after the session. The same measurements were also repeated during the recovery period at intervals of 30, 60 and 120 minutes as well as for 24 and 48 hours afterwards. Measurements of maximal voluntary neural activation

and force production were also recorded at the same time intervals, 1 minute after electrical stimulation in each case. A maximum voluntary contraction with superimposed percutaneous electrical myostimulation was then recorded, 1 minute after the second voluntary contraction. The testing sessions always took place at the same time of day from either 9.00 am to 12.00h or from 14.00 to 1700h to control for circadian variation (Atkinson and Reilly, 1996). The test protocol followed the format as illustrated in Figure 5.8.

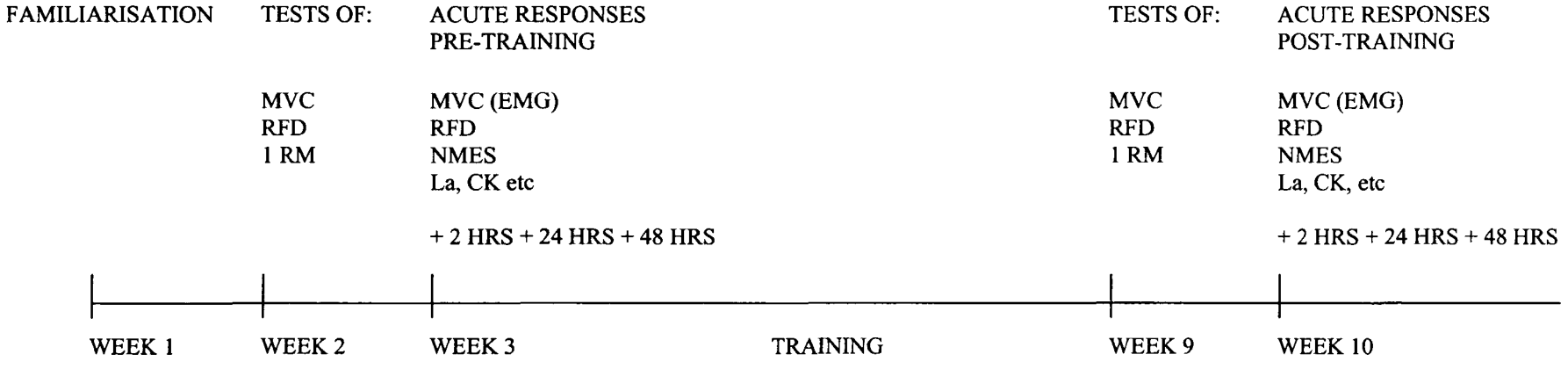


Figure 5.7 Plan of experimental design given to each subject.

TIME	ACTIVITY/MEASURE
BEFORE EXERCISE	
+ 0 min	Base-line blood sample and muscle soreness
+ 15 min	NMES followed by MVC with simultaneous recording of surface EMG and MVS technique
	Exercise session, either HRE or DSE. Rating of perceived exertion (RPE) recorded after each set
AFTER EXERCISE	
+ 3 min	Muscle soreness and blood sample
+ 5 min	NMES, MVC (EMG), MVS
+ 30 min	Blood sample
	NMES, MVC (EMG), MVS
+ 60 min	NMES, MVC (EMG), MVS
+ 120 min	Muscle soreness and blood sample
	NMES, MVC (EMG), MVS
+ 24 hrs	Muscle soreness, blood sample, NMES, MVC (EMG), MVS
+ 48 hrs	Muscle soreness, blood sample, NMES, MVC (EMG), MVS

Figure 5.8 Protocol to quantify the neuromuscular and metabolic responses to a single exercise session before and after a six-weeks heavy resistance and dynamic strength training programme.

5.4.3 Experimental procedures

5.4.3.1 Familiarisation

All subjects were required to attend at least two familiarisation sessions in week 1 (Figure 5.7). In these sessions, subjects were familiarised with contractions produced by neuromuscular electrical stimulation, the performance of maximum voluntary isometric contractions (also with superimposed percutaneous electrical myostimulation), the squat exercise and loaded counter-movement vertical jumps. Approximate loads for the one repetition maximum (1RM) for the squat exercise were determined during week 1. In week 2, measurements of maximum voluntary isometric contraction force, rate of force development and squat 1RM were taken for all subjects. These data were then used to assign subjects to the two different strength-training groups and to determine individual work loads. The one repetition maximum was determined for each subject using the protocol described in Study 2.

5.4.3.2 Strength training sessions

Initially, for the heavy resistance exercise (HRE) training group, subjects performed 5 sets of 6 reps of the back squat exercise at a load approximating to 85% to 90% of the pre-training 1RM. However as subjects improved during the course of training, the load was adjusted for each set and session such that fatigue always occurred on the last repetition, thus establishing a 6RM. Although the loads lifted were heavy and the actual movement velocity was low, each subject was instructed to move the bar as quickly as possible, such that the intended movement velocity was high (Behm and Sale, 1993b).

In the dynamic strength exercise (DSE) training group, the subjects performed 5 sets of 10 loaded counter-movement vertical jumps. The technique of these jumps has been described in detail in Study 2. In the previous study, the load selected for these jumps was 30% of the 1RM. Newton and Wilson (1993) and Wilson *et al.* (1993) proposed that this load corresponds to the load, which maximises the mechanical power output of the musculature. However more recently, Fell *et al.* (2001) have demonstrated that significant increases ($p<0.05$) in average concentric power output are achieved using a load of 20% 1RM. Interestingly there were no further increases in power output when the load was increased to 30% 1RM. Subjective responses from subjects in Study 2 suggested that a load of 30% 1RM was too heavy and subsequently prevented them from working "explosively". In the study by Fell and co-workers, as the load was increased from 20% to 30% 1RM, significant decreases ($p<0.05$) in take-off velocity were observed.

It was initially planned for the start of the training study, that the load, which maximised the mechanical power output of the musculature would be determined for each individual. This load would then be assessed after 2 and 4 weeks so the load would be optimal for the entire 6 weeks training block (Wilson *et al.*, 1993). However for practical purposes a starting load of 20% was used for the first 2 weeks of training, 25% for the next 2 weeks and then 30% for the last 2 weeks of training. For both training groups, 48-72 hours recovery were allowed between training sessions.

No other forms of lower body strength training were permitted during the experimental period, although subjects were allowed to continue with their normal activities such as running or cycling. It is important to note that the effects of the two

different exercise programmes on maximum voluntary isometric contraction force and rate of force development, were also determined by comparing pre- and post training values. As data were available for +3 and +10 days post training, the effects of an unloading week was also examined. Each subject was required to record his food and fluid intake 24 hours prior to the test and also on the three test days pre-training. Subjects were instructed to follow the same diet for the subsequent test sessions.

5.4.3.3 Neuromuscular measurements

The force generated by the quadriceps femoris muscles of the right leg was measured using a strain gauge dynamometer attached to an adapted Lido Isokinetic Dynamometer chair (Loredan, Davis, CA) as described in detail in Study 2. The strain gauge dynamometer was calibrated each week, by applying a series of known weights and converting the resulting voltage into force.

Force data from the strain gauge were amplified and collected on-line by an Archimedes 310 Computer via a 12 bit analogue-to-digital converter. A sample frequency of 1000 Hz was used for the collection of force and electromyographical data from the maximal voluntary contractions and a sample frequency of 100 Hz was used for collection of force data elicited by electrical stimulation. All data were stored on magnetic discs for later analysis.

From the resultant force-time curve, data were recorded for peak force and the average rate of force development (RFD_{avg}) (Viitasalo *et al.*, 1980). Surface electromyographic activity (EMG) was simultaneously recorded during the maximal

isometric testing contractions from the vastus lateralis (VL) muscle of the right leg onto a second channel. Root mean square (RMS) and median frequency (MDF) values were determined from the raw myoelectrical signal (Basmajian and De Luca, 1985). RMS values were calculated for the time periods of 0-500 ms, 500-1500 ms and 1500-2500 ms (Linnamo *et al.*, 1998).

Neuromuscular electrical stimulation (NMES) of the quadriceps was evoked using a Digitimer high voltage stimulator (Hertfordshire, UK). Self-adhering neurostimulation electrodes (Chattanooga, USA; 3" x 5") were placed over the vastus medialis muscle distally (just above the knee) and the vastus lateralis muscle proximally (McDonnel *et al.*, 1987). Stimulation occurred with the voltage kept constant at 250 V. Initially, stimulated twitches (1 Hz) were used to locate the optimum site and current for electrical stimulation of the quadriceps (Cooper *et al.*, 1998; Stokes *et al.*, 1988). The current (mA) from the stimulator was then adjusted until at least 40% of the MVC force was produced during stimulation using a 1 second, 100 Hz pulse. This current was then used throughout the experiment.

The stimulator was computer driven (Amstrad) and delivered trains of stimuli (pulse width 200μs) in a set pattern of frequencies of 20 Hz and 100 Hz. The muscle was stimulated at each frequency for a period of 1 second with an interval of 5 seconds between each stimulation. The mean force for each frequency (F_{20} and F_{100}) was then obtained. A maximum voluntary contraction with superimposed percutaneous electrical myostimulation was also obtained by applying a 1 second pulse of a 100 Hz stimuli during the 3 seconds voluntary contraction at the conditions established above. The pulse was applied once the maximum force level had been attained (Strojnik and

Komi, 1998). Verbal encouragement was also given during the MVS trial. A permanent marking pen was used to outline the position of the EMG and electrical stimulation electrodes on the muscles. This ensured placement of the electrodes would be as similar as possible for the three testing sessions (Keogh *et al.*, 1999).

5.4.3.4 Blood measurements

Finger prick blood samples were taken before the exercise session, 3 minutes and 30 minutes after the session, and 120 minutes after the exercise session. Blood samples were also collected 24 and 48 hours post exercise.

The plasma was pipetted into 5 ml plain tubes and again stored at -80^{0}C for later analysis of potassium and creatine kinase. Blood collected 24 and 48 hours post exercise was analysed for creatine kinase only. The potassium and creatine kinase concentrations of the plasma samples were analysed at the Department of Clinical Chemistry, Royal Liverpool Hospital. Plasma volume changes were also calculated as described in Study 2.

5.4.3.5 Upper leg muscle soreness

Immediate-onset muscle pain and delayed onset muscle soreness (DOMS) were assessed after the exercise bout and also after 24 and 48 hours of recovery. Before taking a blood sample, each subject was required to rate the soreness of the quadriceps femoris muscles of both the stimulated and non-stimulated leg using the graphic rating scale as previously illustrated. The subjects were instructed to indicate the soreness of the entire muscle area in two ways: firstly in a relaxed state (general soreness, GS), and then while performing knee-flexion exercise (leg soreness, LS)

(Thompson *et al.*, 1997). It was demonstrated in Study 2, that subjects did not show any discomfort to the technique of electrical stimulation. However in the present study, two subjects reported increased soreness in the stimulated leg, particularly in the area of the position of the medial electrode. Therefore as no significant differences in muscle soreness were reported between legs in Study 2, muscle soreness data for the left leg is presented here.

5.4.3.6 Ratings of perceived exertion

Ratings of perceived exertion (Borg, 1970) were measured during the course of the pre- and post training exercise sessions using the procedures described in Study 2.

5.4.4 Statistical analyses

5.4.4.1 Training data

To examine the effects of the two training modalities (HRE and DSE) on the maximum measures on strength, the data were analysed using a two-factor analysis of variance (ANOVA), with repeated measures. Statistical analyses of MVC and RFD_{avg} were performed using a 2 x 3 (Group x Time) ANOVA with repeated measures on the last factor, Time (pre-train and + 3 days and + 10 days post training). Statistical analysis of 1 RM was performed using a 2 x 2 (Group x Time) ANOVA with repeated measures on the last factor, Time (pre-train and + 3 days post training).

Post-hoc t-tests for paired samples and independent t-tests were subsequently conducted when significant differences in the ANOVA were found to identify differences within and between group means. For the post-hoc analysis, significance levels were adjusted using a Bonferroni *t* correction. The adjusted *p*-value was determined by dividing alpha (0.05) by the number of repeated comparisons (i.e. 2), such that $p < 0.025$ was the minimum level of significance (Field, 2000).

5.4.4.2 Fatigue and recovery characteristics

The effects of the six-weeks training programmes on the neuromuscular and metabolic responses to a single heavy resistance exercise or dynamic strength exercise session were examined using a three-factor analysis of variance (ANOVA) (Group x Train x Time), with repeated measures on the last 2 factors; train (i.e. the difference between pre- and post training scores) and time (i.e. the changes over time after each exercise session). The third factor, Group represents the difference between the heavy resistance exercise and dynamic strength exercise sessions. Muscle soreness data and RPE scores were also analysed using a three-factor analysis of variance (ANOVA) (Group x Train x Time), with repeated measures on the last 2 factors (Field, 2000).

5.5 Results

5.5.1 Training data

The familiarisation, pre-training and post training strength scores are presented in Table 5.2. A 2 x 2 (Group x Time) ANOVA with repeated measures on the last factor established that there were no significant differences between the familiarisation and pre-training test scores for all three variables and also that there were no significant differences for pre-training scores between the heavy resistance exercise (HRE) or dynamic strength exercise (DSE) training groups.

A significant ($F = 54.35$, $p < 0.05$) main effect for Time was observed for 1RM squat strength, with increases of 29.7% and 14.5% for the heavy resistance and dynamic strength training groups respectively. The increases in strength were significant for both forms of resistance exercise (paired sample t-tests, Bonferroni corrected, $p < 0.025$). A significant ($F = 9.62$, $p < 0.05$) Group x Time interaction was also observed. An independent t-test confirmed that the gains in 1RM strength as a result of the heavy resistance strength-training programme were significantly greater ($p < 0.05$) than those for the dynamic strength-training group.

Table 5.5 Mean (± SD) changes in performance variables following 6-weeks heavy resistance and dynamic strength training.

	Pre-Training		Post-Training	
	Familiarisation	Test	+ 3 days	+ 10 days
Heavy Resistance				
MVC (N)	622.6 125.3	597.4 95.7	627.2 146.9	602.2 134.1
RFD_{avg} (Ns^{-1})	3073.7 1003.8	3006.4 741.1	3134.2 993.0	3075.8 903.0
1 RM	135.0 25.1	137.5 26.0	177.5 32.1	
Dynamic Strength				
MVC (N)	590.8 95.3	584.4 112.8	648.8 98.9	616.2 104.5
RFD_{avg} (Ns^{-1})	3070.4 525.5	3112.7 355.3	3452.6 355.9	3293.7 547.5
1 RM	139.2 11.1	145.0 11.8	165.8 13.2	

Mean changes in MVC in response to the heavy resistance and dynamic strength training regimens are presented in Figure 5.9a. A significant ($F = 7.42$, $p < 0.05$) main effect for Time was observed for MVC. However post-hoc analysis revealed that the 4.3% increase in MVC 3 days after the 6 weeks of heavy resistance training was not significant. A significant increase (paired t-test, Bonferroni corrected, $p < 0.017$) in MVC of 11.8% was observed 3 days after the 6 weeks of dynamic strength training. Although an increase in MVC (5.9%) was still evident 10 days after the last training session, the result was not significant.

Mean changes in RFD_{avg} in response to the two strength training regimens are presented in Figure 5.9b. Small but non-significant increases were observed 3 and 10 days after 6 weeks of heavy resistance training, 4.3% and 3.1% respectively. Gains in RFD_{avg} of 11.4% and 5.6% were apparent after the dynamic strength training programme, but again these gains were not significant.

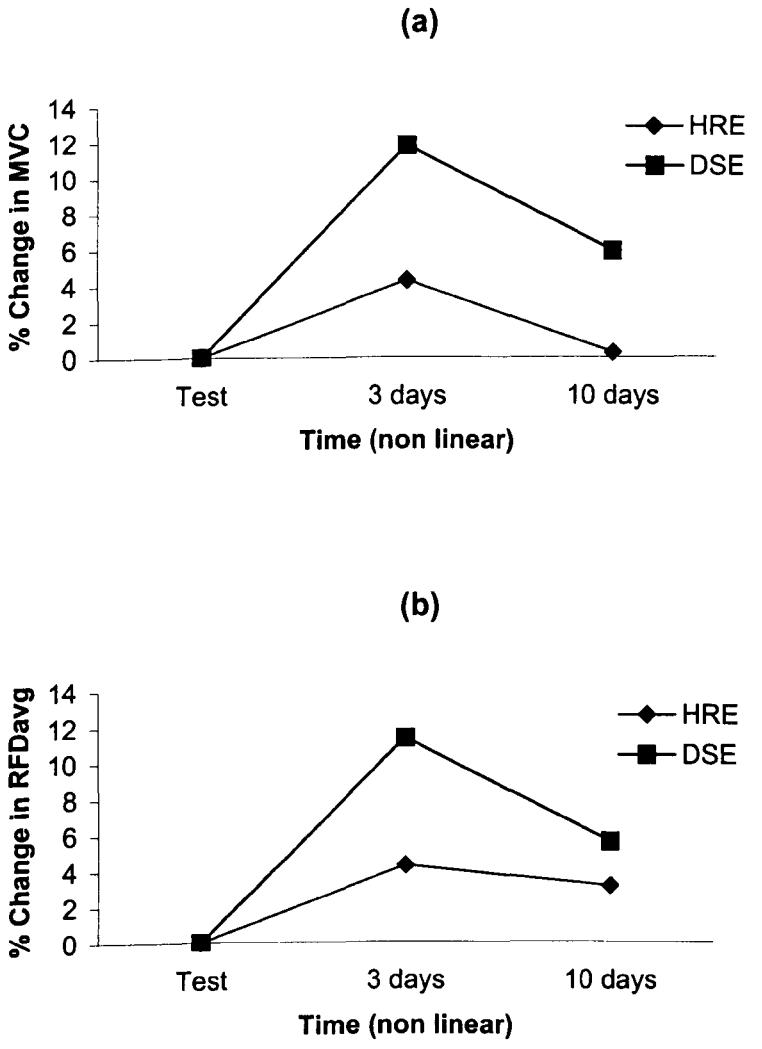


Figure 5.9 Time course of: (a) MVC and, (b) RFD_{avg} development following 6-weeks heavy resistance and dynamic strength training.

Closer examination of the data revealed that there is a large intra-individual variability in response to the different strength training regimens. From Table 5.5, it can be seen that the SDs for MVC and RFD_{avg} +3 and +10 days after the HRE training programme are considerably larger than for the same variables following the DSE training programme. Therefore data for individual subjects for changes in MVC and RFD_{avg} are presented in Figure 5.10 and Figure 5.11 respectively.

In response to the 6 weeks heavy resistance training programme, 3 out of the 6 subjects actually showed large increases in RFD_{avg} ranging from 16.6% to 33.6%. These increases were still evident 10 days after the last training session (Figure 5.11a). However it is important to note that the remaining 3 subjects showed large decrements in force following the training programme, which is therefore reflected in the mean scores and standard deviations. On the other hand, training responses were more consistent across the dynamic strength training group, as illustrated in Figure 5.11b, with only one non-responder.

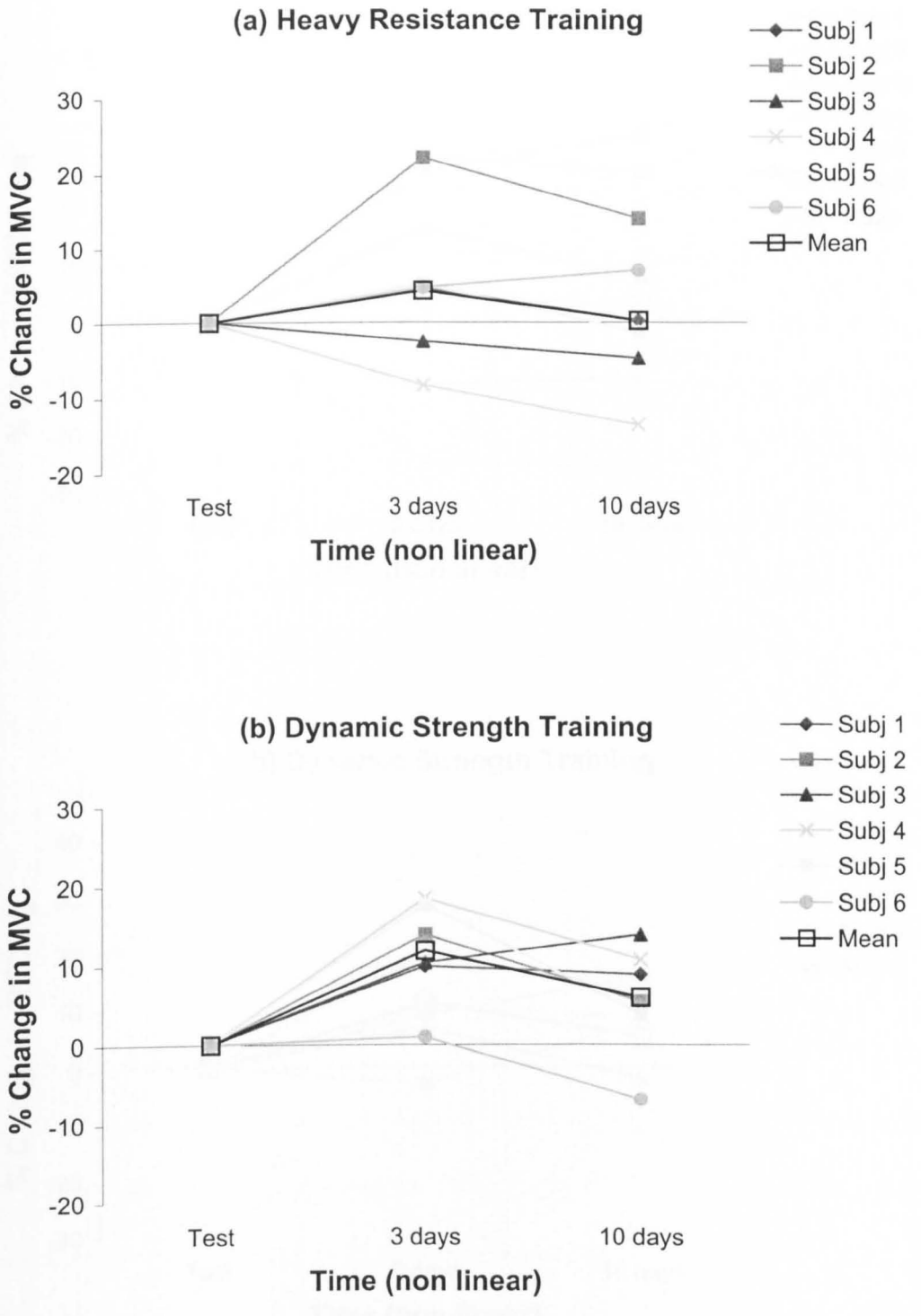


Figure 5.10 Time course of MVC for individual subjects following 6-weeks: (a) heavy resistance and (b) dynamic strength training. Mean data are also presented.

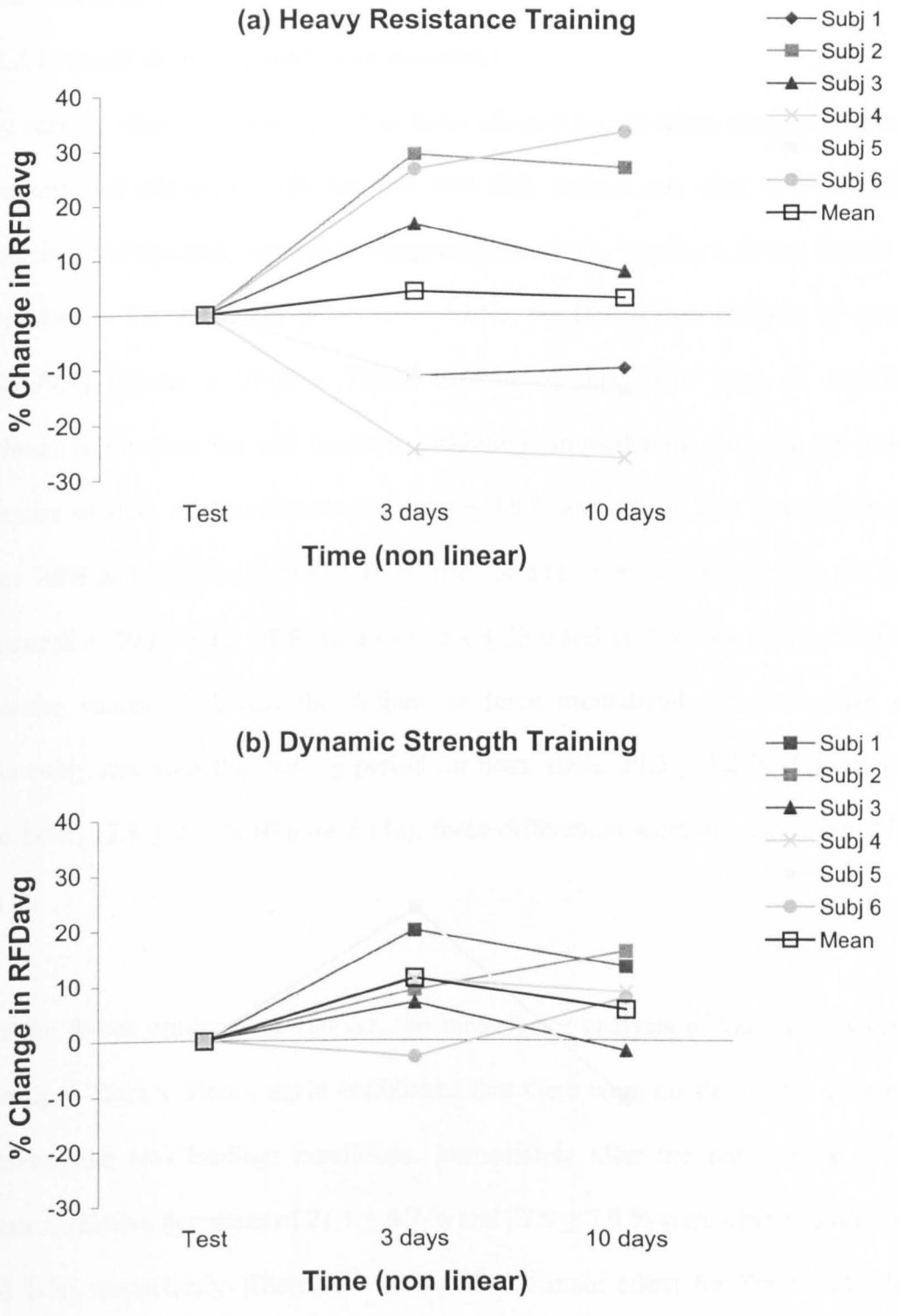


Figure 5.11 Time course of RFD_{avg} for individual subjects following 6-weeks: (a) heavy resistance and (b) dynamic strength training. Mean data are also presented.

5.5.2 Fatigue and recovery characteristics

5.5.2.1 NMES force-frequency characteristics

The relative changes (mean ± SD) in force elicited by electrical stimulation at each frequency of stimulation (20 Hz and 100 Hz), before and after 6 weeks heavy resistance and dynamic strength training are presented in Figures 5.12 and Figure 5.13 respectively. For the forces produced at 20 Hz, the three-factor analysis of variance (ANOVA) (Group x Train x Time), established that there were no significant differences between the two loadings conditions. Immediately after the pre-training exercise session, relative decreases of 40.4 ± 9.5 % and 35.1 ± 12.4 % were observed after HRE and DSE respectively. Even after 24 and 48 hours of recovery, the forces produced at 20 Hz after HRE were still 15.4 ± 23.0 and 16.5 ± 19.4 % from their pre-exercise values. Although the deficits in force immediately after exercise were noticeably less after the training period for both, HRE, 29.2 ± 3.2 % (Figure 5.10a) and DSE, 27.8 ± 8.6 % (Figure 5.11a), these differences were not significant (Table 5.11).

For the forces produced at 100 Hz, the three-factor analysis of variance (ANOVA) (Group x Train x Time), again established that there were no significant differences between the two loadings conditions. Immediately after the pre-training exercise session, relative decreases of 21.1 ± 9.7 % and 27.9 ± 7.9 % were observed after HRE and DSE respectively. There was no significant main effect for Train and relative decreases after the 6 weeks training period for HRE and DSE were 15.4 ± 6.9 % and 21.0 ± 10.7 % respectively. Equally the 6 weeks training had no significant effect on the recovery characteristics after HRE (Figure 5.12b) or DSE (Figure 5.13b).

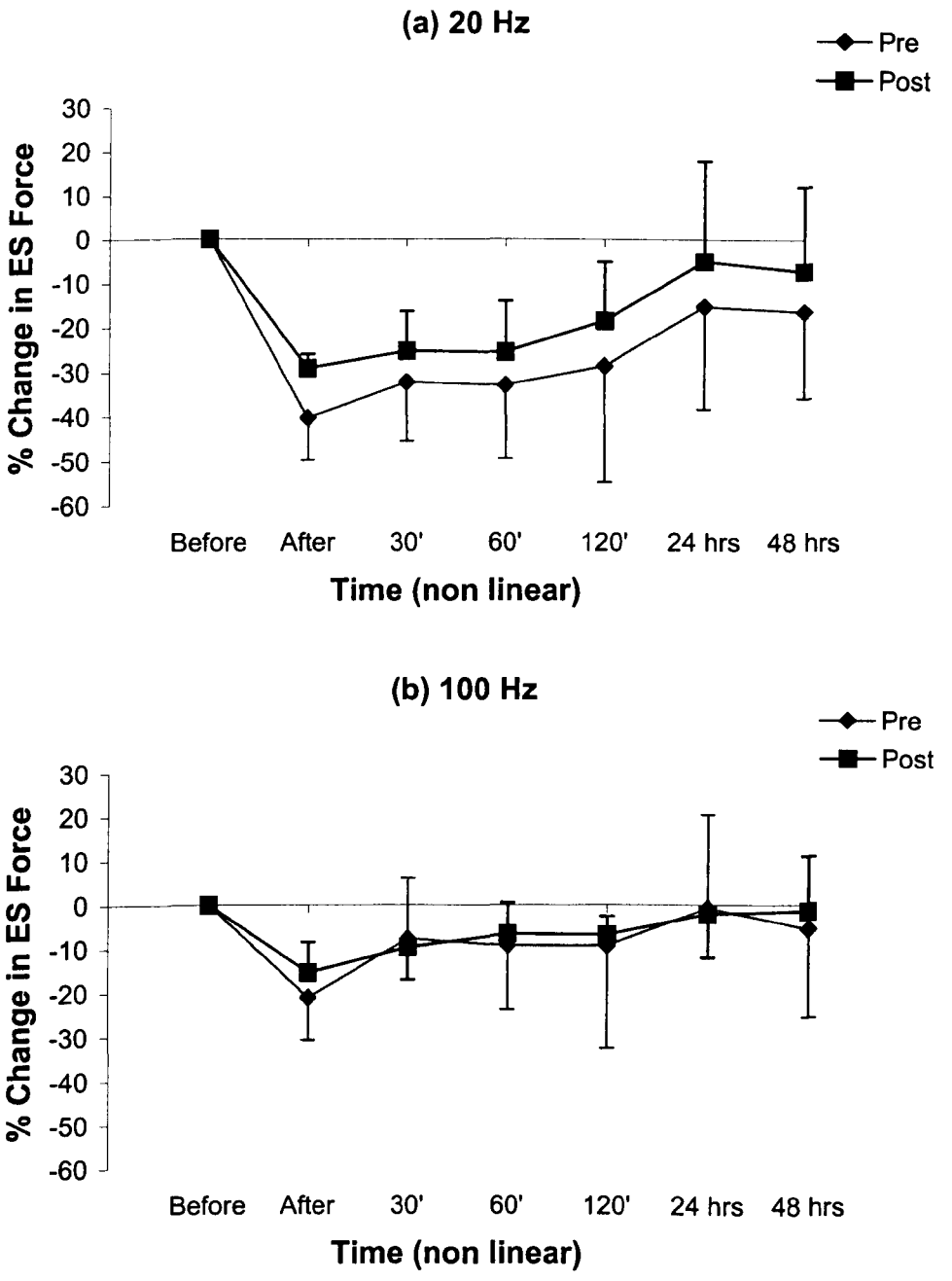


Figure 5.12 Percentage change (mean ± SD) in force elicited by electrical stimulation at frequencies of (a) 20 Hz and (b) 100 Hz, pre-and post 6-weeks heavy resistance training.

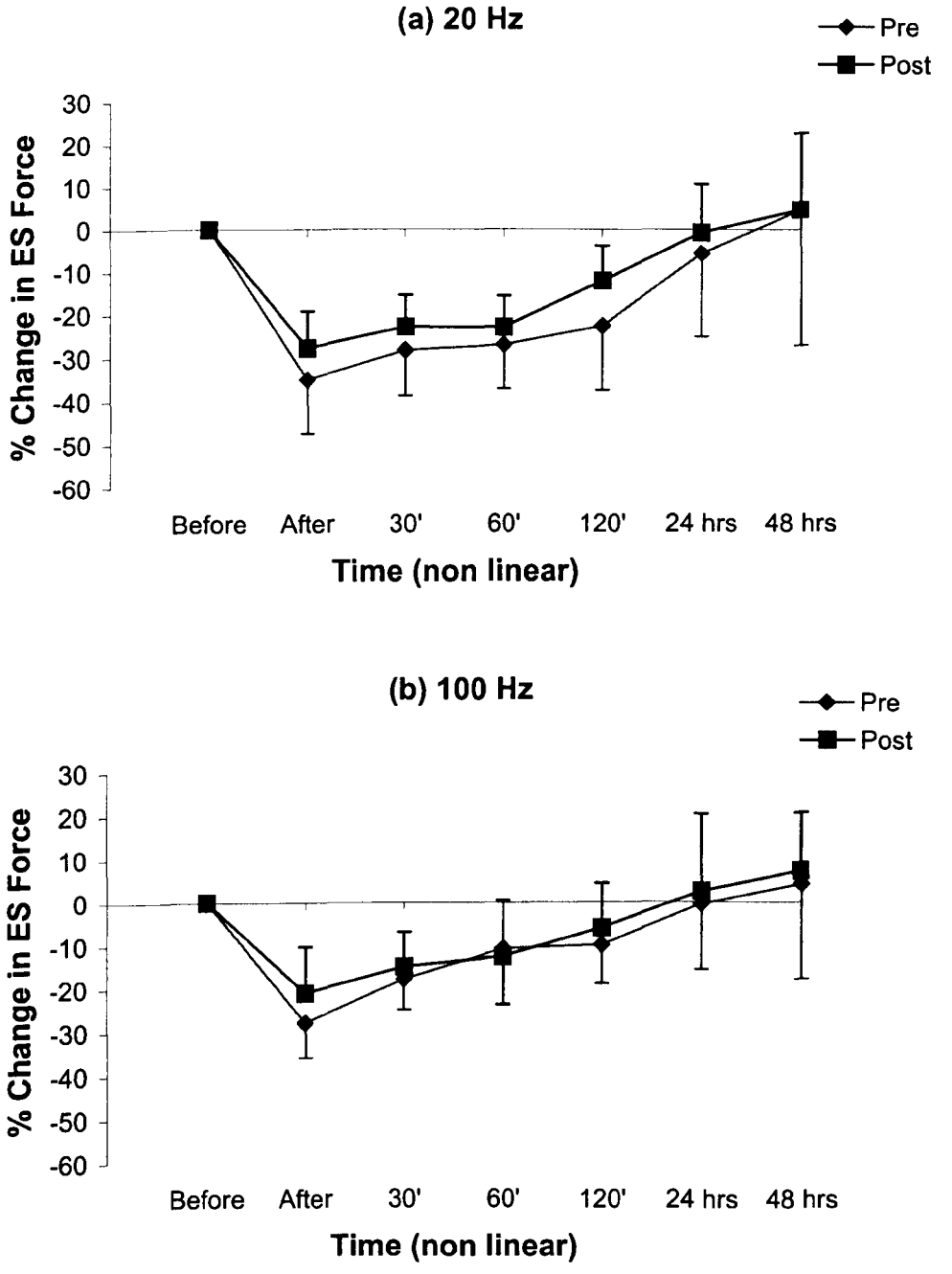


Figure 5.13 Percentage change (mean ± SD) in force elicited by electrical stimulation at frequencies of (a) 20 Hz, and (b) 100 Hz, pre-and post 6-weeks dynamic strength training.

5.5.2.2 Maximum voluntary contraction force (MVC)

The mean (± SD) percentage changes in MVC pre- and post 6 weeks heavy resistance and dynamic strength training are presented in Figure 5.14. The acute responses to a single exercise session pre- and post 6 weeks training for each subject are presented in Appendix 8.

Pre-training, the relative decrease in force immediately after HRE was 17.7 ± 10.1 %. Peak force did not recover within the first 2 hours after exercise and a deficit in force production was still evident after 24 hours (12.4 ± 14.1 %) and 48 hours (13.0 ± 16.6 %) of recovery respectively. It is interesting to note that for subjects 3 and 4, the deficits in force after 48 hours of recovery were very large indeed, 41.3 % and 24.6 % respectively.

Post training, the relative decrease in force immediately after exercise was less (8.3 ± 4.5 %), although again peak force did not recover within the first 2 hours after exercise. On the other hand, mean peak force (Appendix 8) did fully recover after 48 hours, with 3 out of the 6 subjects producing peak forces ranging from 8.9 to 14.3 % above pre-exercise values. However this trend was not the case for subjects 3 and 4, with deficits in peak force again still evident after 48 hours of recovery (9.3 % and 9.8 % respectively.

For DSE, the relative decrease in force immediately after the pre-training exercise session was 10.5 ± 5.5 % compared to 5.0 ± 8.6 % post-training. Some recovery of force took place during the first hour of recovery, pre-training, but then decreased again over the second hour of recovery (Figure 5.14b). Even after the 6 weeks training period, peak force did not recover within the first 2 hours after exercise.

The 3 factor ANOVA established that although the deficits in force after HRE were greater than for DSE, there were no significant differences between the loading conditions (Table 5.11). On the other hand, the differences between pre-and post training scores were significantly different ($F = 7.01$, $p < 0.05$) as indicated by the significant main effect for Train. Furthermore, although the decreases in force even after training were significant ($F = 7.84$, $p < 0.05$), the significant Train x Time interaction ($F = 3.94$, $p < 0.05$) indicates that the 6 weeks training period of either HRE or DSE has a significant effect on the changes in force over time and hence the recovery characteristics. An absence of a Condition x Time interaction demonstrated that the recovery characteristics were not dependent on the training regimen, although it appeared that HRE had a more beneficial effect in reducing the decline in MVC.

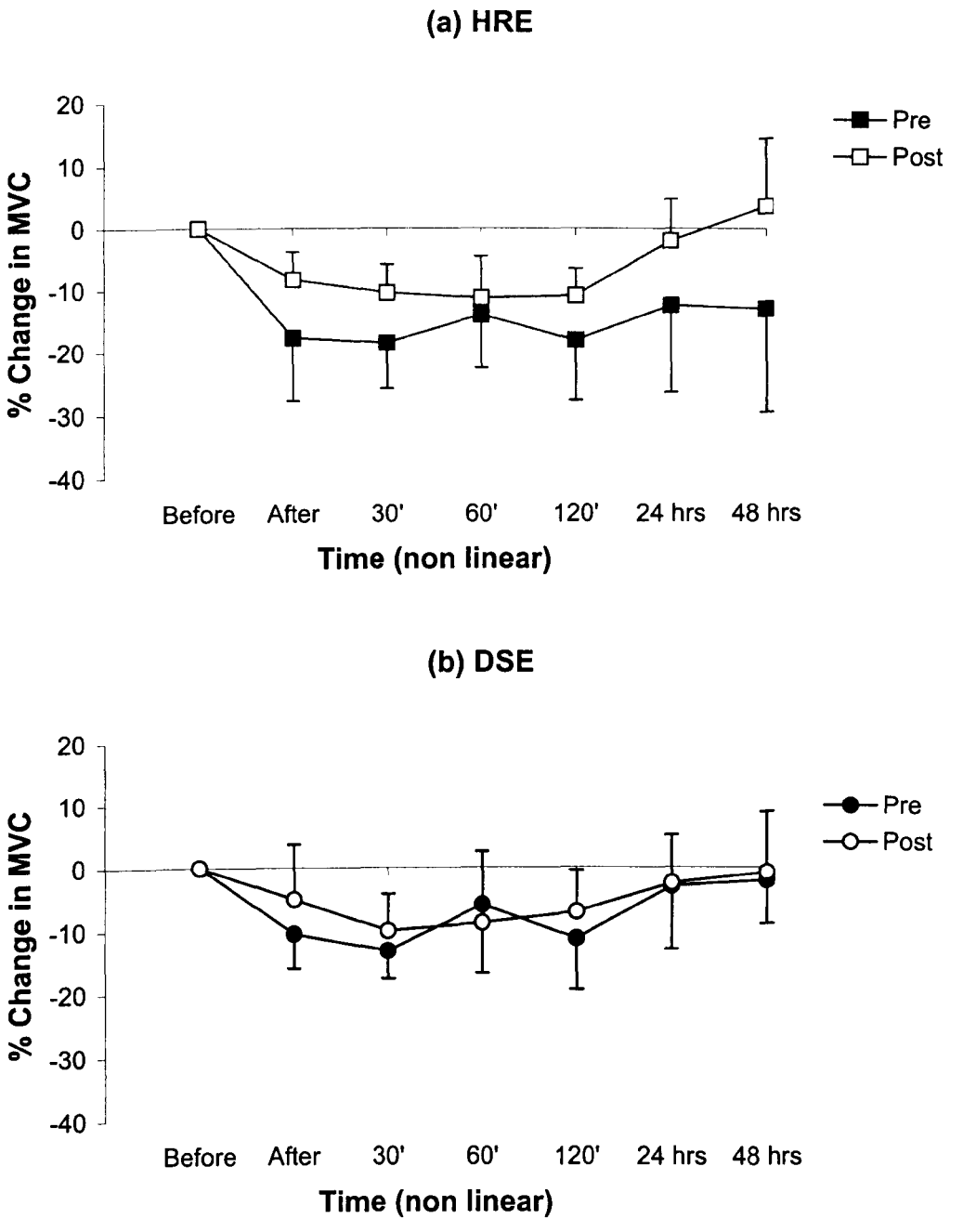


Figure 5.14 Percentage change (mean ± SD) in maximum voluntary contraction (MVC) force pre- and post- 6weeks: (a) heavy resistance training (HRE) and (b) dynamic strength training (DSE).

5.5.2.3 Maximum voluntary contraction force with superimposed percutaneous electrical myostimulation (MVS)

The mean (± SD) percentage changes in MVC and MVS pre- and post 6 weeks heavy resistance and dynamic strength training are presented in Figure 5.15 and Figure 5.17 respectively. The percentage difference between MVC and MVS values for each loading conditioning, pre- and post training are presented in Appendix 8. The 3 factor ANOVA established that there were no significant differences between loading conditions, although there was a significant main effect for time ($F = 11.01$, $p < 0.05$). With regard to the mean data, for HRE, in response to the pre-training session, the MVS technique increased MVC by 4.6 ± 6.8 % after 48 hours of recovery. As illustrated in Figure 5.15a, MVS force recovered from 24 to 48 hours after the HRE, whereas a decrease in MVC was observed. As the SDs were considerably larger for MVS after 24 and 48 hours of recovery data were plotted for individual subjects (Figure 5.16) to illustrate their agreement with the mean trend.

On the other hand, for DSE, in response to the pre-training session, the MVS technique increased the MVC values immediately after, and 30 minutes after the exercise session by 5.8 ± 6.5 % and 6.3 ± 6.9 % respectively. No other noticeable increases in voluntary force generation were observed in response to the loading sessions

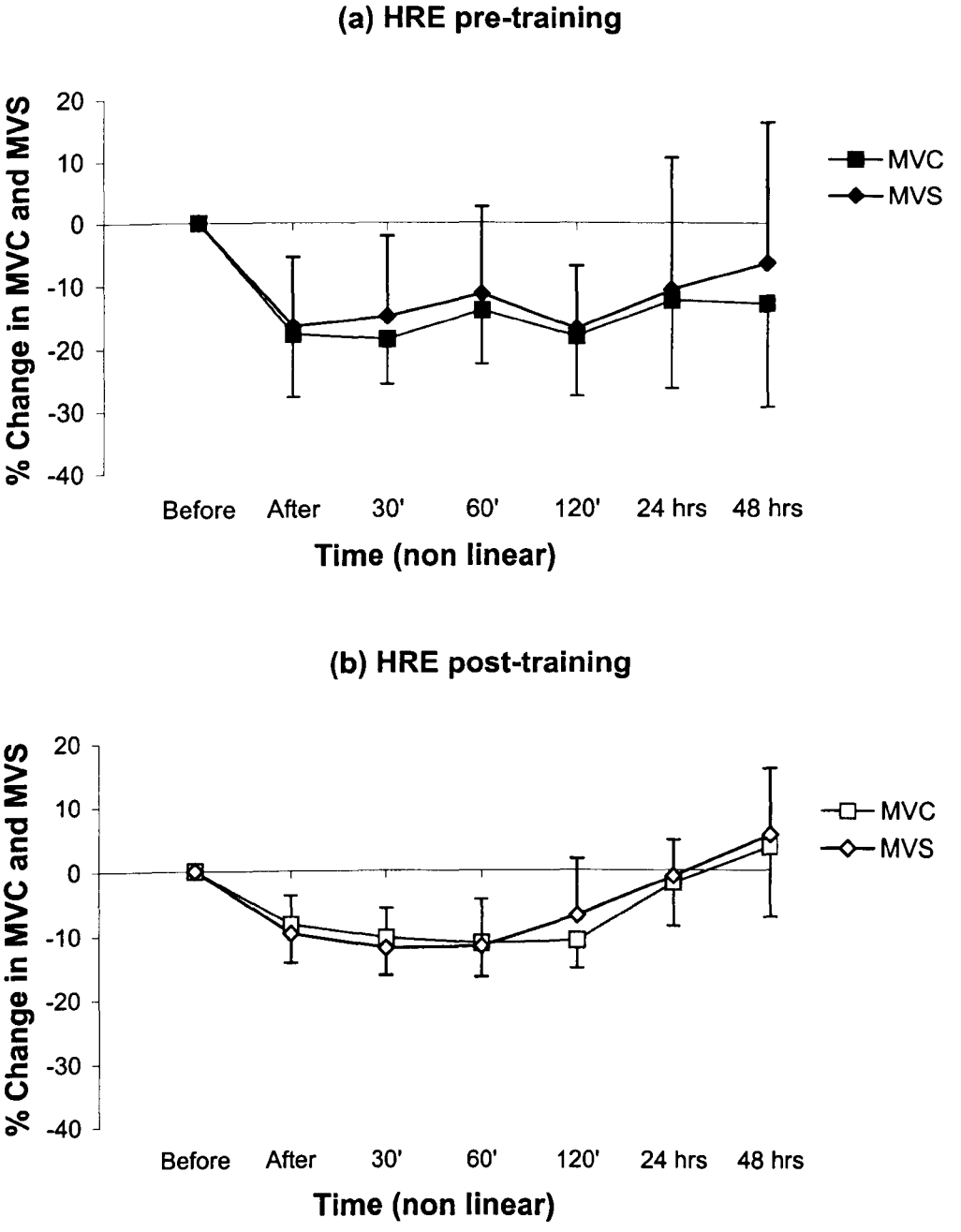


Figure 5.15 Percentage change in maximum voluntary contraction (MVC) force and MVC with superimposed percutaneous electrical myostimulation (MVS) following a single bout of heavy resistance exercise: (a) pre-training and (b) post-training.

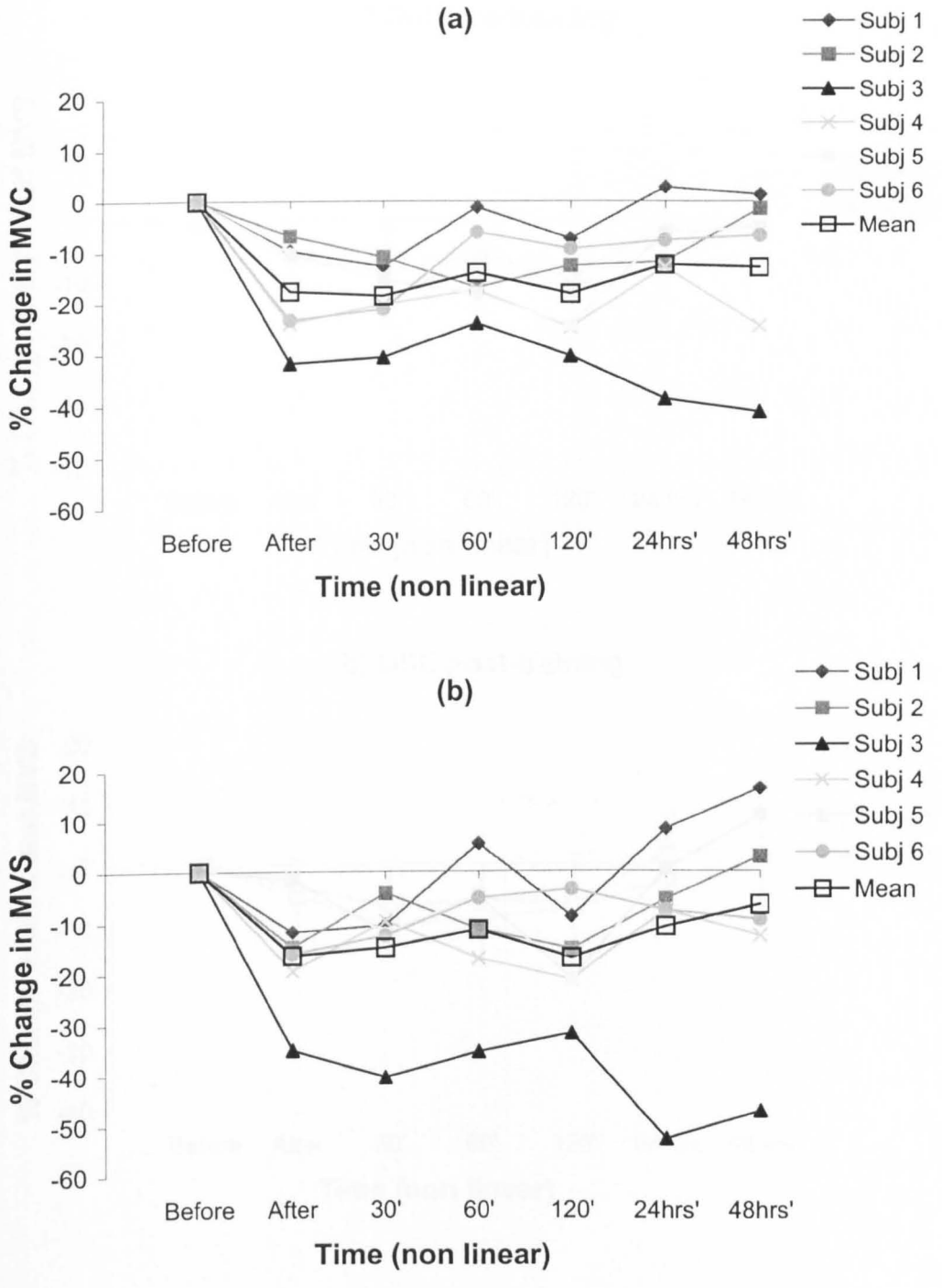


Figure 5.16 Percentage change in (a) maximum voluntary contraction (MVC) force and (b) MVC with superimposed percutaneous electrical myostimulation (MVS) following a single bout of heavy resistance exercise (pre-training) for individual subjects. Mean data are also presented.

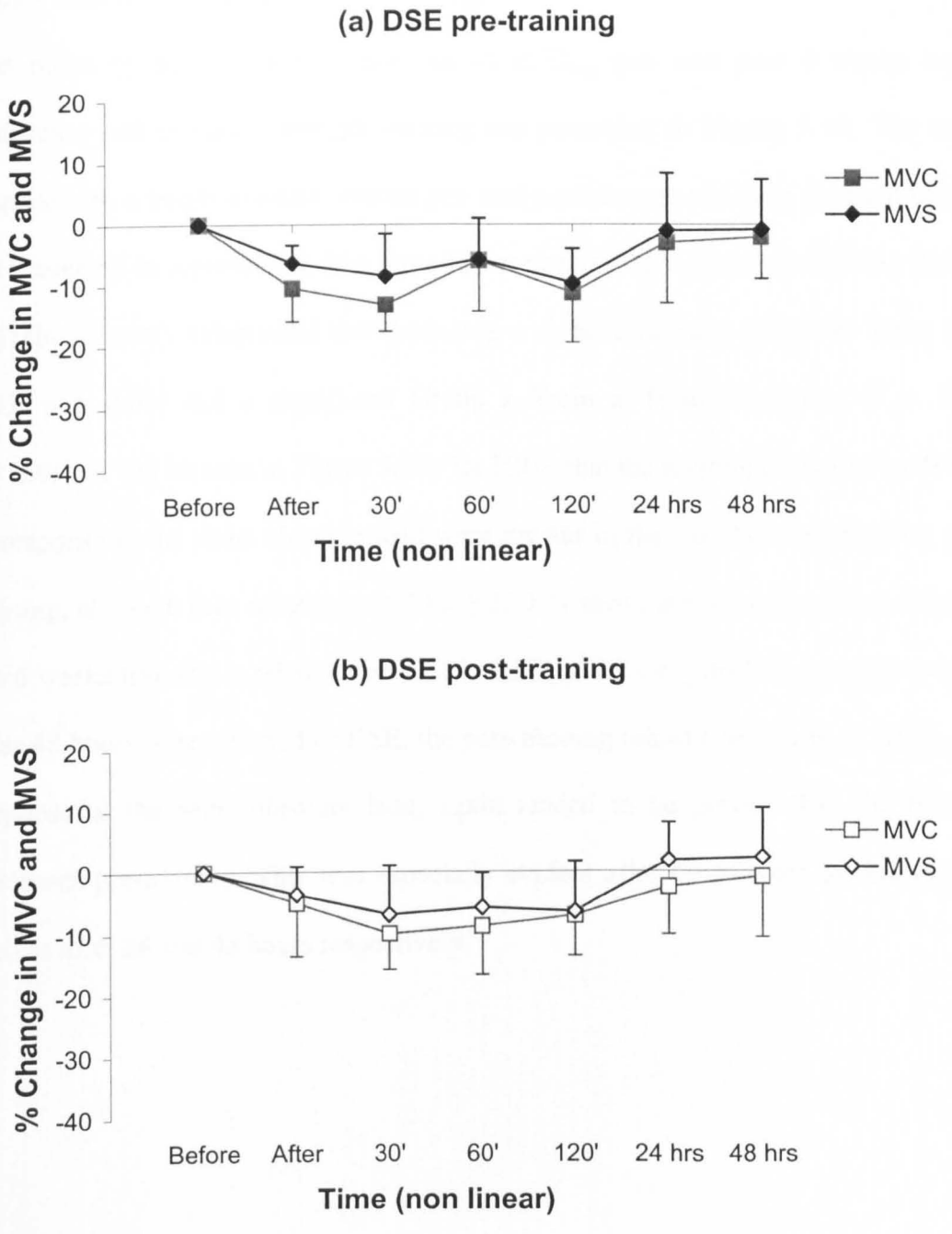


Figure 5.17 Percentage change in maximum voluntary contraction (MVC) force and MVC with superimposed percutaneous electrical myostimulation (MVS) following a single bout of dynamic strength exercise: (a) pre-training and (b) post-training.

5.5.2.4 Rate of force development (RFD_{avg})

The mean (± SD) percentage changes in RFD_{avg} pre- and post 6 weeks heavy resistance and dynamic strength training are presented in Figure 5.18. The acute responses to a single exercise session pre- and post 6 weeks training for each subject are presented in Appendix 8. The three-factor analysis of variance (ANOVA) (Group x Train x Time), established that there was a significant main effect for Time ($F = 9.03$, $p < 0.05$) and a significant Group x Train x Time interaction ($F = 3.76$, $p < 0.05$). It can be seen in Figure 5.16a for HRE, that the relative decreases in RFD_{avg} in response to the same absolute load were greater in the first hour of recovery post training, although then recovered to 20.2 ± 33.1 % above pre-exercise values. Prior to the 6 weeks training, a relative decrease in RFD_{avg} of 14.9 ± 30.1 % was still evident after 48 hours of recovery. For DSE, the post-training relative decreases in RFD_{avg}, in response to the same absolute load, again tended to be greater than the relative decreases pre-training. This was especially evident after 60 minutes of recovery as well as after 24 and 48 hours respectively.

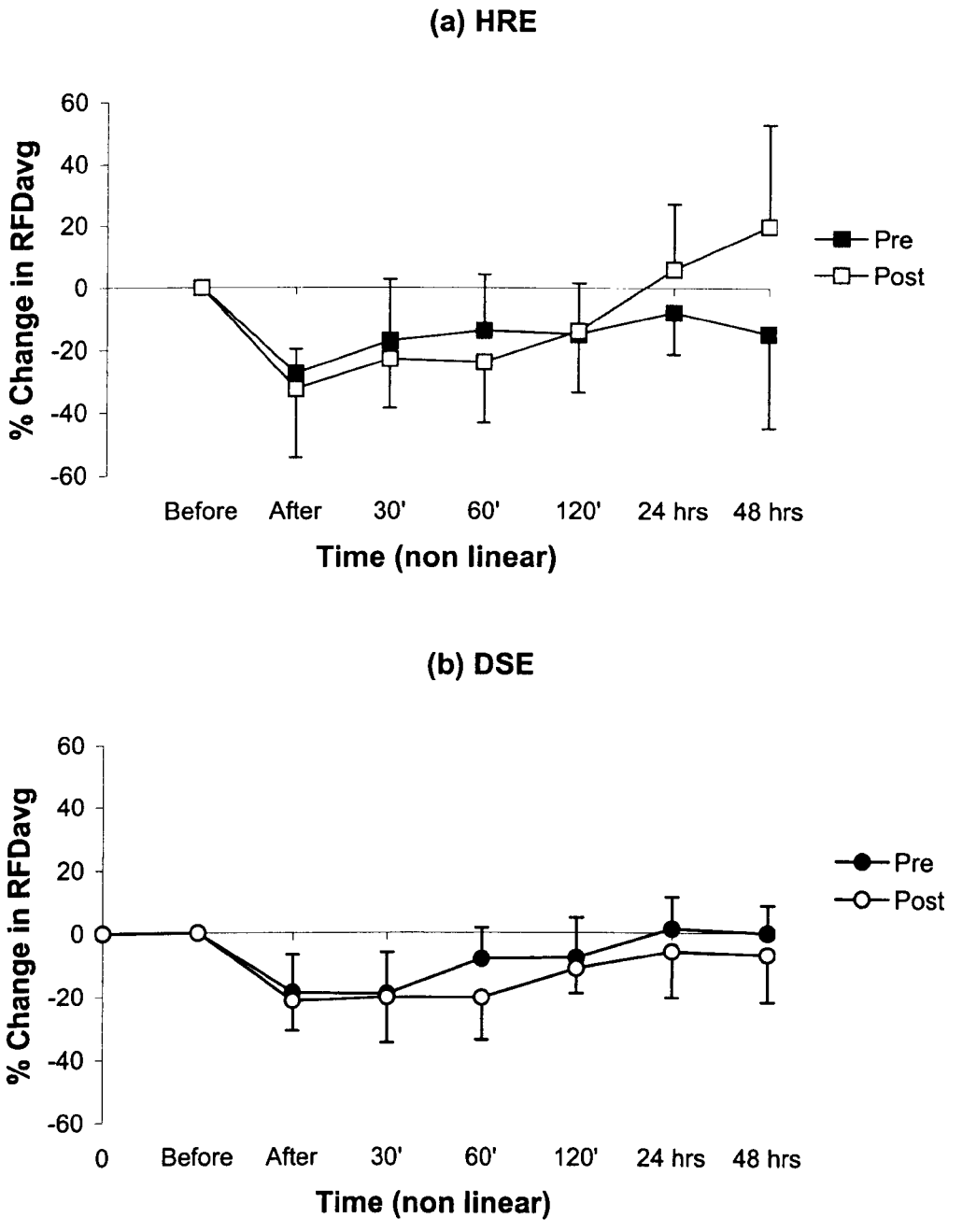


Figure 5.18 Percentage change (mean ± SD) in average rate of force development (RFD_{avg}) pre- and post 6 weeks: (a) heavy resistance training (HRE) and (b) dynamic strength training (DSE).

5.5.2.5 Surface electromyographic activity (EMG)

Several data sets were missing for subjects in the DSE group and therefore surface electromyographic activity is not reported here for this loading condition. Nevertheless the mean (± SD) absolute changes and the mean (± SD) relative changes in the EMG data after HRE, for pre- and post training are presented in Table 5.6. A two-way ANOVA (Train x Time) with repeated measures established that there were no significant main effects for Train or Time for each of the RMS values calculated over the time periods of the force-time curve. However a definite trend can be seen whereby after the 6 weeks of training, the relative decreases in EMG amplitude are greater and recovery is slower during both the early contraction phase (0-500 ms) and peak force phase (500-1500 ms), although the Train x Time interaction confirmed that these results were not significant.

With regards the median frequency, a significant main effect for Time was observed ($F = 4.40$, $p < 0.05$), although there was no significant main effect for Train. Median frequency of the vastus lateralis muscle increased after the pre-training HRE session. This shift to higher frequencies was prolonged up to 30 minutes after the session. This trend was not evident after the 6 weeks of training. Only a small shift to the right was observed immediately after exercise followed by a shift to lower frequencies.

TABLE 5.6 Absolute and relative changes (mean ± SD) in RMS values and Median Frequency (MDF) after heavy resistance exercise (HRE).

	Pre-training							Post-training						
	Before	After	30 min	60 min	120 min	24 hrs	48 hrs	Before	After	30 min	60 min	120 min	24 hrs	48 hrs
Δ Absolute RMS														
0-500 ms	1.623	1.437	1.534	1.603	1.568	1.645	1.584	1.628	1.428	1.472	1.523	1.541	1.675	1.650
	(0.212)	(0.322)	(0.247)	(0.148)	(0.250)	(0.217)	(0.082)	(0.381)	(0.488)	(0.498)	(0.438)	(0.410)	(0.316)	(0.368)
500-1500 ms	1.756	1.601	1.660	1.727	1.641	1.786	1.746	1.772	1.608	1.650	1.696	1.676	1.746	1.709
	(0.126)	(0.158)	(0.109)	(0.096)	(0.185)	(0.104)	(0.102)	(0.358)	(0.429)	(0.473)	(0.323)	(0.361)	(0.340)	(0.387)
1500-2500 ms	1.759	1.628	1.695	1.738	1.670	1.833	1.781	1.775	1.672	1.643	1.683	1.706	1.760	1.762
	(0.152)	(0.167)	(0.127)	(0.145)	(0.231)	(0.141)	(0.112)	(0.366)	(0.379)	(0.464)	(0.355)	(0.349)	(0.367)	(0.346)
MDF	57.89	62.13	60.67	57.65	54.63	58.46	56.66	58.38	59.77	56.59	55.94	54.05	60.56	58.68
	(4.089)	(4.824)	(4.387)	(4.336)	(6.147)	(3.136)	(2.687)	(9.515)	(6.471)	(9.650)	(6.263)	(5.222)	(8.888)	(8.936)
Δ Relative RMS														
0-500 ms	0.0	-12.4	-5.8	-0.4	-2.9	1.5	-0.7	0.0	-14.6	-11.8	-7.7	-6.2	4.3	2.1
	(0.0)	(10.5)	(5.9)	(9.5)	(12.8)	(6.7)	(16.5)	(0.0)	(15.8)	(12.0)	(10.3)	(7.2)	(9.8)	(10.1)
500-1500 ms	0.0	-8.9	-5.4	-1.4	-6.2	1.8	-0.3	0.0	-10.4	-8.5	-4.0	-5.5	-1.0	-3.5
	(0.0)	(4.6)	(3.6)	(6.0)	(12.6)	(4.7)	(7.2)	(0.0)	(10.1)	(11.9)	(4.9)	(4.8)	(6.1)	(8.3)
1500-2500 ms	0.0	-7.5	-3.5	-1.1	-4.7	4.4	1.7	0.0	-6.1	-9.0	-5.2	-3.7	-0.7	-0.4
	(0.0)	(3.8)	(4.6)	(6.4)	(14.1)	(6.0)	(8.3)	(0.0)	(7.8)	(11.7)	(6.7)	(4.2)	(3.9)	(3.0)
MDF	0.0	7.5	4.8	-0.3	-5.7	1.1	-1.9	0.0	3.4	-3.0	-3.4	-6.5	4.4	0.8
	(0.0)	(7.0)	(4.3)	(6.3)	(7.1)	(4.3)	(4.7)	(0.0)	(10.0)	(8.1)	(7.4)	(8.1)	(9.9)	(5.2)

5.5.2.6 Plasma lactate concentrations

The mean (± SD) changes in plasma lactate concentration are presented in Table 5.7. The three-factor ANOVA (Group x Train x Time) established a significant main effect for Time ($F = 14.87$, $p < 0.05$), but not for Group or Train. Therefore lactate levels increased significantly after HRE and DSE however there were no significant differences between loading conditions. Furthermore, although the elevation in lactate was greater after training for DSE, 4.9 ± 2.7 mmol l^{-1} compared to 4.2 ± 1.8 mmol l^{-1}, this increase was again not significant.

TABLE 5.7 Mean (± SD) changes in plasma lactate values after heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Unit	Before	After	30 min	120 min
HRE Pre-training	mmol l^{-1}	1.0 (0.3)	6.1 (3.8)	1.5 (0.7)	0.9 (0.4)
Post-training	mmol l^{-1}	1.1 (0.7)	5.7 (3.8)	1.5 (0.8)	0.7 (0.1)
DSE Pre-training	mmol l^{-1}	0.8 (0.3)	4.2 (1.8)	1.0 (0.3)	0.7 (0.3)
Post-training	mmol l^{-1}	1.0 (0.4)	4.9 (2.7)	1.0 (0.4)	0.6 (0.2)

5.5.2.7 Creatine kinase activity and upper leg muscle soreness

The 3-factor AVOVA with repeated measures demonstrated no significant difference for Group, Train or Time. However it can be seen that creatine kinase levels were somewhat elevated 24 and 48 hours after HRE (pre-training) and that no response was apparent after the 6 weeks training period. For DSE, levels peaked 24 hours after the initial exercise session although the response was small in physiological terms. Small increases were also apparent after 24 and 48 hours of recovery following the training period.

On the other hand, with regards the ratings for leg soreness, the 3-factor ANOVA with repeated measures demonstrated a significant main effect for Group ($F = 10.30$, $p < 0.05$), Train ($F = 7.26$, $p < 0.05$) and Time ($F = 9.61$, $p < 0.05$). Furthermore there was also a significant Train x Time interaction ($F = 6.68$, $p < 0.05$). Both forms of exercise produced significant ratings for soreness, although the ratings were significantly greater after HRE compared to DSE. Further, ratings were significantly lower after training for both HRE and DSE.

TABLE 5.8 Creatine kinase activity and upper leg muscle soreness (DOMS), after heavy resistance exercise and dynamic strength exercise (Mean ± SD).

	Pre-training						Post-training					
	Before	After	30 min	120 min	24 hrs	48 hrs	Before	After	30 min	120 min	24 hrs	48 hrs
Heavy												
CK activity	172	195	187	219	898	911	267.3	296.3	280.0	292.2	256.7	216.8
IU l^{-1}	(48)	(58)	(53)	(67)	(1476)	(1695)	(202.5)	(232.7)	(218.0)	(218.0)	(143.9)	(84.0)
% change in CK	0.0	13.5	8.8	28.6	381.5	379.3	0.0	8.6	3.4	8.9	8.2	0.5
activity	(0.0)	(6.2)	(5.9)	(23.5)	(714.7)	(826.2)	(0.0)	(7.6)	(5.1)	(9.3)	(28.3)	(31.7)
General Soreness	0.0	1.2	—	1.7	5.8	5.2	0.0	1.5	—	1.5	1.3	1.3
	(0.0)	(1.5)	—	(1.4)	(3.8)	(4.9)	(0.0)	(2.5)	—	(2.8)	(2.4)	(1.8)
Leg Soreness	0.0	2.7	—	2.3	8.0	6.7	0.0	1.8	—	1.8	1.8	1.5
	(0.0)	(3.4)	—	(2.3)	(2.7)	(3.9)	(0.0)	(2.9)	—	(3.6)	(2.4)	(2.1)
Dynamic												
CK activity	217	238	228	244	345	249	133	139	136	145	174	191
IU l^{-1}	(164)	(180)	(173)	(189)	(326)	(132)	(58)	(63)	(57)	(59)	(90)	(105)
% change in CK	0.0	10.6	6.6	13.4	99.9	39.3	0.0	4.5	2.7	10.7	40.0	47.7
activity	(0.0)	(7.0)	(7.3)	(15.2)	(195.7)	(69.4)	(0.0)	(5.8)	(5.0)	(18.3)	(70.6)	(75.4)
General Soreness	0.0	0.5	—	0.5	3.0	1.3	0.0	0.0	—	0.5	0.5	0.3
	(0.0)	(1.2)	—	(1.2)	(4.3)	(1.5)	(0.0)	(0.0)	—	(1.2)	(0.5)	(0.8)
Leg Soreness	0.0	0.5	—	1.0	4.5	3.2	0.0	0.0	—	0.5	1.2	0.3
	(0.0)	(1.2)	—	(1.5)	(4.2)	(4.4)	(0.0)	(0.0)	—	(1.2)	(1.2)	(0.8)

5.5.2.8 Potassium concentrations and plasma volume changes

Several data sets were missing for subjects in the HRE group and therefore changes in potassium concentration are not reported here for this loading condition. For DSE, potassium concentration decreased by 6.3 ± 4.4 % immediately after the pre-training exercise session and by 10.7 ± 4.4 % immediately after the post-training session at the same absolute load. A 2 factor ANOVA with repeated measures established that these differences were significant ($F = 14.00$, $p < 0.05$), although there was no significant training effect.

TABLE 5.9 Mean values (± SD) of potassium (K^+) concentration at rest, and after 3 and 30 minutes of recovery following dynamic strength exercise (DSE).

	Unit	Before	+ 3min	+ 30 min
Pre-training	mmol l^{-1}	4.3 (0.2)	4.1 (0.4)	4.3 (0.2)
Post-training	mmol l^{-1}	4.5 (0.3)	4.0 (0.3)	4.4 (0.2)

TABLE 5.10 Percentage plasma volume changes (Mean ± SD) following heavy resistance exercise (HRE) and dynamic strength exercise (DSE).

	Before	After	30 min	120 min	24 hrs	48 hrs
HRE						
Pre-training	0.0 (0.0)	-8.6 (5.6)	0.3 (6.9)	-3.7 (5.7)	-3.9 (6.6)	1.5 (9.6)
Post-training	0.0 (0.0)	-7.4 (8.8)	0.2 (9.3)	-1.9 (7.4)	-3.0 (6.0)	4.2 10.4
DSE						
Pre-training	0.0 (0.0)	-7.0 (3.8)	0.1 (2.5)	-0.8 (3.5)	-0.2 (5.8)	-0.6 (3.5)
Post-training	0.0 (0.0)	0.2 (5.3)	6.9 (6.3)	2.7 (6.5)	1.6 (6.6)	4.0 (6.6)

Pre- and post training plasma volume changes were very similar in response to the single HRE session. However it can be seen from Table 5.10 that very different changes in plasma volume occurred in response to the single DSE session after the 6-week DSE training programme. Decreases in plasma volume were apparent in response to the pre-training session, whereas relative increases in plasma volume were observed immediately, and 30 minutes after the post training DSE session. The 3 factor ANOVA with repeated measures established that there was a significant main effect for Time ($F = 9.61$, $p < 0.05$), although not between loading conditions. Furthermore there was no significant main effect for Train.

5.5.2.9 Ratings of perceived exertion

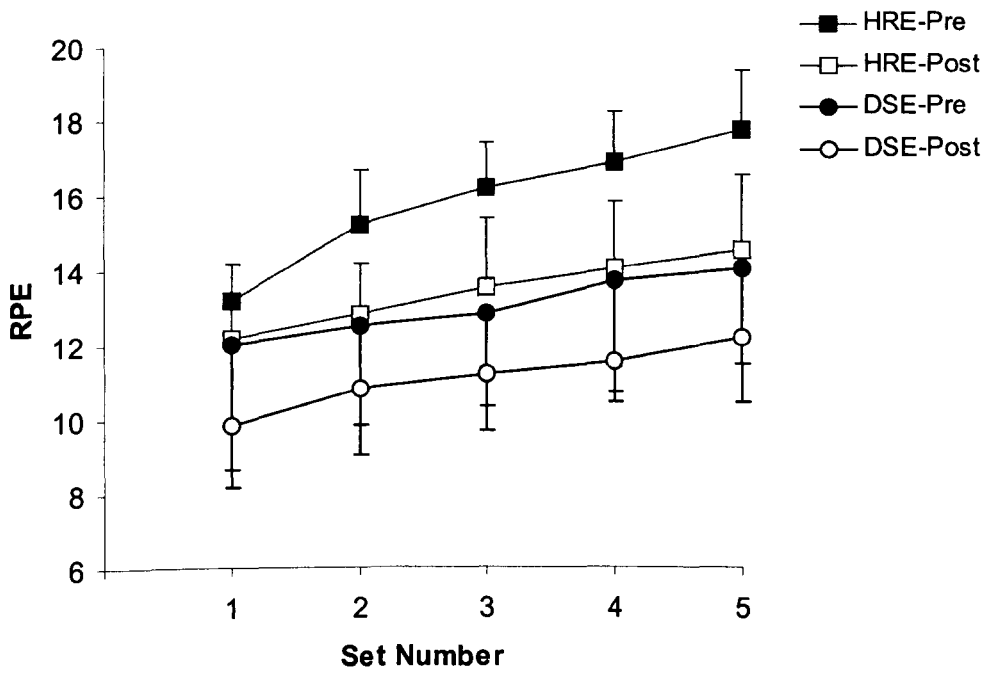


Figure 5.19 The response of rating of perceived exertion (RPE) to heavy resistance exercise (HRE) and dynamic strength exercise (DSE) for pre- and post testing sessions.

The 3 factor ANOVA with repeated measures established that there were significant main effects for Group ($F = 18.04$, $p < 0.05$), Train ($F = 21.62$, $p < 0.05$), and Time ($F = 33.68$, $p < 0.05$). Furthermore, a significant Group x Time interaction ($F = 4.63$, $p < 0.05$) was also observed. The significant Group x Time interaction can be explained by the fact that the ratings of perceived exertion in response to the pre-training HRE session increased from 13.2 ± 1.0 after set 1 up to 17.7 ± 1.6 after set 5. Such increases in RPE values from set to set were not observed after any of the other loading sessions, pre- or post training (Appendix 8).

TABLE 5.11 Results of the three-factor analysis of variance (ANOVA) (Group x Train x Time), with repeated measures on the last two factors; Train (i.e. the difference between pre- and post training scores) and Time (i.e. the changes over time after each exercise session). The third factor Group represents the difference between the heavy resistance exercise (HRE) and dynamic strength exercise (DSE) sessions.

	GROUP		TRAIN		TIME		GROUP x TRAIN		GROUP x TIME		TRAIN x TIME		GROUP x TRAIN x TIME	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
F_{20}	0.57	0.484	4.21	0.096	11.29	0.003*	0.07	0.796	1.08	0.372	0.39	0.773	0.19	0.926
F_{100}	0.26	0.632	0.46	0.529	8.09	0.001*	0.15	0.713	1.89	0.207	0.30	0.792	0.52	0.686
MVC	2.05	0.211	7.01	0.046*	7.84	0.000*	1.32	0.303	0.28	0.846	3.94	0.009*	1.12	0.373
MVS	1.78	0.240	4.30	0.093	11.01	0.002*	0.50	0.510	1.01	0.431	1.74	0.163	0.58	0.649
RFD_{avg}	0.38	0.564	0.04	0.843	9.03	0.001*	1.08	0.347	0.62	0.599	2.72	0.043*	3.76	0.011*
La	0.77	0.420	0.47	0.525	14.87	0.012*	0.19	0.678	0.20	0.724	0.14	0.747	0.72	0.439
CK	0.74	0.430	1.74	0.244	1.93	0.222	1.45	0.283	0.66	0.459	1.50	0.276	1.28	0.311
DOMS (GS)	5.81	0.061	3.79	0.109	8.07	0.000*	0.74	0.430	1.97	0.138	3.96	0.016*	1.75	0.179
DOMS (LS)	10.30	0.024*	7.26	0.043*	12.45	0.000*	1.71	0.248	1.32	0.309	6.68	0.001*	1.38	0.275
Δ PV	1.12	0.337	2.67	0.163	9.61	0.000*	1.44	0.285	1.39	0.274	0.25	0.849	1.21	0.339
RPE	18.04	0.008*	21.62	0.006*	33.68	0.000*	0.17	0.695	4.63	0.008*	1.36	0.301	2.72	0.123

* $p < 0.05$
GS – General Soreness
LS – Leg Soreness

5.6 Discussion

5.6.1 Training data

It is well documented that the choice of training method can make a considerable difference in the outcome of a resistance training programme (Adams *et al.*, 1992; Lyttle *et al.*, 1996; Newton *et al.*, 1999; Newton and McEvoy, 1994; Wenzel and Perfetto, 1992; Wilson *et al.*, 1993). Furthermore the choice of training mode can influence the adaptations to a training programme (Kaneko *et al.*, 1983; Häkkinen and Komi, 1985a; 1985b; Häkkinen *et al.*, 1985a; 1985b; Newton *et al.*, 1996; Toji *et al.*, 1997; Weiss *et al.*, 1999). However despite the extent of this research, controversy still exists as to the optimal resistance training method to enhance fast force production characteristics.

The influence of different training stimuli on the neuromuscular system can be characterised by specific shifts in the force-time curve. In untrained subjects, heavy resistance exercise can produce beneficial effects both in the early parts and in the high force portions of the force-time curve. In trained subjects, however evidence suggests that high velocity training may be necessary for making alternations to the early portions of the force-time curve and hence improve explosive strength (Häkkinen, 1989; 1994b). In the present study, HRE appears to produce a beneficial response for maximal strength while DSE appears to beneficially affect both this and rate of force development. These findings are in agreement with Wilson *et al.* (1993) who demonstrated that high power training such as DSE increases a wide range of athletic variables to a greater extent than does traditional heavy weight training, especially in subjects with a reasonable initial level of strength.

The long term neuromuscular training and detraining adaptations to resistance exercise have received extensive reviews (e.g. Behm, 1995; Häkkinen, 1989; 1994b; Komi, 1986; Moritani, 1992; 1993). Training blocks to develop peak force and rate of force development as used in the present study are normally 4-6 weeks in length (Sale, 1988). Athletes will adopt such training levels shortly before important competitions, however little scientific information is available regarding the short-term detraining effects after such a training period. Consequently athletes and coaches cannot be sure in the optimal time interval required between the last training session and the competition to use the adaptations from the strength training in an optimal manner.

The time course of strength gains can be explained by the interaction of neural and muscular (contractile apparatus and connective tissue) factors. Some research has recommended that athletes should finish strength training with heavy loads, at least 7-10 days (Schlumberger and Schmidtbleicher, 1998a) and even up to 3 weeks (e.g. Schlumberger and Schmidtbleicher, 1998b) before competition, to allow for complete muscle regeneration. However it has been well documented that detraining subsequent to strength training leads to a decrease in the maximal voluntary neural activation of detrained muscles (Häkkinen and Komi, 1983; Narici *et al.*, 1989; Häkkinen and Komi, 1985a). This decrease in maximum EMG amplitude does not necessarily take place in the very first week (Häkkinen *et al.*, 1989), but during the first 2-4 weeks of detraining (Häkkinen and Komi, 1983). The decreases in MVC and RFD +10 days after the last training session substantiate these findings. The use of an unloading phase to facilitate gains in MVC and RFD following 6-weeks heavy resistance and dynamic strength training is therefore not supported here.

It should also be noted that during the training period subjects were allowed to continue with their normal endurance activities such as running or cycling, which may account for some of the large intra-individual variability in terms of the training response. Some subjects may have performed a higher endurance-training load than others. The concurrent use of strength and endurance training methods has been shown to compromise strength gains and the ability to produce explosive movements (Chromiak and Mulvaney, 1990; Dudley and Djamil, 1985; Hennessy and Watson, 1994; Hickson, 1980). Due to the catabolic processes and neural interference mechanisms associated with endurance training, it is often believed that the latter should be kept to a minimum if maximal strength and rate of force development are the main concerns of the training phase (King and Poliquin, 1991). However for players engaged in team sports it is not possible to eliminate endurance type work from the training cycle especially during the season.

5.6.2 Fatigue and recovery characteristics

The main finding from the present study was the significant reduction in the decline of MVC in response to either a single HRE or DSE exercise session following 6 weeks of heavy resistance and dynamic strength training respectively (Figure 5.14). Although there was no significant difference between the two loading conditions, HRE appeared to have a more beneficial effect for reducing the decline in MVC. The deficits in 20 Hz force immediately after exercise and during recovery were also noticeably less after the training period for both HRE (Figure 5.12a) and DSE (Figure 5.13a). This trend was more evident for HRE, but again the difference was not significant (Table 5.11).

The presence of a central limitation of the contraction process after HRE was highlighted in Study 2 by comparing the recovery of 100 Hz force with the recovery of MVC. Consequently for this study, the technique of superimposing a 100 Hz pulse during the performance of a MVC trial was used to determine the presence of central fatigue. When comparing the recovery of 100 Hz force (Figure 5.12b) and MVC (Figure 5.14a) over the initial two hour recovery period, after HRE (pre-training data) there does not appear to be the same central limitation as identified in Study 2. This is confirmed by comparing the changes in MVC and MVS (Figure 5.15a). However after 48 hours, MVS was tending to recover, whereas a further reduction MVC occurred. As the SDs for the data after 24 and 48 hours of recovery were larger than for the initial recovery period, data were plotted for the individual subjects together with the mean response (Figure 5.16).

Although the magnitude of the force losses, were considerably different for each subject, the individual plots confirmed the trend illustrated in Figure 5.15a. This possibly indicates the presence of a central limiting mechanism, which may have restricted recruitment of partially damaged or vulnerable motor units (Brown *et al.*, 1996). Peak (absolute) creatine kinase levels were observed after 48 hours of recovery. Creatine kinase is a well-accepted marker of muscle tissue disruption, although the association between the severity of damage and the magnitude of CK response remains unclear (Byrnes *et al.*, 1985a). It should also be noted that motivation could also have been a problem as muscle soreness was still present 48 hours after the HRE pre-training session.

Some research has suggested that in trained strength athletes compared to untrained subjects, lactate will be lower as a result of strength training exercise at both absolute loads (Stone *et al.*, 1987) and at relative (% 1RM) intensities (McMillan *et al.*, 1993). Pierce *et al.*, (1993) have also demonstrated that an 8-weeks high volume strength training programme results in beneficial effects on lactate and RPE responses to a single strength exercise session at an absolute load (repetitions x weight). The strength exercise session consisted of 7 sets of parallel squats at percentages of the initial 1 RM: 1 x 10 repetitions at 45% of 1RM, 1 x 10 repetitions at 55 % of 1RM and 5 x 10 % at 62.5 % of 1 RM. Peak lactic acid dropped significantly from 11.9 $\pm$ 4.2 $mmol.l^{-1}$ to 5.1 $\pm$ 2.6 $mmol.l^{-1}$ from pre- to post training respectively in response to the single strength exercise session. Ratings of perceived exertion were also significantly lower at each set (S1-S7) from pre- to post training.

Pierce *et al.* (1993) suggested that these post-training responses were indicative of a reduced physiological and perceived stress and furthermore the reduced stress would enhance the ability to continue exercise. An explanation for the decrease in lactate was suggested that in using absolute loads, there is a decrease in the relative post training load, which would allow fewer units to be recruited during each set, thus creating a motor unit reserve. In the present study, significant decreases in RPE values were observed after training, although lactate did not significantly decrease after HRE, and increased after DSE. It is therefore unlikely that the reduction in decline in MVC can be explained by this mechanism.

One possible explanation for the reduction in decline in MVC could therefore be skeletal muscle adaptation. From above, creatine kinase levels were somewhat

elevated 24 and 48 hours after HRE (pre-training) whereas no response was apparent after the 6 weeks training period. Speculation on the mechanisms for such an adaptation have included the damage and removal of a pool of susceptible or vulnerable fibres (Armstrong *et al.*, 1983) increased ability to repair initial damage (Clarkson and Tremblay, 1988) and increased muscle connective tissue content (Lapier *et al.*, 1995). Muscle soreness ratings in response to a single HRE session were also significantly reduced after the training programme. Such adaptation appeared less apparent for DSE, where small increases in CK were observed after 24 and 48 hours of recovery even following the 6-weeks training period.

Improvements of fatigue resistance were not evident for RFD_{avg} and 100 Hz force. Furthermore deficits in RFD_{avg} tended to be greater after the training periods, particularly in response to DSE. During the very early stages of contraction (the first 100 ms), in order to generate high rates of force development, high firing frequencies in the order of 100 Hz are required (Sale, 1992). A neural adaptation to high velocity training may consist of an acquired ability to increase the maximum motor unit firing rates in ballistic actions such as explosive jumps squats (Häkkinen *et al.*, 1985b). This is likely to be in addition to the increased activation of fast twitch muscle fibres following the training period. The greater increase in lactate in response to the DSE session at the same absolute load may possibly support this explanation. Fast twitch muscle fibres are characterised by their high myosin ATPase activity (Close, 1972) and increased susceptibility to fatigue (e.g. Komi and Tesch, 1979; Thorstensson and Karlsson, 1976). The specific neural adaptations to DSE provide an explanation for the greater increases in RFD_{avg} compared to HRE following the 6 weeks of dynamic strength training. It should also be noted that these neural changes have been shown

to differ vastly from high load strength training (Hakkinen and Komi, 1985a), further supporting the concept of specificity of training.

It can be seen from Figure 5.13, that the decreases in 100 Hz force throughout recovery were greater after DSE compared to HSE, for both pre- and post training sessions. In Study 2, a slightly greater deficit in 100 Hz force was observed after a single DSE session, but only for immediately post exercise. Recovery of 100 Hz force then tended to be quicker after DSE. It is important to note that in Study 2 a load of 30 % 1RM was used for DSE, whereas in the present study a load of 20 % 1RM was used for the DSE testing sessions. Recently Fell *et al.* (2001) observed a significant decrease in take-off velocity when the load used in a counter-movement vertical jump was increased from 20 to 30 % 1RM, although this was not accompanied by a decrease in average concentric power output. The results of the present study therefore suggest that a load of 20% 1RM is optimal to increase the maximum motor unit firing rates. However due to the need for high frequency recruitment of the muscle fibres it does not appear that the human body can provide any compensatory mechanism to reduce this fatigue after DSE or HRE.

It has been suggested that the depletion of extracellular K^+ concentration is dependent on the frequency and duration of stimulation (Martin and Morad, 1982). As described in Study 2, Marcos and Ribas (1995) found a linear relationship between the magnitude of the increase in plasma K^+ concentration during exercise and the magnitude of the decrease immediately after cessation of exercise. Thus the greater decreases in K^+ concentration after dynamic strength training (Table 5.9) may possibly reflect the of higher frequency action potentials as suggested above.

5.7 Conclusions

It is concluded that DSE appears to have an advantage over HRE for producing an increase in both maximal voluntary contraction force and rate of force development. Both HRE and DSE significantly reduced the decline in maximal peak force following the six weeks training period, with HRE appearing to have the more beneficial effect. However improved fatigue resistance was not evident for rate of force development. Deficits in rate of force development tended to be greater following the 6 weeks training programmes, especially in response to DSE.

CHAPTER 6

GENERAL DISCUSSION

6.1 Methodological considerations

The methodological studies described in the present thesis were designed to establish the protocols to reliably assess the neuromuscular responses to heavy resistance and dynamic strength exercise.

Isometric tests have been used extensively to assess neuromuscular function, although controversy exists whether this testing modality can be successfully used to derive information on the dynamic functional capacity of muscle. The rate of force development (RFD) has typically been quantified using isometric testing protocols (Bemben *et al.*, 1990; 1992; Häkkinen, 1993; 1994a; Häkkinen *et al.*, 1985a; 1985b; Häkkinen *et al.*, 1986; Linnamo *et al.*, 1988; Strojnik and Komi, 1998). While some researchers have reported that such tests are significantly related to dynamic human performance (Jaric *et al.*, 1989; Veloso *et al.*, 1999; Viitasalo and Aura, 1984; Viitasalo *et al.*, 1981), others have reported that isometric RFD is not related to sprinting (Mero *et al.*, 1981; Wilson *et al.*, 1995) or jumping performance (Young and Bilby, 1993). Further, Wilson *et al.* (1993) reported that power training enhanced cycling and jumping performance; however no effect was observed on maximum isometric RFD suggesting that isometric tests of muscular function are not always sensitive to dynamically induced training adaptations.

In the training study presented in Study 3, significant increases in squat 1RM strength were observed in response to the 6-week HRE training programme. An independent t-test confirmed that the gains in 1RM strength as a result of the heavy resistance strength training programme were significantly greater ($p < 0.05$) than those for the

dynamic strength-training group. However these dynamic strength gains were not reflected in the measures of isometric peak force. Some studies and reviews of the literature have noted that the magnitude of measured increases in strength depends on the similarity between the strength test and the actual training exercise (Behm, 1995; Fry *et al.*, 1992; Rasch and Morehouse, 1957; Rutherford and Jones, 1986; Sale, 1988; 1992). Studies in which the strength testing was not specific (strength was measured on an apparatus different from that used in training) have not shown strength gain differences (Messier and Dill, 1985; Saunders, 1980; Silvester *et al.*, 1992). In the studies by Saunders (1980) and Silvester *et al.* (1992), training was dynamic and strength testing was isometric, which likely attenuates any strength gains or differences. It should be noted however that significant gains in MVC and RFD_{avg} were evident after DSE.

The primary issue for strength and conditioning experts is the effect of resistance training on sport specific activities or measures of performance. A number of researchers have adopted this approach. For example vertical jumping ability is important for many sports and is often used as a general indicator of the fast force production capabilities of the leg extensor muscles (Wilson *et al.*, 1995; Young, 1995). The vertical jump has been tested from a static squat position (SJ), with a preliminary dip or counter-movement (CMJ), and following a drop from various heights (DJ). Both CMJ and DJ involve muscle pre-stretching and can be considered tests of reactive strength (Young, 1995). All three measures have also been used as indices of neuromuscular performance in the analysis of fatigue and recovery characteristics. For example, the DJ has been used to investigate the effects of SSC fatigue on the interaction between muscle-tendon stiffness regulation and stretch-

reflex sensitivity (e.g. Horita *et al.*, 1996; Nicol *et al.*, 1996). These studies have revealed that strenuous SSC exercise induces continuous decline of stiffness regulation and stretch reflex sensitivity and have related this with structural damage. The stretch-shortening cycle characteristic of the DJ (and also the CMJ) is therefore considered a powerful tool in the study of fatigued muscle (Komi, 1999). Consequently such dynamic tests of neuromuscular performance should be considered for future study, although the reliability of these measurements would need to be determined. These tests were not considered for the present study due to the large number of other variables being recorded, and the fact that they are associated with high variability.

It is interesting to note that the deficits in maximal voluntary neural activation observed in this thesis were not as large as found in previous studies (e.g. Häkkinen, 1993; 1994a), although this may be due to the choice of muscle group used for assessing changes in neural activation. Häkkinen *et al.* (1988) after very heavy resistance exercise, whereby subjects were lifting up to 100 % of their one repetition maximum for only 2-3 repetitions, have observed very clear decreases in integrated EMG in the vastus medialis, but only slight changes in the vastus lateralis. This observation that differences may exist in the same muscle group is in line with previous findings reported during continuous isometric fatiguing conditions (Viitasalo, 1983). In the assessment of changes in maximal voluntary neural activation, Häkkinen (1993; 1994a) and Häkkinen *et al.* (1988) have traditionally averaged the EMG activity from the vastus medialis, vastus lateralis and rectus femoris muscles whereas in the present study, signals were only collected from the vastus lateralis.

For future study the measurement of surface electromyography from all three muscle groups should be considered. The measurement from all three muscle groups was not considered for the present study again due to the large number of other variables that were being recorded. Taking the average of measurements from the three muscle groups may also help to reduce the higher variability that was associated with the electromyographical variables, especially for between-day measurements. Results from Study 1A demonstrated that the electromechanical delay (EMD), the amplitude of the EMG signal calculated over the first 100 ms, and also the force measurements, RFD_{max}, F_{30} and I_{100} were characterised by very high variability and therefore were not considered for the exercise studies. This high variability is most likely related to the computation methods used to calculate the onset of EMG and force respectively and therefore should be re-examined. It has been discussed that these variables provide valuable information with regards the fast force production characteristics of the exercised muscles.

Other procedural considerations for future study could include electrode site preparation. One of the main considerations for collection of surface electromyographical data is the technique of skin preparation. The procedure of Okamoto *et al.* (1987) is often recommended in preference to the technique of skin abrasion, although it may require ethical approval. A sterile lancet is used to gently mark two lines on the skin in the direction of the line joining the proposed sites of the electrodes. The angle and pressure of the lancet should be carefully adjusted so that only the superficial layer of dead skin is broken. The electrodes are then placed on the faint red scratch lines approximately 3 cm apart.

6.2 Fatigue and recovery characteristics

The exercise studies described in the present thesis were designed to provide a greater understanding of the neuromuscular and metabolic characteristics of fatigue and recovery in response to heavy resistance and dynamic strength training in subjects engaged in team sports. It was suggested that close examination of the process of recovery taking place during rest after the termination of strenuous fatigue loading would provide valuable information as to the optimal recovery period required to overcome the effect of fatigue prior to competition. In addition, the effects of 6-weeks heavy resistance and dynamic strength training programmes on the fatigue and recovery characteristics were also explored.

In Study 2, significant decreases in maximal peak force and rate of force development were observed after HRE and DSE. Although there were no significant differences between the loading conditions, a clear trend was apparent in that the deficits in peak force and rate of force development were greater and recovery was slower after HRE compared to DSE. Interestingly Frick and Schmidtbleicher (1999) observed a significant Condition x Time interaction for the fatigue and recovery characteristics in response to two distinct loading conditions for the upper body, whereas this difference was not apparent for the lower body.

The lack of significant findings in the present study may be due in part to the low subject number but also the large intra-individual variability (i.e. variability in individual responses) to the loading conditions. Plots of data for individual subjects illustrated that individual responses did not necessarily follow the mean trend. This

variability may be due to the influence of genetic factors in the response to resistance training. More specifically, the question of whether responses to exercise training are variable in the population and whether the observed heterogeneity is related to the genotype is referred to as genotype*training interaction (Thomis *et al.*, 1998). In addition, muscular adaptations are also determined by developmental factors. In the absence of neural input certain muscle fibres are produced that can respond to certain physiological perturbations (e.g. weight training or unloading) and those that do not respond: responders and non-responders. As the proportions of these fibre types will vary within different muscles and between individuals, a given training stimulus is unlikely to elicit the same strength or hypertrophic response in all muscles or to be similar for different individuals (Enoka, 1994). It is clearly evident that strength training is subject to large intra-individual variability, and therefore it is possible to defend the use of only six subjects for Study 2, and the use of six subjects in each training group for Study 3, as even with a larger number it is not guaranteed that all subjects would have responded in the same manner.

With regard to the role of fatigue as a stimulus for the development of strength, it is argued that greater short-term increases in strength are achieved when subjects are required to lift to failure (Rooney *et al.*, 1994. However persistent 'training to failure' (> 7 weeks) could be counterproductive and may actually lead to deterioration in neuromuscular performance (Stone *et al.*, 1996). Stone *et al.* (1996) have even suggested that training to failure is only advisable for a maximum period of 3 weeks. Such consistent training to failure as carried out by the HRE group may therefore provide an explanation why 3 out of the six subjects demonstrated large decreases in rate of force development following the 6 weeks training period. For the DSE group,

greater and more consistent gains in peak force and rate of force development were observed. However it should be noted that although the DSE group did not train to failure, significant decreases in peak force and rate of force development (and hence fatigue) were still evident in response to an acute loading session, with complete recovery taking at least 48 hours.

In Study 3, it was found that 6 weeks of heavy resistance and dynamic strength training reduced the decline in MVC in response to a single HRE or DSE session at the same absolute load. It has been suggested that due to an increased EMG activity (as a result of training) working at the same absolute load would mean fewer motor units would need to be recruited, thus creating a motor unit reserve (Pierce *et al.*, 1999). However, relative decreases in EMG amplitude were greater (not significant), after the 6 weeks training period in response to a single HRE session.

It was also clearly evident that lactate levels were not significantly reduced after training for HRE, and for DSE, lactate levels actually increased in response to the post-training single exercise session. It is therefore more likely that alterations in motor control as a consequence of the 6 weeks training resulted in less antagonist activity during the performance of the MVC trials (Behm and St-Pierre, 1998) leading to the reduction in decline in force. Training induced decreases in antagonist activity have been confirmed both in cross-sectional studies involving dynamic contractions (Patton and Mortensen, 1971) and longitudinal isometric training studies (Carolan and Cafarelli, 1992). Equally as illustrated by the reductions in creatine kinase levels and muscle soreness ratings in response to the post-training loading sessions, muscular adaptations may also play a role in improving fatigue resistance.

In Study 2 and Study 3, isometric measures of neuromuscular performance (MVC and RFD_{avg}) were generally back to within pre-exercise values after 48 hours of recovery, and in some instances, a super-compensation effect was observed (Zatsiorky, 1995), such that force values were greater than pre-exercise values. Based on these findings, a subsequent training session would be recommended after a recovery period of 48 hours. On the other hand, Horita *et al.* (1997) demonstrated using a countermovement vertical jump (no load) that impairment of stretch-shorten cycle performance (SSC) after exhaustive rebound jumps lasted at least 4 days. Consequently competitive performance where movements utilising the stretch-shorten cycle (SSC) are required (e.g. jumps and sprints) would not be recommend until after this period. Such impairment may be associated to the progressive degenerative processes that occur in the subsequent days post exercise as described by Clarkson and Sayers (1999), Fridén *et al.* (1983) and Jones *et al.*, (1996). Thus as described above, a SSC test would perhaps give more information as to the state of 'readiness' prior to training or competition.

In the present study the diets of each subject were not analysed for energy content prior to each test, although subjects were requested to consume the same pre-test meal. Equally, the diets of each subject were not controlled for the training study. The effects of carbohydrate (CHO) supplementation on aerobic performance are well known (e.g. Karlsson and Saltin, 1971; Wright *et al.*, 1991), where muscle and liver glycogen have been associated with decrements in performance. This line of research has indicated that the ingestion of CHO before and during endurance activities can prolong exercise duration (e.g. Coyle *et al.*, 1983) and increase work output (e.g.

Hargreaves *et al.*, 1984). Consequently endurance athletes typically attempt to maximise CHO intake to maintain a high CHO status.

Conversely, intake of CHO by body builders and those engaging in resistance exercise training tends to be lower than that found in endurance athletes, since a greater emphasis is placed on protein intake for body builders and weight lifters (Walberg-Rankin, 1995). Indeed it has been observed that a high CHO diet (65% of total calories) does not facilitate strength or lean body mass gains compared to a low to moderate CHO diet (40% of total calories). It is clear that intense resistance exercise can place a significant demand on muscle glycogen (Robergs *et al.*, 1991; Tesch *et al.*, 1986) and therefore it has been suggested pre-exercise CHO status may affect the quality of the resistance exercise training session and consequently the training responses. However, as previously discussed, recent evidence suggests it the accumulation of selected metabolic by-products, rather than the depletion of energy substrates, that are the major factors in neuromuscular fatigue (Allen and Westerblad, 2001; Favero, 1999; Jones, 1999; Westerblad *et al.*, 2002).

Nevertheless Haff *et al.* (1999) demonstrated that carbohydrate supplementation significantly increased the number of squats performed to exhaustion during the second training session on a given day. Equally, Leveritt and Abernathy (1999) demonstrated that a 2 days carbohydrate restriction programme caused a significant decrease in the number of squat repetitions performed. In contrast, Mitchell *et al.* (1997) found that after a 2 days low carbohydrate diet, resistance exercise performance was not affected. The authors concluded that although muscle glycogen levels were low, there was adequate CHO to fuel the activity. Furthermore as no

differences in lactic acid accumulation were observed between the high CHO and low CHO conditions, the authors also concluded that the low CHO levels had not impaired the rate of glycogenolysis.

Further support for maintaining an adequate carbohydrate intake during strength training is provided by Gleeson *et al.* (1998) who observed that a low carbohydrate diet was associated with a larger rise in cortisol (a catabolic hormone) during exercise, a greater fall in the plasma glutamine concentration during recovery and a larger neutrophilia during the post-exercise period. Depleted muscle glutamine stores will inhibit protein synthesis and may therefore cause a catabolic state in the body. This has implications for long-term training where gains in strength are largely determined by muscular rather than neural adaptations.

The analyses of certain serum hormones such as testosterone, growth hormone and cortisol might therefore be advantageous for the evaluation of exercise stress and over-training. Hormonal responses are known to take place in relation to the intensity and duration of strenuous exercises (e.g. Aakvaag *et al.*, 1978), although the acute responses of these hormones to strenuous resistance exercise are subject to diurnal variation (Häkkinen *et al.*, 1988). A protecting role of plasma catecholamines in exercise-induced hyperkaliaemia has been described (Blake and Paterson, 1992; Sneyd *et al.*, 1992) and that an increase in Na^+ -K^+ pump activity could be influenced by circulating catecholamine concentrations. Further it has been demonstrated that catecholamines, particularly adrenaline produce an activation of the Na^+ -K^+ pump of skeletal muscle in rats (Ballyani and Grafe, 1988; Everts *et al.*, 1988) thus potentially restoring membrane potential (Hultman *et al.*, 1987).

In summary, the aim of this thesis was to examine the acute neuromuscular and metabolic effects of fatigue and short-term recovery from fatigue in players engaged in team sports following two distinct types of resistance exercise. It has been suggested that HRE may be superior to DSE for the enhancement of speed-strength characteristics due to the significantly longer time under tension (i.e. the high loads compel the motor neurons to fire high frequency impulses for comparatively long times). However the results of this thesis clearly demonstrate that DSE has a distinct advantage over HRE for the development of speed-strength characteristics and also that fatigue after DSE tends to be less and recover quicker than after HRE.

Both HRE and DSE significantly reduced the decline in maximal peak force following a six weeks training period, although in this case HRE appeared to have the more beneficial effect. Improved fatigue resistance was not however evident for rate of force development. Deficits in rate of force development tended to be greater following the 6 weeks training programmes, especially in response to DSE.

The overall findings therefore suggest that in players engaged in teams sports, DSE is a superior form of resistance exercise for the development of speed-strength, however improvements in fatigue resistance are not achieved when maximal motor unit firing rates are required.

6.3 Directions for further research

From conducting this research and reviewing the literature, the following directions for future work are proposed in order to advance the understanding of the neuromuscular and metabolic characteristics of fatigue and recovery in response to different resistance exercise protocols employed by players engaged in team sports.

Due to the lack of significant differences, it is recommended that the experiments are repeated but with a larger number of subjects.

The results of Study 1A demonstrated that the measurements of electromechanical delay (EMD), the amplitude of the EMG signal calculated over the first 100 ms, and the force measurements, RFD_{max}, F_{30} and I_{100} were characterised by high variability. It is therefore recommended that the computation methods used to calculate the onset of EMG and force respectively are re-examined. It is also recommended for future study that measurements of EMG are recorded from the vastus lateralis, vastus medialis and rectus femoris muscle groups.

As discussed above the stretch-shorten cycle (SSC) has been found to be a powerful tool to study fatigued muscle. It is therefore recommended that SSC tests of performance, namely the counter-movement vertical jump and drop jump are included in the test battery. However as these measurements tend to be quite variable, the reliability of these tests also need to be quantified.

It has been suggested that alterations in motor control with training could lead to a decreased antagonist activity opposing the intended movement, thus resulting in the reduced decline in maximal peak force. To investigate this potential mechanism it is recommended for future study that surface electromyography activity of the hamstrings is also recorded during the performance of an MVC and expressed as a percentage of the leg extensors activity for pre- and post training.

Hormonal responses are also known to take place in relation to the intensity and duration of strenuous exercises. The combined study of neuromuscular and hormonal responses to high intensity strength training sessions may therefore provide additional information about the acute adaptations in the human body.

In addition to the re-examination of the lower body, it would be of interest to examine the acute neuromuscular and metabolic fatigue and short-term recovery from fatigue following forms of upper body resistance exercise. Frick and Schmidtbleicher (1999) have demonstrated that for the upper body, the recovery process clearly depends on the training regimen.

It is envisaged that conducting further research in this area will lead to a greater understanding of the recovery processes in order to provide optimum recovery strategies in response to different resistance exercise protocols.

CHAPTER 7

REFERENCES

Aagard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., Hakjaer-Kristensen, J. and Dyhre-Poulson, P. (1997). Neural adaptation to strength training in man: spinal and supra-spinal mechanisms [Abstract]. In *Proceedings of the Second Annual Congress of the European College of Sports Science*, pp 336-337.

Aakvaag, A. Sand, T., Opstad, P. K., Fonnum, F. (1978). Hormonal changes in serum in young men during prolonged physical strain. *European Journal of Applied Physiology*, **39**, 283-291.

Abe, Y., Brechue, W. F., Fujita, S. and Brown, J. B. (1998). Gender differences in FFM accumulation and architectural characteristics of muscle. *Medicine and Science in Sports and Exercise*, **30**, 1066-1070.

Acierno, S. P. and Baratta, R. V. and Solomonow, M. (1995). *A Practical Guide to Electromyography for Biomechanists*. Baton Rouge, L.A. Lousiana State University.

Adams, K., O'Shea, J. P., O'Shea, K. L. and Climstein, M. (1992). The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *Journal of Applied Sport Science Research*, **1**, 36-41.

Ainscoe, M. and Hardy, L. (1987). Measurement for warm-up decrement. *Perceptual and Motor Skills*, **64**, 1081-1082.

Ajan, T. and Baroga, L. (1988). *Weightlifting: Fitness for all Sports*. Budapest, International Weightlifting Federation.

Alexander, R. McN. and Vernon, A. (1975). The dimensions of the knee and ankle muscles and the forces they exert. *Journal of Human Movement Studies*, **1**, 115-123.

Allen, D. G., Lännergren, J. and Westerblad, H. (1995). Muscle cell function during prolonged activity: cellular mechanisms of fatigue. *Experimental Physiology*, **80**, 497-527.

Allen, D. G. and Westerblad, H. (2001). Role of phosphate and calcium stores in muscle fatigue. *Journal of Physiology*, **536**, 657-665.

Altman, D. G. (1991). *Practical Statistics for Medical Research*. London: Chapman and Hall.

Altman, D. G. and Bland, J. M. (1983). Measurement in medicine: the analysis of method comparison studies. *Statistician*, **32**, 307-317.

Andearssen, S and Arendt-Nielsen, L. (1987). Muscle fibre conduction velocity in motor units of the human anterior tibial muscle: a new size principle parameter. *Journal of Physiology*, **391**, 561-571.

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

Appell, H. J., Soares, J. M. C. and Duarte, J. A. R. (1992). Exercise, muscle damage and fatigue. *Sports Medicine*, **13**, 108-115.

Arendt-Nielsen, L. and Mills, K. R. (1985). The relationship between mean power frequency of the EMG power spectrum and muscle fibre conduction velocity. *Electrencephalography and Clinical Neurophysiology*, **60**, 130-134.

Arendt-Nielsen, L. and Mills, K. R. (1988). Muscle fibre conduction velocity, mean power frequency, mean EMG voltage and force during submaximal fatiguing contractions of human quadriceps. *European Journal of Applied Physiology*, **58**, 20-25.

Armstrong, R. B. (1984). Mechanisms of exercise-induced delayed onset muscle soreness: a brief review. *Medicine and Science in Sports and Exercise*, **16**, 529-538.

Armstrong, R. B., Ogilvie, R. W. and Schwane, J. A. (1983). Eccentric exercise-induced injury to rat skeletal muscle. *Journal of Applied Physiology*, **54**, 80-93.

Armstrong, R. B., Warren, G. L. and Warren, J. A. (1991). Mechanisms of exercise-induced muscle fibre injury. *Sports Medicine*, **12**, 184-207.

Ashley, G. C. and Ridgway, E. B. (1970). On the relationships between membrane potential, calcium transient and tension in single barnacle muscle fibres. *Journal of Physiology*, **209**, 105-130.

Åstrand, P.O. and Rodahl, K. (1986). *Textbook of Work Physiology*. Third Edition. New York: McGraw Hill, pp 115-126.

Atha, J. (1981). Strengthening muscle. *Exercise and Sport Science Reviews*, **9**, 1-73.

Atkinson, G. (1994). Effects of age on human circadian rhythms in physiological and performance measures [PhD Thesis]. Liverpool John Moores University.

Atkinson, G. (1995). A comparison of statistical methods for assessing measurement repeatability in ergonomics research. In *Sport Leisure and Ergonomics* (edited by G. Atkinson and T. Reilly), pp 218-222. London: E and FN Spon.

Atkinson, G., Greeves, J., Reilly, T. and Cable, N. T. (1995). Day-to-day and circadian variability of leg strength measured with the Lido isokinetic dynamometer [Abstract]. *Journal of Sports Sciences*, **13**, 18-19.

Atkinson, G. and Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, **26**, 217-238.

Atkinson, G. and Reilly, T. (1996). Circadian variation in sports performance. *Sports Medicine*, **21**, 292-312.

Aura, O. and Viitasalo, J. T. (1989). Biomechanical characteristics of jumping. *International Journal of Sports Biomechanics*, **5**, 89-98.

Baker, D., Wilson, G. and Carlyon, R. (1994). Generality versus specificity: a comparison of dynamic and isometric measures of strength and speed-strength. *European Journal of Applied Physiology*, **68**, 350-355.

Ballyani, K. and Grafe, P. (1988). Changes in intracellular ion activities induced by adrenaline in human and rat skeletal muscle. *Pflügers Archives*, **411**, 283-288.

Bartlett, R. (1996). Electromyography. In *Biomechanical Analysis of Movement in Sport and Exercises* (edited by R. Bartlett), pp 37-52. Leeds: British Association of Sport and Exercise Sciences.

Bartlett, R. (1997). Electromyography. In *Introduction to Sports Biomechanics* (edited by R. M. Bartlett), pp 228-253. London: E + FN SPON.

Basmajian, J. V. and Deluca, C. J. (1985). *Muscles Alive: Their Functions Revealed by Electromyography*. Fifth Edition. Baltimore, M. D.: Williams and Wilkins.

Baumgarter, T. M. (1989). Norm-referenced measurement: reliability. In *Measurement Concepts in Physical Education and Exercise Science* (edited by M. J. Safrit and T. M. Wood), pp 45-72. Champaign, Illinois: Human Kinetics.

Bauer, T. (1984). Rugby: rationale, design and development of rugby training programmes. *National Strength and Conditioning Association Journal*, **6**, 61-62, 64.
Bauer, T. (1986). Power training for rugby. *National Strength and Conditioning Association Journal*, **8**, 28-32.

Beelen, A., Sargeant, A. J., Jones, D. A. and de Ruiter, C. J. (1995). Fatigue and recovery of voluntary and electrically elicited dynamic force in humans. *Journal of Physiology*, **484**, 227-335.

Behm, D. G. (1995). Neuromuscular implications and applications of resistance training. *Journal of Strength and Conditioning Research*, **9**, 264-274.

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

Behm, D. G. and Sale, D. G. (1993b). Intended rather than actual movement velocity determines velocity specific training response. *Journal of Applied Physiology*, **74**, 359-368.

Behm, D. G. and St-Pierre, D. M. M. (1998). The effects of strength training and disuse on the mechanisms of fatigue. *Sports Medicine*, **25**, 173-189.

Bélanger, A. Y. and McComas, A. J. (1981). Extent of motor unit activation during effort. *Journal of Applied Physiology*, **51**, 1131-1135.

Béllemare, F. and Garzaniti, N. (1988). Failure of neuromuscular propagation during human maximal voluntary contraction. *Journal of Applied Physiology*, **64**, 1084-1093.

Bemben, M. G., Clasey, J. L. and Massey, B. H. (1990). The effect of rate of muscle contraction on the force-time curve parameters of male and female subjects. *Research Quarterly for Exercise and Sport*, **61**, 96-99.

Bemben, M. G., Massey, B. H., Bemben, J. E., Misner, J. E. and Boileau, R. A. (1991). Isometric muscle force production as a function of age in healthy 20- to 74-yr-old men. *Medicine and Science in Sports and Exercise*, **23**, 1302-1310.

Bemben, M. G., Massey, B. H., Boileau, R. A. and Misner, J. E. (1992). Reliability of isometric force-time curve parameters for men aged 20-79 years. *Journal of Applied Sport Science Research*, **6**, 158-164.

Bergström, M. and Hultman, E. (1988). Energy cost and fatigue during intermittent electrical stimulation of human skeletal muscle. *Journal of Applied Physiology*, **65**, 1500-1505.

Biddle, J. H. and Whitehead, J. R. (1980). Strength training for rugby football. *National Strength and Conditioning Association Journal*, **2**, 26-28.

Bigland-Ritchie, B. (1984). Muscle fatigue and the influence of changing neural drive. *Clinics in Chest Medicine*, **5**, 21-34.

Bigland-Ritchie, B., Dawson, N. J., Johansson, R. S. and Lippold, O. C. (1986a). Reflex origin for the slowing of motorneurone firing rates in fatigue of human voluntary contractions. *Journal of Physiology*, **379**, 451-459.

Bigland-Ritchie, B., Donovan, E. F., Roussos, C. S. (1981). Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *Journal of Applied Physiology*, **51**, 1300-1305.

Bigland-Ritchie, B., Furbush, F. and Woods, J. J. (1986b). Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. *Journal of Applied Physiology*, **61**, 421-429.

Bigland-Ritchie, B., Johansson, R., Lippold, O. C. J. and Woods, J. J. (1983). Contractile speed and EMG changes during fatigue of sustained maximal voluntary contractions. *Journal of Neurophysiology*, **50**, 313-324.

Bigland-Ritchie, B., Jones, D. A., Hosking, G. P. and Edwards, R. H. T. (1978). Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. *Clinical Science and Molecular Medicine*, **54**, 609-614.

Bigland-Ritchie, B., Kulkulka, C. G., Lippold, O. C. J. and Woods, J. J. (1982). The absence of neuromuscular transmission failure in sustained maximum voluntary contractions. *Journal of Physiology (London)*, **330**, 265-278.

Bigland-Ritchie, B. and Woods, J. J. (1984). Changes in muscle contractile properties and neural control during human muscular fatigue. *Muscle and Nerve*, **7**, 691-699.

Bilcheck, H. M., Maresh, C. M. and Kraemer, W. J. (1992). Muscular fatigue: a brief overview. *National Strength and Conditioning Association Journal*, 14, 9-15.

Binder-Macleod, S. A., Halden, E. E. and Jungles, K. A. (1995). Effects of stimulation intensity on the physiological responses of human motor units. *Medicine and Science in Sports and Exercise*, **27**, 556-565.

Binder-Macleod, S. A. and McDermond, L. R. (1992). Changes in the force-frequency relationship of the human quadriceps femoris muscle following electrically and voluntary induced fatigue. *Physical Therapy*, **72**, 95-104.

Binkhorst, R. A., Hoofd, L. and Vissers, A. C. A. (1977). Temperature and force-velocity relationship of human muscles. *Journal of Applied Physiology*, **42**, 471-475.

Bishop, D. (1997). Reliability of a 1-h endurance performance test in trained female cyclists. *Medicine and Science in Sports and Exercise*, **29**, 554-559.

Blake, G. J. and Paterson, D. J. (1992). Effect of noradrenaline on systolic blood pressure and mean aortic flow in the anaesthetized rabbit during hyperkaliaemia. *Journal of Physiology*, **446**, 216P.

Bland, J. M. (1995). *An Introduction to Medical Statistics*. Oxford: Oxford University Press.

Bloomfield, J., Blanksby, B., Ackland, T. and Allison, G. (1990). Influence of strength training on overhead throwing velocity of elite water polo players. *Australian Journal of Science and Medicine in Sport*, **Sept**, 63-67.

Bompa, T. O. (1983). *Theory and Methodology of Training*. Dubuque, Iowa: Kendal/Hunt Publishing Inc.

Boobis, L. H. (1987). Metabolic aspects of fatigue during sprinting. In *Exercise: Benefits, Limits and Adaptations* (edited by D. Macleod, R. Maughan, M. Nimmo, T. Reilly and C. Williams), pp 116-143. London: E + FN SPON.

Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Journal of Rehabilitation Medicine*, **2**, 92-98.

Brown, S. J., Child, R. B., Day, S. H. and Donnelly, A. E. (1997). Exercise-induced skeletal muscle damage and adaptation following repeated bouts of eccentric muscle contractions. *Journal of Sports Sciences*, **15**, 215-222.

Brown, S. J., Child, R. B., Donnelly, A. E., Saxton, J. M. and Day, S. H. (1996). Changes in human skeletal muscle contractile function following stimulated eccentric exercise. *European Journal of Applied Physiology*, **72**, 515-521.

Burke, R. E. (1975). Motor unit properties and selective involvement in movement. *Exercise and Sports Science Reviews*, **3**, 31-81.

Byrd, S. K. (1992). Alterations in the sarcoplasmic reticulum: a possible link to exercise-induced muscle damage. *Medicine and Science in Sports and Exercise*, **24**, 531-536.

Byrnes, W. C., Clarkson, P. M., and Katch, F. I. (1985a). Muscle soreness following resistance exercise with and without eccentric contractions. *Research Quarterly in Exercise and Sport*, **56**, 283-285.

Byrnes, W. C., Clarkson, P. M., White, J. S., Hsieh, S. S., Frykman, P. M. and Maughan, R. J. (1985b). Delayed onset muscle soreness following repeated bouts of downhill running. *Journal of Applied Physiology*, **59**, 710-715.

Byström, S. and Kilbom, Å. (1991). Electrical stimulation of human forearm extensor muscles as an indicator of handgrip fatigue and recovery. *European Journal of Applied Physiology*, **62**, 363-368.

Caiozzo, V. J., Perrine, J. J. and Edgerton, V. R. (1981). Trinity-induced alterations of the in vivo force-velocity relationship of human muscle. *Journal of Applied Physiology*, **51**, 750-754.

Cairns, S. P. and Dulhunty, A. F. (1995). High-frequency fatigue in rat skeletal muscle: role of extracellular ion concentrations. *Muscle and Nerve*, **18**, 890-898.

Carey-Smith, R. and Rutherford, O. M. (1995). The role of metabolites in strength training. I. A comparison of eccentric and concentric contractions. *European Journal of Applied Physiology*, **71**, 332-336.

Carolan, B. and Cafarelli, E. (1992). Adaptations in co-activation in response to isometric training. *Journal of Applied Physiology*, **73**, 911-917.

Cavanagh, P. R. and Komi, P. V. (1979). Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. *European Journal of Applied Physiology*, **42**, 159-163.

Chapman, S. J., Grindod, S. R., Jones, D. A. (1984). Cross-sectional area and force production of the quadriceps muscle. *Journal of Physiology*, **353**, 53P.

Christ, C. B., Slaughter, M. H., Stillman, R. J. (1994). Reliability of selected parameters of isometric muscle function associated with testing 3 days x 3 trials in women. *Journal of Strength and Conditioning Research*, **8**, 65-71.

Chromiak, J. A. and Mulvaney, D. R. (1990). A review: The effects of combined strength and endurance training on strength development. *Journal of Applied Sport Science Research*, **4**, 55-60.

Clamann, H. P. and Henneman, E. (1976). Electrical measurement of axon diameter and its use in relating motorneuron size to critical firing level. *Journal of Neurophysiology*, **39**, 844-851.

Clarke, H. H. (1948). Objective strength tests of affected muscle groups involved in orthopaedic disabilities. *Research Quarterly for Exercise and Sport*, **19**, 118-147.

Clarkson, P. M. and Sayers, S. P. (1999). Etiology of exercise-induced muscle damage. *Canadian Journal of Applied Physiology*, **24**, 234-248.

Clarkson, P. M. and Tremblay, I. (1988). Exercise-induced muscle damage, repair, and adaptation in humans. *Journal of Applied Physiology*, **65**, 1-6.

Clarys, J. P. and Cabri, J. (1993). Electromyography and the study of sports movements: a review. *Journal of Sports Sciences*, **11**, 379-448.

Clausen, T. (1986). Regulation of active Na^+ -K^+ transport in skeletal muscle. *Physiological Review*, **66**, 554-580.

Clausen, T. and Nielsen, O. B. (1984). The Na^+, K^+ pump and muscle contractility. *Acta Physiologica Scandinavica*, **152**, 365-373.

Cobb, S. and Forbes, A. (1923). Electromyographic studies of muscular fatigue in man. *American Journal of Physiology*, **65**, 234-251.

Close, R. I. (1972). Dynamic properties of mammalian skeletal muscles. *Physiological Reviews*, **52**, 129-197.

Coldwells, A., Atkinson, G. and Reilly, T. (1994). Sources of variation in back and leg dynamometry. *Ergonomics*, **37**, 79-86.

Cooper, R. G., Edwards, R. H. T., Gibson, H. and Stokes, M. J. (1988). Human muscle fatigue: frequency dependence of excitation force generation. *Journal of Physiology*, **397**, 585-599.

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

Coyle, E. F., Hagberg, J. M., Hurley, B. F., Martin, W. H., Eshani, A. A. and Holloszy, J.O. (1983). Carbohydrate feeding during prolonged strenuous exercise can delay fatigue. *Journal of Applied Physiology*, **55**, 230-235.

Davies, R. E. (1973) The dynamics of the energy rich phosphates. In *Limiting Factors of Physical Performance* pp 55-61. Stuttgart: Georg Thieme Publishing.

Davies, C. T. M. and Rennie, R. (1968). Human Power Ouput. *Nature*, **217**, 770.

Davies, C. T. M. and White, M. J. (1981). Muscle weakness following eccentric work in man. *Pflügers Archives*, **392**, 168-171.

DeLorme, T. L. (1946). Heavy resistance exercises. *Archives of Physical Medicine*, 27, 607-630.

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, **13**, 135-163.

De Luca, C. J. and Knaflitz, M. (1990). *Surface Electromyography: What's New?* Neuromuscular Research Centre, Boston, MA.

De Luca, C. J., LeFever, R. S., McCue, M. P. and Xenakis, A. P. (1982). Behaviour of human motor units in different muscles during linearly varying contractions. *Journal of Physiology (London)*, **329**, 113-128.

Denegar, C. R. and Perrin, D. H. (1992). Effect of transcutaneous electrical nerve stimulation, cold, and a combined treatment on pain, decreased range of motion, and strength loss associated with delayed onset muscle soreness. *Journal of Athletic Training*, **27**, 200-206.

Desmedt, J. E. and Godaux, E. (1977). Ballistic contractions in man: characteristic recruitment patterns of single motor units of the tibialis anterior muscle. *Journal of Physiology*, **264**, 673-693.

Desmedt, J. E. and Godaux, E. (1979). Voluntary motor commands in human ballisitic movements. *Annals of Neurology*, **5**, 415-421.

Digitimer (1998). *Operators Manual.* Digitimer Ltd. Hertfordshire, England.

Dill, D. B. and Costill, D. L. (1974). Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *Journal of Applied Physiology*, **37**, 247-248.

Docherty, D. (1984). Preparing for the rugby season. *New Zealand Journal of Health, Physical Education and Recreation*, **17**, 7-10.

Duchateau, J., Feiereisen, P. and Hainaut, K. (1995). Motor unit activation order during electrical stimulation [Abstract]. In *Proceedings of the XVth Congress of the International Society of Biomechanics*, pp 238-239.

Duchateau, J. and Hainaut, K. (1984). Isometric or dynamic training: differential effect on mechanical properties of human muscle. *Journal of Applied Physiology*, **56**, 296-301.

Duchateau, J. and Hainaut, K. (1986). Nonlinear summation of contractions in striated muscle: 1. Twitch potentiation in human muscle. *Journal of Muscle Research and Cell Motility*, **7**, 11-17.

Dudley, G. A. and Djamil, R. (1985). Incompatibility of endurance and strength training modes of exercise. *Journal of Applied Physiology*, **59**, 1446-1451.

Ebbeling, C. B. and Clarkson, P. M. (1989). Exercise-induced muscle damage and adaptation. *Sports Medicine*, **7**, 207-234.

Edwards, R. H. T. (1978). Physiological analysis of skeletal muscle weakness and fatigue. *Clinical Science and Molecular Medicine*, **54**, 463-470.

Edwards, R. H. T. (1981). Human muscle function and fatigue. In *Human Muscle Fatigue: Physiological Mechanisms* (edited by R. Porter and J. Whelan), pp 1-18. London: Pitman Medical.

Edwards, R. H. T. (1983). Biochemical basis of fatigue. In *Biochemistry of Exercise* (edited by H. G. Knuttgen), pp 3-28. Champaign, Illinois: Human Kinetics Publishers.

Edwards, R. H. T., Hill, D. K., Jones, D. A. (1972). Effect of fatigue on the time course of relaxation from isometric contractions of skeletal muscle in man. *Journal of Physiology*, **227**, 26-27.

Edwards, R. H. T., Hill, D. K., Jones, D. A. and Merton, P. A. (1977a). Fatigue of long duration in human skeletal muscle after exercise. *Journal of Physiology*, **272**, 769-778.

Edwards, R. H. T. and Lippold, O. C. J. (1956). The relation between force and integrated electrical activity in fatigued muscle. *Journal of Physiology (London)*, **132**, 677-681.

Edwards, R. H. T., Young, A., Hosking, G. P. and Jones, D. A. (1977b). Human skeletal muscle function: description of tests and normal values. *Clinical Science and Molecular Medicine*, **52**, 283-290.

Elliott, B. C., Wilson, G. J. and Kerr, G. K. (1989). A biomechanical analysis of the sticking region in the bench press. *Medicine and Science in Sports and Exercise*, **21**, 450-462.

Enoka, R. M. (1988). Muscle strength and its development. New Perspectives. *Sports Medicine*, **6**, 146-148.

Enoka, R. M. (1994). Neuromechanical basis of kinesiology. Champaign, Illinois: Human Kinetic Publishers.

Everard, L. (1997). Can massage play a part in pre-sport warm-up? [Unpublished Thesis]. Liverpool John Moores University.

Everts, M. E., Retterstøl, K. and Clausen, T. (1988). Effects of adrenaline on excitation-induced stimulation of the sodium potassium pump in rat skeletal muscle. *Acta Physiologica Scandinavica*, **143**, 189-198.

Ewing, J. L., Wolf, D. R., Rogers, M. A., Amundson, M. L. and Stull, G. A. (1990). Effects of velocity of isokinetic training on strength, power and quadriceps muscle fibre characteristics. *European Journal of Applied Physiology*, **61**, 159-162.

Favero, T. G. (1999). Sarcoplasmic reticulum Ca^{2+} release and muscle fatigue. *Journal of Applied Physiology*, **87**, 471-483.

Fell, N., Lees, A. and MacLaren, D. P. M. (2001). The influence of added load on muscular performance in the counter-movement jump [Abstract]. *Journal of Sports Sciences*, **19**, 5-6.

Field, A. (2000). *Discovering Statistics Using SPSS for Windows*. London: Sage Publications Ltd.

Fleck, S. J. and Kraemer, W. J. (1997). *Designing Resistance Training Programmes*. Second Edition. Champaign, Illinois: Human Kinetics Publishers.

Folland, J. P., Chong, J., Copeman, E. M. and Jones, D. A. (2001). Acute muscle damage as a stimulus for training-induced gains in strength. *Medicine and Science in Sports and Exercise*, **33**, 1200-1205.

Folland, J. P., Irish, C. S. Roberts, J. C., Tarr, J. E. and Jones, D. A. (2002). Fatigue is not a necessary stimulus for strength gains during resistance training. *British Journal of Sports Medicine*, **36**, 370-373.

Frick, U. and Schmidtbleicher, D. (1999). Recovery following strength training sessions with different training regimen – intramuscular coordination versus muscle hypertrophy [Abstract]. In *Proceedings of the Fourth Annual Congress of the European College of Sports Science*, p 72.

Fridén, J. M. (1984). Changes in human skeletal muscle induced by long term eccentric exercise. *Cell and Tissue Research*, **236**, 365-372.

Fridén, J. M. and Ekblom, B. (1988). Sublethal muscle fibre injuries after high tension anaerobic exercise. *European Journal of Applied Physiology*, 57, 360-368.

Fridén, J. M. and Leiber, R. L. (1992). Structural and mechanical basis of exercise-induced muscle injury. *Medicine and Science in Sports and Exercise*, **24**, 521-530.

Fridén, J. M., Sjöström, M. Ekblom, B. (1983). Myofibrillar damage following intense eccentric exercise in man. *International Journal of Sports Medicine*, **4**, 170-176.

Fry, A. C., Powell, D. R. and Kraemer, W. J. (1992). Validity of isometric testing modalities for assessing short term resistance exercise strength gains. *Journal of Sports Rehabilitation*, **1**, 275-283.

Gandevia, S. C. (1992). Some central and peripheral factors affecting human motoneuronal output in neuromuscular fatigue. *Sports Medicine*, **13**, 93-98.

Gans, C. (1992). Electromyography. In *Biomechanics Structures and Systems: A Practical Approach* (edited by A. A. Briewener), pp 175-204. Oxford: IRL Press.

Garhammer, J. (1993). A review of power output studies of Olympic and power lifting: Methodology, performance, prediction, and evaluation tests. *Journal of Strength and Conditioning Research*, **7**, 76-89.

Gerdle, B., Eriksson, N. E. and Brundin, L. (1990). The behaviour of the mean power frequency of the surface electromyogram in biceps brachii with increasing force and during fatigue. With special regard to the electrode distance. *Electromyography and Clinical Neurophysiology*, **30**, 483-489.

Gerdle, B. Henriksson-Larsen, K., Lorentzon, R., Wretling, M. L. (1991). Dependence of the mean power frequency of the electromyogram on muscle force and fibre type. *Acta Physiologica Scandinavica*, **142**, 457-465.

Gibson, H. and Edwards, R. H. T. (1985). Muscular exercise and fatigue. *Sports Medicine*, **2**, 120-132.

Gleeson, M., Blannin, A. K., Walsh, N. P., Bishop, N. C. and Clark, A. M. (1998). Effect of low- and high-carbohydrate diets on the plasma glutamine and circulating leukocyte responses to exercise. *International Journal of Sport Nutrition*, **8**, 49-59.

Going, S. B., Massey, B. H., Hoshizaki, T. B. and Lohman, T. G. (1987). Maximal voluntary static force production characteristics of skeletal muscle in children 8-11 yrs of age. *Research Quarterly for Exercise and Sport*, **58**, 115-123.

Goldspink, G. (1999). Changes in muscle mass and phenotype and the expression of autocrine and systemic growth factors by muscle in response to stretch and overload. *Journal of Anatomy*, 194, 323-334.

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

Grabiner, M. D., Koh, T. J. and Miller, G. F. (1991). Fatigue rates of vastus medialis oblique and vastus lateralis during static and dynamic knee extension. *Journal of Orthopaedic Research*, **9**, 391-397.

Grange, R. W., Vandemboom, R. and Houston, M. E. (1993). Physiological significance of mysosin phospohorylation in skeletal muscle. *Canadian Journal of Applied Sport Sciences*, **18**, 229-242.

Green, H. J. (1995). Metabolic determinants of activity induced muscular fatigue. In *Exercise Metabolism* (edited by M. Hargreaves), pp 211-256. Champaign, Illinois: Human Kinetics Publishers.

Green, H. J. (1997). Mechanisms of muscle fatigue in intense exercise. *Journal of Sports Sciences*, **15**, 247-256.

Grimby, G., Bjorntorp, P., Fahlen, M., Hoskins, T. A., Hook, O. Oxhoj, H. and Saltin, B. (1973). Metabolic effects of isometric training. *Scandinavian Journal of Clinical Laboratory Investigation*, **31**, 301-305.

Güllich, A. and Schmidtbleicher, D. (1996). MVC-induced short-term potentiation of explosive force. *New Studies in Athletics*, **11**, 67-81.

Gutin, B., Stewark, K., Lewis, S. and Kruper, J. (1976). Oxygen consumption in the first stages of strenuous work as a function of prior exercise. *Journal of Sports Medicine and Physical Fitness*, **16**, 60-65.

Hagbarth, K-E., Kunesch, E. J., Nordin, M., Schmidt, R., Wallin, E. U. (1986). Gamma loop contributing to maximal voluntary contraction in man. *Journal of Physiology*, **380**, 575-591.

Hagberg, M. (1981). Muscular endurance and surface electromyogram in isometric and dynamic exercise. *Journal of Applied Physiology: Respiratory, Environmental and Environmental Physiology*, **51**, 1-7.

Haff, G. G., Stone, M. H., O'Bryant, H. S., Harman, E., Dinan, C., Johnson, R. and Han, K-H. (1997). Force-time dependent characteristics of dynamic and isometric muscle actions. *Journal of Strength and Conditioning Research*, **11**, 269-272.

Haff, G. G., Stone, M. H., Warren, B. J., Keith, R., Johnson, R. L., Nieman, D. C., Williams, F. and Kirksey, K. B. (1999). The effect of carbohydrate supplementation on multiple sessions and bouts of resistance exercise. *Journal of Strength and Conditioning Research*, **13**, 111-117.

Hainaut, K. and Duchateau, J. (1989). Muscle fatigue, effects of training and disuse. *Muscle and Nerve*, **12**, 660-669.

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

Häkkinen, K. (1993). Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise. *International Journal of Sports Medicine*, **14**, 53-59.

Häkkinen, K. (1994a). Neuromuscular fatigue in males and females during strenuous heavy resistance loading. *Electromyography and Clinical Neurophysiology*, **34**, 205-214.

Häkkinen, K. (1994b). Neuromuscular adaptation during strength training, aging, detraining, and immobilization. *Critical Reviews in Physical and Rehabilitation Medicine*, **6**, 161-198.

Häkkinen, K., Alén, M. and Komi, P. V. (1985a). Changes in isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica*, **125**, 573-585.

Häkkinen, K. and Keskinen, K. L. (1989). Muscle cross-sectional area and voluntary force production characteristics in elite strength-trained and endurance-trained athletes and sprinters. *European Journal of Applied Physiology*, **59**, 215-220.

Häkkinen, K. and Komi, P. V. (1983). Electromyographic changes during strength training and detraining. *Medicine and Science in Sports and Exercise*, **15**, 455-460.

Häkkinen, K. and Komi, P. V. (1985a). Changes in electrical and mechanical behaviour of leg extensor muscles during heavy resistance training. *Scandinavian Journal of Sports Sciences*, **7**, 55-64.

Häkkinen, K. and Komi, P. V. (1985b). Effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. *Scandinavian Journal of Sports Sciences*, **7**, 65-76.

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

Häkkinen, K. and Komi, P. V. (1986b). Effects of fatigue and recovery on electromyographic and isometric force- and relaxation-time characteristics of human skeletal muscle. *European Journal of Applied Physiology*, **55**, 588-596.

Häkkinen, K., Komi, P. V. and Alén, M. (1985b). Effect of explosive type strength training on isometric force- and relation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica*, **125**, 587-600.

Häkkinen, K., Komi, P. V. and Kauhanen, H. (1986). Electromyographic and force production characteristics of leg extensor muscles of elite weightlifters during isometric, concentric and various stretch-shortening cycle exercises. *International Journal of Sports Medicine*, 3, 144-151.

Häkkinen, K., Komi, P. V. and Tesch, P. A. (1981). Effect of combined concentric and eccentric strength training and detraining on force-time, muscle fibre and metabolic characteristics of leg extensor muscles. *Scandinavian Journal of Sports Science*, **3**, 50-58.

Häkkinen, K. and Myllylä, E. (1990). Acute effects of muscle fatigue and recovery on force production and relaxation in endurance, power and strength athletes. *Journal of Sports Medicine and Physical Fitness*, 30, 5-12.

Häkkinen, K., Newton, R. U. and Gordon, S. E. (1998). Changes in muscle morphology, electromyographic activity, and force production characteristics during progressive strength training in young and old men. *Journal of Gerontology*, **53A**, B415-423.

Häkkinen, K., Pakarinen, A., Alén, M., Kauhanen, H. and Komi, P. V. (1988). Neuromuscular and hormonal responses in elite athletes to successive strength training sessions in one day. *European Journal of Applied Physiology*, **57**, 133-139.

Häkkinen, K., Pakarinen, A., Komi, P. V., Ruyshi, T. and Kauhanen, H. (1989). Neuromuscular adaptations and hormone balance in strength athletes, physically active males and females during intensive strength training. In *Proceedings of the XIIth International Congress of Biomechanics*, p 8.

Hargreaves, M., Costill, D. L. Coggan, A., Fink, W. J. and Nishibata, I. (1984). Effect of carbohydrate feedings on muscle glycogen utilisation and exercise performance. *Medicine and Science in Sports and Exercise*, **16**, 219-222.

Harris, G. F. and Wertsch, J. J. (1994). Procedures for gait analysis. *Archives of Physical and Medical Rehabilitation*, **75**, 216-225.

Henneman, E., Clamman, H. P., Giles, J. D. and Skinner, R. D. (1974). Rank order of motor neurons within a pool: law of combination. *Journal of Physiology*, **37**, 1338-1348.

Hennessy, L. C. and Watson, A. W. S. (1994). The interference effects of training for strength and endurance simultaneously. *Journal of Strength and Conditioning Research*, **8**, 12-19.

Hering, G., Hennig, E. and Riehle, H. J. (1988). Reproducibility of IEMG measurements on the M. triceps brachii. In *Biomechanics XI-A* (edited by G. de Groot, A. P. Hollander, P. A. Huijing and G. J. van Ingen Schenau), pp 148-152. Amsterdam: Free University Press.

Herzog, W., Guimaraes, A. C. S. and Zhang, Y. T. (1994). Measurement of EMG. In *Biomechanics of the Musculo-Skeletal System* (edited by B. M. Nigg and W. Herzog), pp 308-336.

Herzog, W. and Ter Keurs, H. E. D. J. (1988). Force-length relation of in vivo human rectus femoris muscle. *Pflüegers Archives*, **411**, 642-647.

Heyters, M., Carpentier, A., Duchateau, J. and Hainaut, K. (1994). Twitch analysis as an approach to motor unit activation during electrical stimulation. *Canadian Journal of Applied Physiology*, **19**, 456-467.

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

Hikida, R. S., Staron, R. S., Hagermann, F. C., Sherman, W. M. and Costill, D. L. (1983). Muscle fibre necrosis associated with human marathon runners. *Journal of Neurological Science*, **59**, 185-203.

Hodgkin, A. L. and Huxley, A. F. (1952). The dual effect of membrane potential on sodium conductance in the giant axon of Loligo. *Journal of Physiology*, **116**, 497-506.

Hodgkin, A. L. and Katz, B. (1949). The effect of sodium ions on the electrical activity of the giant axon of the squid. *Journal of Physiology*, **108**, 37-77.

Horita, T., Komi, P. V., Hämäläinen, I. And Avela, J. (1997). Exhausting stretch-shortening cycle (SSC) exercise causes greater impairment in SSC than in concentric performance. In *Proceedings of the XVIth Congress of the International Society of Biomechanics*, p 168.

Horita, T., Komi, P. V., Nicol, C. and Kyröläinen, H. (1996). Stretch-shortening cycle fatigue:interactions among joint stiffness, reflex, and muscle mechanical performance in drop jump. *European Journal of Applied Physiology*, **73**, 393-403.

Howell, D. C. (1992). *Statistical Methods for Psychology*. Belmont, CA: Duxbury Press.

Huczel., H. A. and Clarke, D. H. (1992). A comparison of strength and muscle endurance in strength-trained and untrained women. *European Journal of Applied Physiology*, **64**, 467-470.

Hultman, E., Spriet, L. L. and Sodelund, K. (1987) Energy metabolism and fatigue in working muscle. In *Exercise: Benefits, Limits and Adaptations* (Edited by D. Macleod, R. Maughan, M. Nimmo, T. Reilly and C. Williiams), pp 63-85. London: E + FN SPON.

Ikai, M. and Steinhaus, A. (1961). Some factors modifying the expression of human strength. *Journal of Applied Physiology*, **16**, 157-163.

Inger, F. and Strømme, S. B. (1979). Effects of active, passive or no warm-up on the physiological response to heavy exercise. *European Journal of Applied Physiology*, **40**, 273-282.

Ivy, J. L., Withers, R. T., Brose, G., Maxwell, B. D. and Costill, D. L. (1981). Isokinetic contractile properties of the quadriceps with relation to fibre type. *European Journal of Applied Physiology*, **47**, 247-255.

James, C., Sacco, P. and Jones, D. A. (1995). Loss of power during fatigue of human leg muscles. *Journal of Physiology*, **484**, 237-246.

Jaric, S., Ristanovic, D. and Corcos, D. M. (1989). The relationship between muscle kinematic parameters and kinematic variables in a complex movement. *European Journal of Applied Physiology*, 59, 370-376.

Jereb, B. and Strojnik, V. (1995). Fatigue effects of three anaerobic power tests. In *Proceedings of the XVth Congress of the International Society of Biomechanics*, pp 434-435.

Johansson, C. A., Kent, B. E. and Shepard, K. F. (1983). Relationship between verbal command volume and magnitude of muscle contraction. *Physical Therapy*, **63**, 1260-1265.

Jöllenbeck, T. (1999). Electromechanical activation and relaxation delay of the knee extensor and flexor muscles [Abstract]. In *Proceedings of the Fourth Annual Congress of the European College of Sports Science*, p 157.

Jones, D. A. (1981). Muscle fatigue due to changes beyond the neuromuscular junction. In *Human Muscle Fatigue: Physiological Mechanisms* (edited by R. Porter and J. Whelan), pp 178-196. London: Pitman Medical.

Jones, D. A. (1996a). High- and low- frequency fatigue revisited. *Acta Physiologica Scandinavica*, **156**, 265-270.

Jones, D. A. (1996b). Causes of human muscle fatigue [Abstract]. In *Proceedings of the First Annual Congress Frontiers in Sport Science: The European Perspective*, pp 26-27.

Jones, D. A. (1999). Muscle fatigue during high intensity exercise. In *Physiological Determinants of Exercise Tolerance in Humans* (edited by B. J. Whipp and A. J. Sargeant), pp 1-11. London: Portland Press.

Jones, D. A. and Bigland-Ritchie, B. (1986). Electrical and contractile changes in muscle fatigue. In *Biochemistry of Exercise: International Series on Sport Sciences* (edited by B. Saltin), Vol 16, pp 377-392. Champaign, Illinois: Human Kinetics Publishers.

Jones, D. A., Bigland-Ritchie, B. and Edwards, R. H. T. (1979). Excitation frequency and muscle fatigue: mechanical responses during voluntary and stimulated contractions. *Experimental Neurology*, **64**, 401-413.

Jones, D. A. and Folland, J. P. (2001). Strength training in young adults. In *Sports Medicine for Specific Ages and Abilities* (edited by N. Maffuli, K. M. Chan, R. MacDonald, R. M. Malina and A. W. Parker), pp 57-64. Edinburgh: Churchill Livingstone.

Jones, D. A., Newham, D. J., Round, J. M., Tolfree, S. E. (1986). Experimental human muscle damage: morphological changes in relation to other indices of damage. *Journal of Physiology*, **375**, 435-448.

Jones, D. A. and Rutherford, O. M. (1987). Human muscle strength training: the effects of three different regimes and the nature of the resultant changes. *Journal of Physiology*, **91**, 1-11.

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

Johnson, E. W. (1988). *Practical Electromyography*. Second Edition. Baltimore, M. D.: Williams and Wilkins.

Juel, C., Bangsbo, J., Graham, T. and Saltin, B. (1990). Lactate and potassium fluxes from human skeletal muscle during and after intense, dynamic, knee extensor exercise. *Acta Physiologica Scandinavica*, **140**, 147-159.

Kaneko, M., Fuchimoto, T., Toji, H. and Suuei, K. (1983). Training effect of different loads on the force-velocity relationship and mechanical power output in human muscle. *Scandinavian Journal of Sports Sciences*, **5**, 50-55.

Kanehisa, H. and Myashita, M. (1983). Effect of isometric and isokinetic muscle training on static strength and dynamic power. *European Journal of Applied Physiology*, **50**, 365-371.

Karlsson, J. and Saltin, B. (1971). Diet, muscle glycogen and endurance performance. *Journal of Applied Physiology*, **31**, 203-206.

Keogh, J. W. L., Wilson, G. J. and Weatherby, R. P. (1999). A cross-sectional comparison of different resistance training techniques in the bench press. *Journal of Strength and Conditioning Research*, **13**, 247-258.

King, I. (1993). Strength training for rugby. *New Zealand Journal of Sports Medicine*, **4**, 62-65.

King, I. And Poliquin, C. (1991). Theory and methodology of strength training: long-term periodisaton. *Sports Coach*, **April-June**, 22-26.

Kirsch, R. F. and Rymer, W. Z. (1992). Neural compensation for fatigued induced changes in muscle stiffness during perturbations of elbow angle in human. *Journal of Neurophysiology*, **68**, 449-470.

Kleiner, D. M., Worley, M. E. and Blessing, D. L. (1996). Creatine kinase response to various protocols of resistance exercise. *Journal of Strength and Conditioning Research*, **10**, 15-19.

Komi, P. V. (1986). Training of muscle strength and power: Interaction of neuromotoric, hypertrophic, and mechanical factors. *International Journal of Sports Medicine*, **7**, 10-15.

Komi, P. V. (1998). Neural mechanisms in strength and power training. In *Proceedings of the International Conference on Weightlifting and Strength Training*, Lahti, Finland. pp 11-16.

Komi, P. V. (1999). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. In *Proceedings of the XVIIth Congress of the International Society of Biomechanics*, p 5.

Komi, P. V. and Buskirk, E. R. (1970). Reproducibility of electromyographic measurements with inserted wire electrodes and surface electrodes. *Electromyographic*, **4**, 357-364.

Komi, P. V. and Rusko, H. (1974). Quantitative evaluation of mechanical and electrical changes during fatigue loading of eccentric and concentric work. *Scandinavian Journal of Rehabilitation Medicine*, [Suppl] 3, 121-126.

Komi, P. V. and Tesch, P. (1979). EMG frequency spectrum, muscle structure and fatigue during dynamic contractions in man. *European Journal of Applied Physiology*, **42**, 41-50.

Komi, P. V. and Viitasalo, J. T. (1976). Signal characteristics of EMG at different levels of muscle tension. *Acta Physiologica Scandinavica*, **96**, 267-276.

Komi, P. V. and Viitasalo, J. T. (1977). Changes in motor unit activity and metabolism in human skeletal muscle during and after repeated eccentric and concentric contractions. *Acta Physiologica Scandinavica*, **100**, 246-254.

Kovanen, V., Suominen, H. and Heikkinen, E. (1984a). Collagen of slow twitch and fast twitch muscle fibres in different types of rat skeletal muscle. *European Journal of Applied Physiology*, **52**, 235-242.

Kovanen, V., Suominen, H. and Heikkinen, E. (1984b). Mechanical properties of fast and slow skeletal muscle with special reference to collagen and endurance training. *Journal of Applied Physiology*, **17**, 725-735.

Knuttgen, H. G. and Kraemer, W. J. (1987). Terminology and measurement in exercise performance. *Journal of Applied Sports Science Research*, **1**, 1-10.

Kramer, H., Kuchler, G. and Brauer, D. (1972). Investigations of the potential distribution of activated skeletal muscles in man by means of surface electrodes. *Electromyography*, **12**, 19-27.

Kroll, W., Clarkson, P. Kamen, G., Lambert, J. (1980). Muscle fibre type composition and knee extension isometric strength fatigue patterns in power- and endurance-trained males. *Research Quarterly in Exercise and Sport*, **51**, 323-333.

Kroon, G. W. and Naeije, M. (1991). Recovery of the human biceps electromyogram after heavy eccentric, concentric or isometric exercise. *European Journal of Applied Physiology*, **63**, 444-448.

Kulkulka, C. G. and Clamann, H. P. (1981). Comparison of the recruitment and discharge properties of motor units in human brachial biceps and adductor polis during isometric contractions. *Brain Research*, **291**, 45-55.

Lapier, T. K., Burton, H. W., Almo, R. and Cerney, F. (1995). Alterations in intramuscular connective tissue after limb casting affect contraction-induced muscle injury. *Journal of Applied Physiology*, **78**, 1065-1069.

Lamb, D. R. (1984). *Physiology of Exercise. Responses and Adaptations*. New York: MacMillan Publishing, pp 311-325.

Lamb, G. D. (1999). Excitation-contraction coupling and fatigue in skeletal muscle. In *Biochemistry of Exercise X* (edited by M. Hargreaves and M. Thompson), pp 99-110.

Latash, M. L., Yee, M. J., Orpett, C., Slingo, A. and Nicholas, J. J. (1994). Combining electrical muscle stimulation with voluntary contraction for studing muscle fatigue. *Archives of Physical Medicine and Rehabilitation*, **75**, 29-35.

Leiber, R. L., Thornell, L. E. and Fridén, J. (1996). Muscle cytoskeletal disruption occurs within the first 15 min of cyclic eccentric exercise. *Journal of Applied Physiology*, **80**, 278-284.

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.

Leveritt, M. L. and Abernathy, P. J. (1999). Effects of carbohydrate restriction on strength performance. *Journal of Strength and Conditioning Research*, **13**, 52-57.

Lindström, L., Kadefors, R. and Petersén, I. (1977). An electromyographic index for localised muscle fatigue. *Journal of Applied Physiology*, **43**, pp 750-754.

Lindström, L., Magnusson, R. and Petersén, I. (1970). Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signals. *Electromyography and Clinical Neurophysiology*, **10**, 341-356.

Lindström, L. and Petersén, I. (1983). Power spectrum analysis of EMG signals and its applications. In *Progress in Clinical Neurophysiology* (edited by E. Desmedt), pp. 1-51, Basel: Karger.

Linnamo, V., Häkkinen, K. and Komi, P. V. (1998). Neuromuscular fatigue and recovery in maximal compared to explosive strength loading. *European Journal of Applied Physiology and Occupational Physiology*, **77**, 176-181.

Lippold, O. C. J. (1955). Fatigue in finger muscles. *Journal of Physiology (London)*, **128**, 33P.

Lucas, S. M., Ruff, R. L. and Binder, M. D. (1987). Specific tension measurements in single soleus and medial gastrocnemius muscle fibres of the cat. *Experimental Neurology*, **95**, 142-154.

Lyttle, A. D., Wilson, G. J. and Ostrowski, K. J. (1996). Enhancing performance: maximal power versus combined weights and plyometrics training. *Journal of Strength and Conditioning Research*, **10**, 173-179.

MacDougall, J. D., Elder, G. C. B., Sale, D. G., Moroz, J. R. and Sutton, J. R. (1980). Effects of strength training and immobilisation on human muscle fibres. *European Journal of Applied Physiology*, **43**, 23-34.

MacDougall, J. D, Sale, D. G., Always, S. E. and Sutton, J. R. (1984). Muscle fibre number in biceps brachii in body builders and control subjects. *Journal of Applied Physiology*, **57**, 1399-1403.

Marcos, E. and Ribas, J. (1995). Kinetics of plasma potassium concentrations during exhausting exercise in trained and untrained men. *European Journal of Applied Physiology*, **71**, 207-214.

Martin, G. and Morad, M. (1982). Activity-induced potassium accumulation and its uptake in frog ventricular muscle. *Journal of Physiology (London)*, **328**, 205-227.

Maton, B. (1981). Human motor unit activity during the onset of muscle fatigue in submaximal isometric isotonic contraction. *European Journal of Applied Physiology*, **46**, 271-281.

McBride, J. M., Radzwich, R., Mangino, L., McCormick, M., McCormick, T., Volek, J., Bush, J. A., Augilera, B., Newton, R. U. and Kraemer, W. J. (1995). Responses of serum creatine kinase activity to heavy resistance exercise in endurance and recreationally trained women. *Journal of Strength and Conditioning Research*, **9**, 139-142.

McComas, A. J. (1996). *Skeletal Muscle: Form and function*. Champaign, Illinois: Human Kinetics Publishers.

McDonagh, M. J. N., Hayward, C. M. and Davies, C. T. M. (1983). Isometric training in human elbow flexor muscles: the effects on voluntary and electrically evoked forces. *Journal of Bone and Joint Surgery*, **65**, 355-358.

McDonnel, M. C., Delitto, A., Sinacore, D. R. and Rose, S. J. (1987). Electrically elicited fatigue test of the quadriceps femoris muscle. *Physical Therapy*, **67**, 941-945.

McKenna, M.J. (1992). The role of ionic processes in muscular fatigue during intense exercise. *Journal of Sports Medicine*, **13**, 135-145.

McKenna, M. J. (1995). Effects of training on potassium homeostasis during exercise. *Journal of Molecular and Cellular Cardiology*, **27**, 941-949.

McKenna, M. J., Schmidt, T. A., Hargreaves, M., Cameron, L., Skinner, S. L. and Kjeldsen, K. (1993). Sprint training increases human skeletal muscle Na^+-K^+- ATPase concentration and improves K^+ regulation. *Journal of Applied Physiology*, **75**, 173-180.

McMillan, J., Stone, M. H., Sartin, J., Keith, R., Marple, D., Brown, C. and Lewis, R. D. (1993). 20-hour physiological responses to a single weight-training session. *Journal of Strength and Conditioning Research*, **7**, 9-21.

McNair, P. J., Depledge, J., Brettkelly, 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. (1993). Evaluating player fitness in professional rugby league: reducing subjectivity. *Strength and Conditioning Coach*, **1**, 11-17

Merletti, R. (1999). Standards for reporting EMG data. *Journal of Electromyography and Kinesiology*, 9, III-IV.

Merletti, R. Knaflitz, M. and DeLuca, C. J. (1990). Myoelectric manifestations of fatigue in voluntary and electrically elicited contractions. *Journal of Applied Physiology*, **69**, 1810-1820.

Mero, A. Komi, P. V. and Gregor, R. J. (1992). Biomechanics of sprint running. *Sports Medicine*, **13**, 376-392.

Mero, A., Luhtanen, P., Viitasalo, J. T. and Komi, P. V. (1981). Relationship between the maximal running velocity, muscle fibre characteristics, force production and force relaxation of sprinters. *Scandinavian Journal of Sports Science*, **3**, 16-22.

Merton, P. A. (1954). Voluntary strength and fatigue. *Journal of Physiology, (London)*, **123**, 553-564.

Messier, S. P. and Dill, M. E. (1985). Alterations in strength and maximal oxygen uptake consequent to Nautilus circuit weight training. *Research Quarterly in Exercise and Sport*, **56**, 345-351.

Metzger, J. and Moss, R. (1990). pH modulation of the kinetics of a single Ca^{2+} sensitive cross-bridge state transition in mammalian single skeletal muscle fibres. *Journal of Physiology*, **428**, 751-764.

Mills, K. R. (1982). Power spectral analysis of electromyogram and compound muscle action potential during muscle fatigue and recovery. *Journal of Physiology*, **326**, 401-409.

Milner-Brown, H. S. and Miller, R. G. (1986). Muscle membrane excitation and impulse propagation velocity are reduced during muscle fatigue. *Muscle and Nerve*, **9**, 367-374.

Milner-Brown, H. S., Stein, R. B., and Yemm, R. (1973). The orderly recruitment of human motor units during voluntary isometric contractions. *Journal of Physiology*, **230**, 359-370.

Mitchell, J. B., DiLauro, P. C., Pizza, F. X. and Cavender, D. L. (1997). The effect of pre-exercise status on resistance exercise performance. *International Journal of Sports Nutrition*, **7**, 185-196.

Moffroid, M. T. and Whipple, R. H. (1970). Specificity of speed of exercise. *Physical Therapy*, **50**, 1692-1699.

Moffroid, M., Whipple, R., Hofkosh, J., Lowman, E. and Thistle, H. (1969). A study of isokinetic exercise. *Physical Therapy*, **49**, 735-747.

Moritani, T. (1992). Time course of adaptations during strength and power training. In *Strength and Power in Sports. The Encylopedia of Sports Medicine* (edited by P. V. Komi), pp 266-277. Oxford: Blackwell.

Moritani, T. (1993). Neuromuscular adaptations during the acquisition of muscle strength, power and motor tasks. *Journal of Biomechanics*, **26**, 95-107.

Moritani, T. Muro, M. and Nagata, A. (1986) Intramuscular and surface electromyogram changes during muscle fatigue. *Journal of Applied Physiology*, **60**, 1179-1185.

Moussavi, R. S., Carson, P. J., Boska, M. D., Weiner, M. W. and Miller, R. G. (1989). Nonmetabolic fatigue in exercising human muscle. *Neurology*, **39**, 1222-1226.

Mueller, K. J. and Behrle, M. (1987). Comparison of static and dynamic strength of the arm extensor muscles. In *Biomechanics X-A* (edited by B. Johnsson), pp 501-505. Champaign, Illinois: Human Kinetics Publishers.

Mueller, K. J. and Schmidtbleicher, D. (1987). Innervation pattern of isometric and concentric contractions of the human triceps brachii during elbow extension. In *Biomechanics X-A* (edited by B. Johnsson), pp 479-483. Champaign, Illinois: Human Kinetics Publishers.

Narici, M. V., Roi, G. S., Landoni, L., Minetti, A. E. and Cerretelli, P. (1989). Changes in force, cross-sectional area and neural activation during strength training and detraining of the human quadriceps. *European Journal of Applied Physiology*, **59**, 310-319.

Nevill, A. and Atkinson, G. (1998). Assessing measurement agreement (repeatability) between three or more trials [Abstract]. *Journal of Sports Sciences*, **16**, 29.

Newham, D. J., Jones, D. A. and Clarkson, P. M. (1987). Repeated high-force eccentric exercise, effects on muscle pain and damage. *Journal of Applied Physiology*, **63**, 1381-1386.

Newham, D. J., McCarthy, T. and Turner, J. (1991). Voluntary activation of human quadriceps during and after isokinetic exercise. *Journal of Applied Physiology*, **71**, 2122-2126.

Newham, D. J., McPhail, G., Mills, K. R., Edwards, R. H. T. (1983a). Ultrastructural changes after concentric and eccentric muscle contractions. *Journal of Neurological Science*, **61**, 109-122.

Newham, D. J., Mills, K. R., Quigley, B. M. and Edwards, R. H. T. (1983b). Pain and fatigue following concentric and eccentric muscle contractions. *Clinical Science*, **64**, 55-62.

Newton, R. U. and Kraemer, W. J. (1994). Developing explosive muscular power: Implications for a mixed methods training strategy. *Strength and Conditioning*, **16**, 0-31.

Newton, R. U., Kraemer, W. J. and Häkkinen, K. (1999). Effects of ballistic training on preseason preparation of elite volleyball players. *Medicine and Science in Sports and Exercise*, **31**, 323-390.

Newton, R. U., Kraemer, W. J., Häkkinen, K., Humphries, B. J. and Murphy, A. J. (1996). Kinematics, kinetics, and muscle activation during explosive upper body movements. *Journal of Applied Biomechanics*, **12**, 31-43.

Newton, R. U. and McEvoy, K. P. (1994). Baseball throwing velocity. A comparison of medicine ball training and weight training. *Journal of Strength and Conditioning Research*, **8**, 198-203.

Newton, R. U. and Wilson, G. J. (1993). The kinetics and kinematics of powerful upper body movements: The effect of load [Abstract]. In *Proceedings of the XIVth Congress of the International Society of Biomechanics*, pp 936-937.

Nicol, C., Komi, P. V., Horita, T. and Kyrölälainen, Takala, T. E. S. (1996). Reduced stretch-reflex sensitivity after exhausting stretch-shortening cycle exercise. European *Journal of Applied Physiology*, **72**, 401-409.

Nilsson, J. Panizza, M. and Hallet, M. (1993). Principles of digital sampling of a physiological signal. *Electrencephalography and Clinical Neurophysiology*, **89**, 349-358.

Nilsson, J., Tesch, P. and Thorstensson, A. (1977). Fatigue and EMG of repeated fast voluntary contractions in man. *Acta Physiologica Scandinavica*, **101**, 194-198.

Norris, F. H. (1963). *The EMG: A Guide and Atlas for Practical EMG*. New York, Gruve and Stratton.

Nosaka, K. and Kuramata, T. (1991). Muscle soreness and serum enzyme activity following consecutive drop jumps. *Journal of Sports Sciences*, **9**, 213-220.

Okamoto, T. Tsutsumi, H. Goto, Y. and Andrew, P. (1987). A simple procedure to attenuate artefacts in surface electrode recordings by painlessly lowering skin impedance. *Electromyography and Clinical Neurophysiology*, **27**, 173-176.

Pääsuke, M., Ereline, J. and Gapeyeva, H. (1999). Neuromuscular fatigue during repeated exhaustive submaximal static contractions of knee extensor muscles in endurance-trained, power-trained and untrained men. *Acta Physiologica Scandinavica*, **166**, 319-326.

Patton, N. J. and Mortensen, O. A. (1971). An electromyographic study of reciprocal activity of muscles. *Anatomical Record*, **170**, 255-268.

Petrofsky, J. S., Glaser, R. M., and Phillips, C. A. (1982). Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics*, **25**, 213-223.

Petrofsky, J. S. and Lind, A. R. (1980a). Frequency analysis of the surface electromyogram during sustained isometric contractions. *European Journal of Applied Physiology*, **43**, 173-182.

Petrofsky, J. S. and Lind, A. R. (1980b). The influence of temperature on the amplitude and frequency components of the EMG during brief and sustained isometric contractions. *European Journal of Applied Physiology*, **44**, 189-200.

Pierce, K., Rozenek, R. and Stone, M. H. (1993). Effects of high volume weight training on lactate, heart rate and perceived exertion. *Journal of Strength and Conditioning Research*, **7**, 211-215.

Poliquin, C. (1989). Theory and methodology of strength training. *Sports Coach*, **12**, 25-27.

Poliquin, C. and Patterson, P. (1989). Classification of strength qualities. *National Strength and Conditioning Association Journal*, **11**, 48-50.

Pryor, J. F., Wilson, G. J. and Murphy, A. J. (1994). The effectiveness of eccentric, concentric and isometric rate of force development tests. *Journal of Human Movement Studies*, **27**, 153-172.

Pullinen, T. and Komi, P. V. (1995). Exhaustive SSC-Exercise: Decline of force production is related to the delayed increase in serum creatine-kinase activity [Abstract]. In *Proceedings of the XVth Congress of the International Society of Biomechanics*, pp 746-747.

Pyne, D. B. (1994). Exercise induced muscle damage and inflammation: a review. *The Australian Journal of Science and Medicine in Sport*, **September/December**, 49-58.

Rasch, P. J. and Morehouse, L. E. (1957). Effect of static and dynamic exercises on muscular strength and hypertrophy. *Journal of Applied Physiology*, **11**, 29-34.

Ratkeviius, A., Skurvydas, A. Povilonis, E. Quistorff, B. and Lexell, J. (1998). Effects of contraction duration on low-frequency fatigue in voluntary and electrically-induced exercise of human quadriceps muscle in humans. *European Journal of Applied Physiology*, **77**, 462-468.

Robergs, R. A., Pearson, D. R., Costill, D. L., Fink, W. J., Pascoe, D. D., Benedict, M. A., Lambert, C. P. and Zachweija, J. J. (1991). Muscle glycogenolysis during differing intensities of weight-resistance exercise. *Journal of Applied Physiology*, **70**, 1700-1706.

Robinson, J. M., Stone, M. H., Johnson, R. L., Penland, C. M., Warren, B. J. and Lewis, R. D. (1995). Effects of different weight training exercise / rest intervals on strength, power and high intensity exercise endurance. *Journal of Strength and Conditioning Research*, **9**, 216-221.

Rodenburg, J. B., Bar, P. R. and DeBoer, R. W. (1993). Relations between muscle soreness and biochemical and functional outcomes of eccentric exercise. *Journal of Applied Physiology*, **74**, 2976-2983.

Rossignol, S. (1975). Startle responses recorded in the leg of man. *Electroencephalography and Clinical Neurophysiology*, **39**, 389-397.

Round, J. M., Jones, D. A. and Cambridge, G. (1987). Cellular infiltrates in human skeletal muscle: Exercise induced damage as a model for inflammatory disease? *Journal of Neurological Science*, **82**, 1-11.

Round, J. M., Jones, D. A., Honour, J. W. (1999). Hormonal factors in the development of differences in strength between boys and girls during adolescence: a longitudinal study. *Annals of Human Biology*, **26**, 49-62.

Rube, N. and Secher, N. H. (1981). Paradoxical influence of encouragement on muscle fatigue. *European Journal of Applied Physiology*, **46**, 1-7.

Rube, N. and Secher, N. H. (1990). Effect of training on central factors in fatigue following two and one-leg static exercise in man. *Acta Physiologica Scandinavica*, **141**, 87-95.

Rutherford, O. M. and Jones, D. A. (1986). The role of learning and coordination in strength training. *European Journal of Applied Physiology*, **55**, 100-105.

Rutherford, O. M. and Jones, D. A. (1992). Measurement of fibre pennation using ultrasound in human quadriceps in vivo. *European Journal of Applied Physiology*, **65**, 433-437.

Sadoyama, T. and Miyano, H. (1981). Frequency analysis of surface EMG to evaluation of muscle fatigue. *European Journal of Applied Physiology*, **47**, 239-246.

Safrit, M. J. and Wood, T. M. (Editors) (1989). *Measurement Concepts in Physical Education and Exercise Science*. Champaign, Illinois: Human Kinetics Publsihers.

Sahlin, K. (1986). Muscle fatigue and lactic acid accumulation. Acta Physiologica Scandinavica, **128** [Suppl 556], 83-91.

Sahlin, K. (1992). Metabolic factors in fatigue. *Sports Medicine*, **13**, 99-107.

Sale, D. G. (1987). Influence of exercise training on motor unit activation. *Exercise and Sports Science Reviews*, **15**, 95-151.

Sale, D. G. (1988). Neural adaptations to resistance training. *Medicine and Science in Sports and Exercise*, **30**, S135-S245.

Sale, D. G. (1991). Testing strength and power. In *Physiological Testing of the High Performance Athlete* (edited by J. D. MacDougall, H. A. Wenger and H. J. Green), pp 21-106. Champaign, Illinois: Human Kinetics Publishers.

Sale, D. G. (1992). Neural adaptation to strength training. In *Strength and Power in Sports. The Encylopedia of Sports Medicine* (edited by P. V. Komi), pp 249-265. Oxford: Blackwell.

Sale, C. (1997). Fatigue and recovery of voluntary and electrically elicited force generation following treadmill running [MSc Thesis]. Liverpool John Moores University.

Sale, D. G., and MacDougall, J. D. (1981). Specificity in strength training: A review for the coach and athlete. *Canadian Journal of Applied Sport Sciences*, **6**, 87-92.

Saunders, M. T. (1980). A comparison of two methods of training on the development of muscular strength and endurance. *Journal of Orthopaedics and Sports Physical Therapy*, **Spring**, 210-213.

Schlumberger, A., Ochs, C., Hänsel, F. and Schmidtbleicher, D. (1999). Effect of the instruction on parameters of the force-time curve in isometric strength measurements [Abstract]. In *Proceedings of the Fourth Annual Congress of the European College of Sports Science*, p 542.

Schlumberger, A. and Schmidtbleicher, D. (1998a). Development of dynamic strength and movement speed after high intensity resistance training [Abstract]. In *Proceedings of the International Conference on Weightlifting and Strength Training,* pp 153-154.

Schlumberger, A. and Scmidtbleicher, D. (1998b). Time course of detraining adaptations after high-intensity resistance training [Abstract]. In *Proceedings of the Third Annual Congress of the European College of Sports Science*, p 176.

Schmidtbleicher, D. (1985). Structural analysis of motor strength qualities and its application to training. *Science Periodical on Research Technology in Sport*, **Sept**.

Schmidtbleicher, D. (1988). Muscular mechanics and neuromuscular control. In *Swimming Science V, International Series of Sport Sciences* (edited by B. E. Ungerechts, K. Wilke, and K. Reischle), pp 131-148. Champaign, Illinois: Human Kinetics Publishers.

Schmidtbleicher, D. (1992). Training for power events. In *Strength and Power in Sports. The Encylopedia of Sports Medicine* (edited by P. V. Komi), pp 381-395. Oxford: Blackwell Scientific.

Schmidtbleicher, D. and Buehrle, M. (1987). Neuronal adaptation and increase of cross sectional area studying different strength training methods. In *Biomechanics X-B* (Edited by B. Johnson), pp 615-620. Champaign, Illinois.: Human Kinetics Publishers.

Shaver, L. G. (1964). Maximum dynamic strength, relative dynamic endurance and their relationships. *Research Quarterly*, **42**, 460-465.

Schott, J., McKully, K. and Rutherford, O. M. (1995). The role of metabolites in strength training. II. Short versus long isometric contractions. *European Journal of Applied Physiology*, **71**, 337-341.

Shellock, F. G. (1986). Physiological, psychological, and injury prevention aspects of warm-up. *National Strength and Conditioning Association Journal*, **8**, 24-27.

Shellock, F. G. and Prentice, W. E. (1985). Warming-up and stretching for improved physical performance and prevention of sports-related injuries. *Sports Medicine*, **2**, 267-278.

Shephard, R. J. (1992). Exercise physiology and performance of sport. In *Sport Science Review: Sport Physiology*, **1**, 2-3.

Signorile, J. F., Weber, B., Roll, B., Caruso, J. F., Lowensteyn, I. and Perry, A. C. (1994). An electromyographical comparison of the squat and knee extension exercises. *Journal of Strength and Conditioning Research*, **8**, 178-183.

Silvester, L. J., Stiggins, C., McGowen, C. and Bryce, G. R. (1992). The effect of variable resistance and free weight training programmes on strength and vertical jump. *National Strength and Conditioning Association Journal*, **3**, 30-33.

Sjödin, B. (1992). Anaerobic function. *Sport Science Review: Sport Physiology*, **1**, 13-27.

Sjøgaard, G. (1990). Exercise-induced muscle fatigue: the significance of potassium. *Acta Physiologica Scandinavica*, **140**, [Suppl. 593], 1-63.

Sjøgaard, G. (1991). Role of exercise-induced potassium fluxes underlying muscle fatigue: a brief review. *Canadian Journal of Physiology and Pharmacology*, **69**, 238-245.

Sjøgaard, G., Adams, R. P., Saltin, B. (1985). Water and ion shifts in skeletal muscle of humans with intense dynamic knee extension. *American Journal of Physiology*, **248**, R190-R196.

Sjøgaard, G. and Saltin, B. (1982). Extra- and intracellular water spaces in muscles of man at rest and with dynamic exercise. *American Journal of Physiology*, **243**, R271-R280.

Sjöström, M., Lexell, J., Eriksson, A. and Taylor, C. C. (1991). Evidence of fibre hyperplasia in human skeletal muscles in healthy young men? *European Journal of Applied Physiology*, 62, 301-304.

Skurvydas, A. (1998). Changes in muscle contraction properties after two different strength training sessions [Abstract]. In *Proceedings of the International Conference on Weightlifting and Strength Training*, Lahti, Finland. pp 159-160.

Sleivert, G. G. and Wenger, H. A. (1992). Reliability of measuring isometric and isokinetic peak torque, rate of torque development, integrated electromyography, and tibial nerve conduction velocity. *Archives of Physical Medicine and Rehabilitation*, **75**, 1315-1321.

Smith, L. L. (1991). Acute inflammation: the underlying mechanism in delayed onset muscle soreness? *Medicine and Science in Sports and Exercise*, **23**, 542-551.

Smith, L. L. (1992). Causes of delayed onset muscle soreness and the impact on athletic performance: A review. *Journal of Applied Sports Science Research*, **6**, 135-141.

Sneyd, J. R., Linton, R. A. F. and Band, D. M. (1992). Intravenous infusion of adrenaline during exercise in man. *Journal of Physiology*, **446**, 210P.

Spriet, L. L. (1987). Muscle pH, glycolytic ATP turnover and the onset of fatigue. In *Exercise: Benefits, Limits and Adaptations* (edited by D. Macleod, R.Maughan, M.Nimmo, T. Reilly and C. Williams), pp 85-103. London: E + FN SPON.

Stauber, W. T. (1989). Eccentric action of muscles: physiology injury and adaptation. *Exercise and Sport Science Reviews*, **17**, 157-185.

Stephens, J. A. and Taylor, A. (1972). Fatigue of maintained voluntary muscle contraction in man. *Journal of Physiology (London)*, **220**, 1-18.

Stokes, M. J. (1985). Reliability and repeatability of methods for measuring muscle in physiotherapy. *Physiotherapy Practice*, **1**, 71-76.

Stokes, M. J., Cooper, R. G. and Edwards, R. H. T. (1988). Normal muscle strength and fatigability in patients with effort syndromes. *British Medical Journal*, **297**, 1014-1016.

Stone, M. H., Chandler, J., Conley, M.S., Kramer, J. B. and Stone, M. E. (1996). Training to muscular failure: is it necessary? *Journal of Strength and Conditioning*, **18**, 44-48.

Stokes, M. J., Edwards, R. H. T. and Cooper, R. G. (1989). Effect of low frequency fatigue on human muscle strength and fatigability during subsequent stimulated activity. *European Journal of Applied Physiology*, **59**, 278-283.

Stone, M. H., Pierce, K., Godsen, R., Wilson, G. D., Blessing, D. and Rozenek, R. (1987). Heart rate and lactate levels during weight training exercise in trained and untrained males. *Physician and Sports Medicine*, **15**, 97-106.

Strass, D. (1991). Force-time and electromyographical characteristics of arm shoulder muscles in explosive type force production in sprint swimmers. *Journal of Swimming Research*, **7**, 19-27.

Strike, P. W. (1991). *Statistical Methods in Laboratory Medicine.* Oxford: Butterworth-Heinemann.

Strojnik, V. and Komi, P. V. (1996a). High-low frequency fatigue during prolonged stretch-shortening cycle exercise [Abstract]. In *Proceedings of The International Pre-Olympic Scientific Congress*, Dallas Texas, p 119.

Strojnik, V. and Komi, P. V. (1996b). Changes in isometric MVC force during prolonged maximal stretch-shortening cycle exercise [Abstract]. In *Proceedings of the First Annual Congress Frontiers in Sport Science: The European Perspective*, pp 490-491.

Strojnik, V. and Komi, P. V. (1998). Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *Journal of Applied Physiology*, **84**, 344-350.

Strojnik, V. and Mesesnel, D. (1994). Fatigue and regeneration after different loadings. In *The Way to Win, International Congress on Applied Sport Science Research in Sports* (edited by J. Viitasalo and U. Kujala), pp 211-214. Helsinki, Finland.

Stulen, F. B. and DeLuca, C. J. (1978). The relation between the myoelectrical signal and physiological properties of constant-force isometric contractions. *Electrencephalography and Clinical Neurophysiology*, **45**, 681-698.

Suminiski, R. R., Robertson, R. J., Arslanian, S., Kang, J., Utter, A. C., DaSilva, S. G., Goss, F. L. and Metz, K. F. (1997). Perception of effort during resistance exercise. *Journal of Strength and Conditioning Research*, **11**, 261-265.

Sweeney, H. L., Bowman, B. F. and Stull, J. T. (1993). Myosin light chain phosphorylation in vertebrae striated muscle: Regulation and function. American Journal of Physiology, **264**, C1085-C1095.

ter Haar Romney, B. M., Dernier, van der Gon, J. J. and Gielen, C. C. A. M. (1982). Changes in recruitment orderof motor units in the human biceps muscle. *Experimental Neurology*, 78, 360-368.

Tesch, P., Colliander, E. and Kaiser, P. (1986). Muscle metabolism during intense, heavy resistance exercise. *European Journal of Applied Physiology*, **55**, 362-366.

Tesch, P., Komi, P. V. and Häkkinen, K. (1987). Enzymatic adaptations consequent to long-term strength training. *International Journal of Sports Medicine*, 8, 66-69.

Tesch, P. Sjödin, B. and Karlsson, J. (1978a). Relationship between lactate accumulation, LDH activity, LDH isozyme and fibre type distribution in human skeletal muscle. *Acta Physiologica Scandinavica*, **103**, 40-46.

Tesch, P. Sjödin, B., Thorstensson, A. and Karlsson, J. (1978b). Muscle fatigue and its relation to lactate accumulation and LDH activity in man. *Acta Physiologica Scandinavica*, **103**, 413-420.

Thomas, J. R. and Nelson, J. K. (1990). *Research Methods in Physical Activity.* Champaign, Illinois: Human Kinetics.

Thomis, M. A. I., Beunen, G. P., Maes, H. H., Blimkie, C. J., Van Leemputte, M., Claessons, A. L., Marchal, G., Willems, E. and R. F. Vlietinck. (1998). Strength training: importance of genetic factors. *Medicine and Science in Sports and Exercise*, **30**, 724-731.

Thompson, L. V., Balog, E. M., Riley, D. A., and Fitts, R. H. (1992). Muscle fatigue in frog semitendinosus: alterations in contractile function. *American Journal of Physiology*, **262**, C1500-C1506.

Thompson, D., Nicholas, C. W. and Williams, C. (1997). Delayed-onset muscular soreness, serum creatine kinase and aspartate aminotransferase activities after prolonged, intermittent, high intensity shuttle running. [Abstract]. In *BASES Conference Proceedings*, pp 64-66.

Thorstensson, A. and Karlsson, J. (1976). Fatiguability and fibre composition of human skeletal muscle. *Acta Physiologica Scandinavica*, **98**, 318-322.

Thorstensson, A. Larsson, L., Tesch, P. and Karlsson, J. (1977). Muscle strength and fibre and fibre composition in athletes and sedentary men. *Medicine and Science in Sports and Exercise*, **9**, 26-30.

Tidow, G. (1990). Aspect of strength training in athletics. *New Studies in Athletics*, **1**, 93-110.

Toji, H., Suei, K. and Kaneko, M. (1997). Effects of combined training loads on relations among force, velocity, and power development. *Canadian Journal of Applied Physiology*, **22**, 328-326.

Thomis, M. A. I., Beunen, G. P., Maes, H. H., Blimkie, C. J., Van Leemputte, M., Claessons, A. L., Marchal, G., Willems, E. and R. F. Vlietinck. (1998). Strength training: importance of genetic factors. *Medicine and Science in Sports and Exercise*, **30**, 724-731.

Tornvall, G. (1963). Assessment of physical capabilities with special reference to the evaluation of maximal voluntary isometric muscle strength and maximal working capacity. *Acta Physiologica Scandinavica*, **58**, Suppl. 201.

Trimble, M. H. and Enoka, R. M. (1991). Mechanisms underlying the training effects associated with neuromuscular electrical stimulation. *Physical Therapy*, **71**, 273-280.

Vaz, M. A., Zhang, Y. T., Herzog, W., Guimares, A. C. S. and MacIntosh, B. R. (1996). The behaviour of rectus femoris and vastus lateralis during fatigue and recovery: an electromyographic and vibromyographic study. *Electromyography and Clinical Neurophysiology*, **36**, 221-230.

Veloso, A., Armada, P., Pezarat-Correia, P., Carita, I. And Abrantes, J. (1999). Isometric force and drop jump tests in relation with acceleration phase in sprint running. In *Proceedings of the Fourth Annual Congress of the European College of Sports Science*, p 202.

Viitasalo, J. T. (1982). Effects of pretension on isometric force production. *International Journal of Sports Medicine*, **3**, 149-152.

Viitasalo, J. T. (1983). Function of the knee extensor muscles during fatigue. In *Biomechanics VIII-A* (edited by H. Matsui and K. Kobayashi), 271-277. Champaign, Illinois: Human Kinetics Publishers.

Viitasalo, J. T. and Komi, P. V. (1975). Signal characteristics of EMG with special reference to reproducibility of measurements. *Acta Physiologica Scandinavica*, **93**, 531-539.

Viitasalo, J. T. and Komi, P. V. (1977). Signal characteristics of EMG during fatigue. *European Journal of Applied Physiology*, **37**, 111-121.

Viitasalo, J . T. and Komi, P. V. (1980). EMG, reflex and reaction time components, muscle structure and fatigue during intermittent isometric contractions in man. *International Journal of Sports Medicine*, **1**, 185-190.

Viitasalo, J. T. and Komi, P. V. (1981). Interrelationships between electromyographical, muscle structure, and reflex time measurements in man. *Acta Physiologica Scandinavica*, **111**, 97-103.

Viitasalo, J. T., Häkkinen, K. and Komi, P. V. (1981). Isometric dynamic force production and muscle fibre composition in man. *Journal of Human Movement Studies*, **7**, 199-209.

Viitasalo, J. T., Saukkonen, S. and Komi, P. V. (1980). Reproducibility of measurements of selected neuromuscular performance variables in man. *Electromyography and Clinical Neurophysiology*, **20**, 487-501.

Vincent, W. J. (1999). *Statistics in Kinesiology*. Second Edition. Champaign, Illinois: Human Kinetics Publishers.

Vint, P. F. and Hinrichs, R. N. (1999). Longer integration intervals reduce variability and improve reliability of EMG derived from maximal isometric exertions. *Journal of Applied Biomechanics*, **15**, 210-220.

Vøllestad, N. K. and Sejersted, O. M. (1988). Biochemical correlates of fatigue: A brief review. *European Journal of Applied Physiology*, **5**, 336-347.

Vos, E. J., Harlaar, J. and Van Ingen Schenau, G. J. (1991). Electromechanical delay during knee extensor contractions. *Medicine and Science in Sports and Exercise*, **23**, 1187-1193.

Walberg-Rankin, J. (1995). A review of nutritional practices and needs of body builders. *Journal of Strength and Conditioning Research*, **9**, 116-124.

Walsh, B. (1990). *Strength Training for Rugby League and Union*. Sydney: Kangaroo Press.

Weiss, L. W., Coney, H. D. and Clark, F. C. (1999). Differential functional adaptations to short-term, low-, moderate-, and high repetition weight training. *Journal of Strength and Conditioning Research*, **13**, 236-241.

Wenzel, R. R. and Perfetto, E. M. (1992). The effect of speed versus non-speed training in power development. *Journal of Applied Sport Science Research*, **6**, 82-87.

Westerblad, H., Allen, D. G. and Lännergren, J. (2002). Muscle fatigue: lactic acid or inorganic phosphate the major cause? *News in Physiological Science*, **17**, 17-21.

Westerblad, H., Duty, S. and Allen, D. G. (1993). Intracellular calcium concentration during low-frequency fatigue in isolated single fibres of mouse skeletal muscle. *Journal of Applied Physiology*, **75**, 382-388.

Williams, M. and Stutzman, L. (1959). Strength variations through the range of motion. *Physical Therapy Review*, **39**, 145-152.

Willoughby, D. S. and Simpson, S. (1998). Supplemental EMS and dynamic weight training: effects on knee extensor strength and vertical jump of female college track and field athletes. *Journal of Strength and Conditioning Research*, **12**, 131-137.

Wilson, G. (1992). Strength training for sport: state of the art review. *Australian Sports Coach*, **11**, 18-21.

Wilson, G. J., Elliott, B. C. and Kerr, G. K. (1989). Bar path and force profile characteristics for maximal and submaximal loads in the bench press. *International Journal of Sports Biomechanics*, **5**, 390-402.

Wilson, G. J. and Murphy, A. J. (1995). Strength diagnosis: the use of pre-training test data to determine individual specific strength training [Abstract]. In *Proceedings of the XVth Congress of the International Society of Biomechanics*, pp 994-995.

Wilson, G. J. and Murphy, A. J. (1996). The use of isometric tests of muscular function in athletic assessment. *Sports Medicine*, **22**, 19-37.

Wilson, G. J., Lyttle, A. D., Ostrowski, K. J. and Murphy, A. J. (1995). Assessing dynamic performance: A comparison of rate of force development tests. *Journal of Strength and Conditioning Research*, **9**, 176-181.

Wilson, G. J., Newton, R. U., Murphy, A. J. and Humphries, B. J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise*, **25**, 1279-1286.

Winter, D. A. (1988). *The Biomechanics and Motor Control of Human Gait.* Waterloo, Ontario: University of Waterloo Press.

Wit, A. (1980). Zagadniena regulacji w procesie rozwoju sily miesnionej na przykladzie zawodnikow uprawiajacych podnoszenie ciezarow [in Polish]. Warsaw: Institute of Sport.

Wright, D. A., Sherman, W. M. and Dernbach, A. R. (1991). Carbohydrate feedings before, during, or in combination improve cycling endurance performance. *Journal of Applied Physiology*, **71**, 1082-1088.

Young, A., Stokes, M., Round, J. M. and Edwards, R. H. T. (1983). The effect of high resistance training on the strength and cross-sectional area of the human quadriceps. *European Journal of Clinical Investigation*, 13, 411-417.

Young, D. B. (1982). Relationship between plasma potassium concentration and plasma potassium excretion. *American Journal of Physiology*, **242**, F599-F603.

Young, W. B. (1993) Training for speed/strength: heavy vs. light loads. *National Strength and Conditioning Association Journal*, **15**, 34-42.

Young, W. B. (1995). Laboratory strength assessment of athletes. *New Studies in Athletics*, **10**, 89-96.

Young, W. B. and Bilby, G. E. (1993). The effect of voluntary effort to influence speed of contraction on strength, muscular power and hypertrophy development. *Journal of Strength and Conditioning Research*, **7**, 172-178.

Young, W. B., Pryor, J. F. and Wilson, G. J. (1995). Effect of instructions on characteristics of counter-movement and drop jump performance. *Journal of Strength and Conditioning Research*, **9**, 232-236.

Zar, J. H. (1993). *Biostatistical Analysis*. London: Prentice Hall International.

Zatsiorsky, V. M. (1995). *Science and Practice of Strength Training*. Champaign, Illinois: Human Kinetics.

Zhou, S., Lawson, D. L., Morrison, W. E. and Fairweather, I. (1995a). Electromechanical delay in isometric muscle contractions evoked by voluntary, reflex and electrical stimulation. *European Journal of Applied Physiology*, **70**, 138-145.

Zhou, S., Lawson, D. L., Morrison, W. E. and Fairweather, I. (1995b). Electromechanical delay of knee extensors: the normal range and the effects of age and gender *Journal of Human Movement Studies*, **28**, 127-146.

Zhou, S., McKenna, M. J., Lawson, D. L., Morrison, W. E. and Fairweather, I. (1996). Effects of fatigue and sprint training on electromechanical delay of knee extensor muscles. *European Journal of Applied Physiology*, **72**, 410-416.

Zuniga, E. Truong, X. and Simons, D. (1970). Effect of skin electrode position on averaged electromyographic potentials. *Archives of Physical Medicine*, **50**, 264-272.

CHAPTER 8

APPENDICES

APPENDIX 2

STATISTICAL POWER AND DETERMINATION OF SAMPLE SIZE

The following equation can be used to determine power and sample size for a repeated measures research design (Zar, 1993).

$$\phi = \sqrt{\frac{n \cdot \delta^2}{2k \cdot s_w^2}}$$

where:

ϕ = Phi - value used to determine statistical power from attached figure.

n = suspected sample size (calculated iteratively)

δ = difference expected to detect (found using previous data)

k = number of the levels of the factor (7 in Study 2 because 7 time points are being measured

s_w^2 = mean square error term obtained from repeated measures ANOVA (found using previous data)

Determination of Sample Size

The following steps were followed to determine the required sample size to obtain sufficient statistical power for the experimental design in Study 2.

1. A value of 40 N was used for δ as this was approximately the average systematic bias between trials determined from the pilot studies.
2. The mean square error term, (s_w^2 = 380.60) was also obtained from the pilot studies.
3. These values were then entered into the formula given above for different values for n. The Excel output is given below.

Excel Output

SAMPLE SIZE	Phi	v_1	v_2	Power
4	1.096	6	18	40%
6	1.342	6	30	65%
8	1.550	6	42	82%
10	1.733	6	54	92%
12	1.898	6	66	98%

where:

v = degrees of freedom and $v_1 = k - 1$, $v_2 = (n - 1)(k - 1)$

4. The calculated values for ϕ (Phi), and the values for v and v were then used to read the power from the figure below. This figure was taken from, Pearson and Hartley (1951) *Biometrika*, **38**, 112-130. Values were read for p = 0.05.

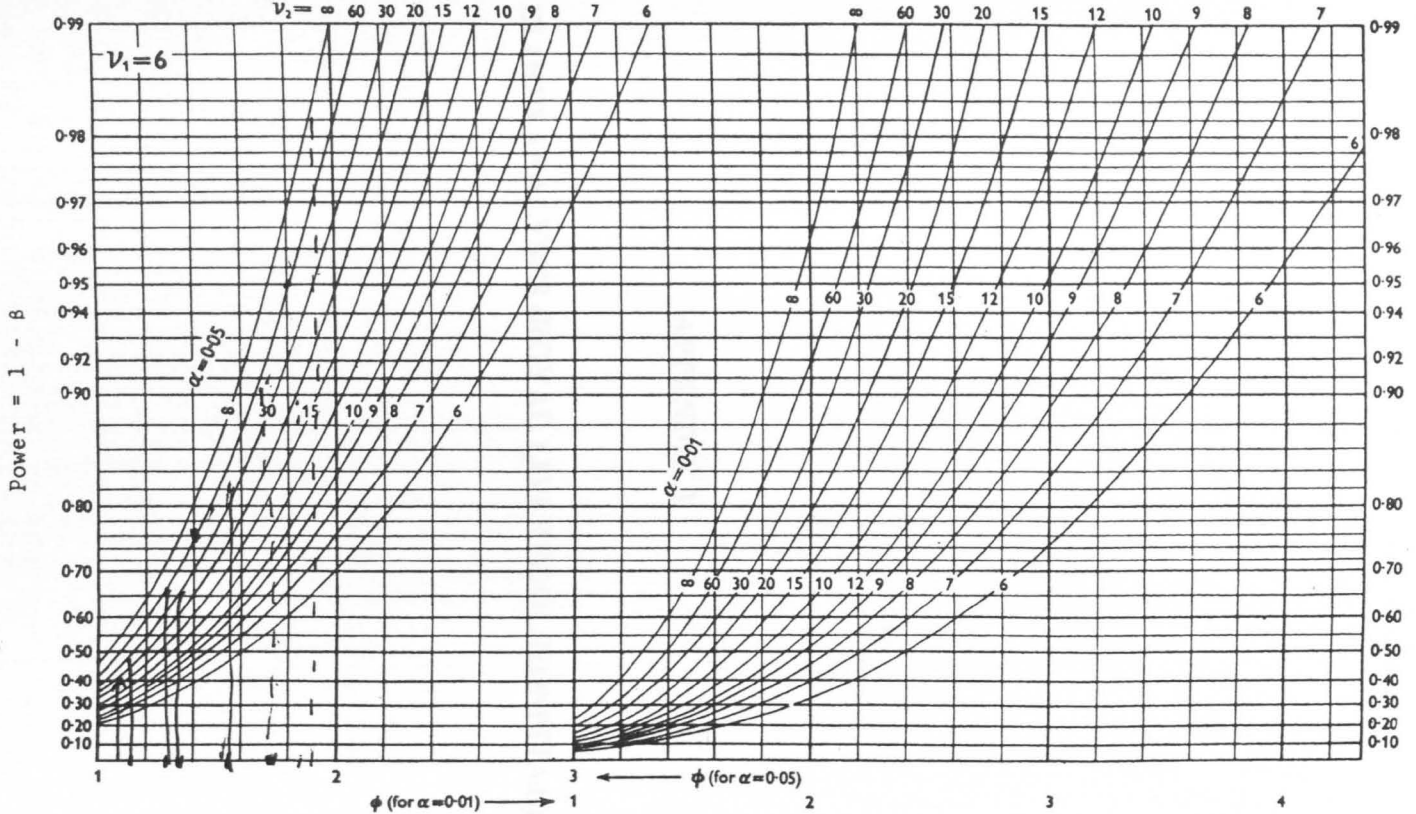


Figure B.1f Power and sample size in analysis of variance; $\nu_1 = 6$.

APPENDIX 3

BLOOD ANALYSES (ROYAL LIVERPOOL HOSPITAL)

HITACHI 747 - Plasma Potassium.

1. Clinical Indications

Plasma potassium concentration is used to assist in the detection, diagnosis and control of hyper / hypokalaemia. Hypokalaemia may be due to prolonged loss of potassium from the body, reduced potassium intake or redistribution. Hyperkalaemia may be due to failure of renal excretion, redistribution or excessive potassium therapy.

2. Analytical Principles

The Hitachi 747 analyser utilises an ion selective electrode which measures potassium ions using potentiometry.

3. Collection

Time and date of sample should be provided. Samples should not be collected from sites where a danger of contamination from intravenous infusion exists.

4. Specimen

A lithium heparin anticoagulated sample is required. Samples must be centrifuged as soon as possible (for 5 minutes at 3000rpm) prior to analysis to obtain a cell free plasma sample. Haemolysed samples and samples left uncentrifuged for a prolonged length of time before analysis may lead to erroneously elevated potassium results.

Serum may also be analysed for potassium.

5. Interference

Haemolysed and delayed samples (>4hours) should not be reported for potassium.
Blood collection tubes containing potassium eg. potassium ethylenediaminetetraacetic acid (EDTA) or potassium fluoride (fluoride/oxalate) must not be used for samples which require potassium analysis.

6. Instrumentation

See Hitachi 747 assay procedure see 747 analysis protocol.

7. Equipment

No additional equipment required.

8. Reagents

Reagents and standards are obtained from:

Boehringer Mannheim UK
(Diagnostics and Biochemicals) Ltd
Bell Lane,
LEWES
East Sussex
BN7 1LG
Tel: 01273 480444
Fax: 01273 480266

1. ISE Diluent - Product No. 1551213
2. ISE Reference Solution - Product No. 1551221

Prepare reagents (1) and (2) by adding 1800mls of freshly deionised water, mix well.
Add 1.2g TRIS (**NOT TRIS chloride**) to reconstituted ISE Reference solution. Add 0.75g TRIS (**NOT TRIS chloride**) to reconstituted ISE Diluent solution.

3. 1M KCl Reference Electrode solution - Product No. 820 652. Ready for use.

Reagent stabilities are as stated on bottle.
On-board stability - expiry date of reagent.
Store stock reagents at room temperature.
COSHH information on above reagents is currently being collated by Boehringer Mannheim.

9. (a) Standards.

Potassium calibration requires:

ISE Standard 1 (Low) Potassium = 3.0 mmol/l Product No.1183974.
ISE Standard 2 (High) Potassium = 7.0 mmol/l Product No.1183982.

These are stable (unopened) until the expiry date on the product, once opened they are stable for 8 hours when stored covered with parafilm.

In addition, an internal standard (labelled Reference Solution) is measured during routine calibration and after every sample. These measurements are used to correct for drift between samples and to provide a periodic single point calibration adjustment.

As the electrical response of each ISE measuring cartridge decreases gradually whilst it is in use it must be replaced when its slope falls below the critical slope value.
The optimal slope value for potassium is 38.0 to 68.0, the critical slope value is < 32.

The slope value is noted after each calibration/recalibration.

The potassium electrode is calibrated daily and recalibrated when indicated by internal quality control.

To compensate for the aqueous nature of the ISE standards an ISE compensator solution is used - see 747 CALIBRATION DATA sheet.

(b) Quality Control

(1) INTERNAL QUALITY CONTROL.
See 747 INTERNAL QC sheet.

(2). EXTERNAL QUALITY CONTROL

Samples from the following EQAS are analysed as follows:
Birmingham - Every 2 weeks.
Wellcome - Every 2 weeks.

10. Method

For Hitachi 747 operation refer to Hitachi 747 protocol.

11. Calculation

Results are presented by the analyser in mmol/l. No raw data is available.

12. Reporting results

Potassium levels are reported in mmol/l.
Potassium results <2.5 and >6.0 are rerun to validate results before being reported.

13. Turnaround Time

Same working day if sample received before 5.00pm.

14. Assay Characteristics

Linearity : 0 - 20.0 mmol/l[1]

Within batch precision : Level 1 (2.96mmol/l) 0.8%[1]
Level 2 (5.90mmol/l) 0.9%[1]

Between batch precision: Level 1 (2.96mmol/l) 1.0%[1]
Level 2 (5.90mmol/l) 1.0%[1]

15. Reference Range

Plasma potassium 3.6 - 5.4 mmol/l

16. Further Information

Maintenance, reagent and calibration logs must be kept up to date and checked daily.
See attached parameter listing for 747 parameter information.
A copy of all in-use parameter information can be found on the 747 Parameters disk.

17. Clinical Interpretation

Potassium is the major intracellular cation, its high cellular concentration being maintained by the Na-K-ATPase pump. Monitoring plasma potassium levels is important because severe deviations from the norm are dangerous.

The commonest causes of hypokalaemia are diuretic therapy and gastrointestinal losses of potassium eg. vomiting, diarrhoea, fistulae. Other causes include mineralocorticoid excess syndromes eg. Conn's syndrome; Cushing's syndrome or 2° hyperaldosteronism (cirrhosis, nephrotic syndrome, cardiac failure). Magnesium depletion should be considered if hypokalaemia does not readily respond to therapy with potassium alone, particularly if there is an associated hypocalcaemia. Hypokalaemia may also result from inadequate potassium intake eg. inappropriate IV therapy, chronic alcoholism.

Pseudo-hyperkalaemia occurs in haemolysed specimens and if there has been a delay in separating the plasma from the red blood cells. The most common causes of true hyperkalaemia are renal failure; drugs eg. potassium-sparing diuretics with potassium supplements ACE inhibitors; β-blockers; mineralocorticoid deficiency eg. Addison's disease, diabetic ketoacidosis, digoxin toxicity.

REFERENCES

1. DCC RLUH Data 1993.

G. Brown
01.11.94
DISC:747
FILE:POT2

P Newland

30.6.95

HITACHI 747 - Plasma Creatine Kinase (CK)

1. Clinical Indications.

Plasma CK estimation is used to assist the detection, diagnosis and control of a variety of disorders including myocardial infarction and muscle diseases such as muscular dystrophy. Elevated levels may also occur after surgery, after physical exertion, in hypothyroidism and after intramuscular injections.

2. Analytical Principles.

The Hitachi 747 analyser utilises the spectrophotometric measurement of NADPH to measure CK activity in clinical samples ie.

$$\text{creatine phosphate} + \text{ADP} \xrightarrow{\text{CK}} \text{creatine} + \text{ATP}$$

$$\text{glucose} + \text{ATP} \xrightarrow{\text{HK}} \text{glucose-6-P} + \text{ADP}$$

$$\text{glucose-6-P} + \text{NADP} \xrightarrow{\text{G6PDH}} \text{gluconate-6-P} + \text{NADPH}$$

The increase in NADPH concentration is monitored spectrophotometrically at 340nm, the rate of the reaction being related directly to the activity of CK in the sample.

3. Collection.

Date and time of sampling should be provided.
Samples should not be collected from sites where a danger of contamination from intravenous infusion exists.

4. Specimen.

A lithium heparin anticoagulated sample is required. Samples must be centrifuged (for 5 minutes at 3000rpm) prior to analysis to obtain a cell free plasma sample.
Serum may also be analysed.

5. Interferences.

None noted.

6. Instrumentation.

For Hitachi 747 assay procedure see 747 analysis protocol.

7. Equipment.

No additional equipment required.

8. Reagents.

Reagents are obtained from:

Boehringer Mannheim UK
(Diagnostics and Biochemicals) Ltd
Bell Lane
East Sussex
BN7 1LG
Tel: 01273 480444
Fax: 01273 480266

Reagent (1) - Buffer/coenzyme
Product No. 1360108
Store unreconstituted reagents at 2-8°C.
Unreconstituted reagent stability is as stated on the bottle.
Add the contents of bottle 1a to bottle 1. Mix to dissolve.
Reconstituted reagent stability - 3 weeks at 2-8°C.

Reagent (2) - Buffer/substrate
Product No. 1360116
Store unreconstituted reagents at 2-8°C.
Unreconstituted reagent stability is as stated on the bottle.
Add the contents of bottle 2a to bottle 2. Mix to dissolve.
Reconstituted reagent stability - 3 weeks at 2-8°C.

Working CK Reagent
Mix 15ml reagent 2 + 75ml regent 1.
On board (10°C) reagent stability - 1 week.

COSHH information is currently being collated by Boehringer Mannheim.

9 (a) Standards.

See 747 CALIBRATION DATA sheets.

The reagent blank value and calibration factor is noted after each recalibration. This is performed daily, with each vial of fresh reagent and when indicated by internal quality control.

9 (b) Quality Control.

(1). INTERNAL QUALITY CONTROL.
See 747 IQC DATA sheet.

(2). EXTERNAL QUALITY CONTROL

Samples from the following EQAS are analysed as follows:
Birmingham - Every 2 weeks.
Murex - Every 2 weeks.

10. Method

For Hitachi 747 operation refer to Hitachi 747 protocol.

11. Calculation

Results are presented by the analyser in U/l. Raw data is available for examination.

12. Reporting results.

CK levels are reported in U/l.
Samples with a level >2000 U/l or samples flagged for possible substrate depletion, are rerun in dilution using a decreased sample volume.
Re-run samples which again show possible substrate depletion are manually diluted x20 and rerun a second time.

13. Turnaround Time.

Same working day if sample received before 5.00pm.

14. Assay Characteristics.

Within batch precision	:	Level 1 (95U/l) 0.7% [1] Level 2 (310U/l) 0.9% [1]
Between batch precision	:	Level 1 (95U/l) 2.2% [1] Level 2 (310U/l) 1.9% [1]
Linearity	:	10 - 2000 U/l (Neat sample) [1] 6000 U/l (Rerun sample) [1]

15. Reference Range.

Plasma CK = Male 33 - 194 U/l.
Female 35 - 143 U/l.

16. Further Information

Maintenance, reagent and calibration logs must be kept up to date and checked daily.

See attached parameter listing for 747 parameter information.
A copy of all in-use parameter information can be found on the 747 Parameters disk.

17. Clinical Interpretation

Creatine kinase (CK) activity is greatest in skeletal muscle, cardiac muscle and in the brain. The liver and red blood cells are devoid of CK activity. Total CK and CK isoenzyme measurements are used in the diagnosis of acute myocardial

infarction (MI). In acute MI, CK is released from myocardium and plasma CK activity begins to rise within 3-6 hours reaching a peak in 18-24 hours and returning to normal by the third day.

Plasma CK activity is raised whenever there is damage to skeletal muscle. Very large increases are seen in rhabdomyolysis, Duchenne's muscular dystrophy, and in polymyositis. Plasma CK increases post-surgically, following intramuscular injections, following grand mal seizures, in hypothermia and hyperthermia, in chronic alcoholism, in diabetic ketoacidosis, renal failure and in hypothyroidism. Prolonged muscular exercise can also result in increased CK levels especially in unfit individuals.

CK isoenzyme analysis is required to differentiate between skeletal and cardiac muscle damage.

REFERENCES

1. DCC Data June 1993.

Gillian Brown
01.11.94
Disc: 747
File: CK2

P Newland

30.6.95

APPENDIX 4

GRAPHIC PAIN RATING FORM

MUSCLE SORENESS QUESTIONNAIRE

Project Title: **Neuromuscular and metabolic characteristics of fatigue in response to heavy resistance and dynamic strength training**

Project Researcher: Neil Fell Director of Studies: Professor. A. Lees
Supervisor: Professor. D. Maclaren

Experiment Title: Neuromuscular and metabolic characteristics of fatigue and recovery in response to heavy resistance and dynamic strength exercise in subjects engaged in team sports

NAME: EXERCISE:

TO THE SUBJECT
You are required to rate the soreness of the quadriceps femoris muscles from no pain to unbearable pain using the graphic pain rating scale (shown below); firstly in a relaxed state (general soreness, **GS**), and then while performing knee-flexion exercise (leg soreness, **LS**).

Please rate the soreness of both the right and left quadriceps by crossing the scale with a small vertical line. You are required to indicate the soreness of the muscle; immediately after exercise, 2 hours after the exercise, and on days, 1, 2, 3, 4 and 5 of recovery. Use the scale directly below to indicate the soreness of the quadriceps before the exercise session.

Graphic pain rating scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

BEFORE EXERCISE

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

Graphic Pain Rating Scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

IMMEDIATELY AFTER EXERCISE

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

2 HOURS AFTER EXERCISE

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

Graphic Pain Rating Scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

DAY 1 OF RECOVERY (+24 HOURS POST EXERCISE)

RIGHT QUADRICEPS

GS No Pain _____ DA SP MSP P VP Unbearable Pain

LS No Pain _____ DA SP MSP P VP Unbearable Pain

LEFT QUADRICEPS

GS No Pain _____ DA SP MSP P VP Unbearable Pain

LS No Pain _____ DA SP MSP P VP Unbearable Pain

DAY 2 OF RECOVERY (+48 HOURS POST EXERCISE)

RIGHT QUADRICEPS

GS No Pain _____ DA SP MSP P VP Unbearable Pain

LS No Pain _____ DA SP MSP P VP Unbearable Pain

LEFT QUADRICEPS

GS No Pain _____ DA SP MSP P VP Unbearable Pain

LS No Pain _____ DA SP MSP P VP Unbearable Pain

Graphic Pain Rating Scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

DAY 3 OF RECOVERY (+72 HOURS POST EXERCISE)

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

DAY 4 OF RECOVERY (+96 HOURS POST EXERCISE)

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

Graphic Pain Rating Scale

Dull Ache	A feeling of discomfort during activity
Slight Pain	An awareness of pain without distress
More Slight Pain	Distracts attention during physical exertion
Painful	Distracts attention from routine occupation (i.e. reading)
Very Painful	Fills the field of consciousness to the exclusion of other events
Unbearable pain	Comparable to the worst pain you can imagine

DAY 5 OF RECOVERY (+120 HOURS POST EXERCISE)

RIGHT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LEFT QUADRICEPS

GS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

LS No Pain ——— DA SP MSP P VP ——— Unbearable Pain

APPENDIX 5

BORG SCALE

BORG'S RATING OF PERCEIVED OF EXERTION	
Number	**How it feels scale (RPE)**
6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

APPENDIX 6

RAW DATA: STUDY 1

STUDY 1A
Maximum Voluntary Isometric Contraction Force (MVC) (N)

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	733.0	742.4	743.2	732.2	718.6	729.2	739.4	730.5	725.4	735.1	707.1	726.6	728.3	739.4	753.0	732.2
2	666.6	694.3	675.4	678.5	662.0	687.8	678.1	679.3	651.9	660.0	667.0	673.9	680.5	634.6	646.9	669.1
3	644.6	685.5	681.6	664.7	683.9	649.6	709.4	726.7	724.8	721.7	717.9	771.1	766.0	743.7	748.3	709.3
4	636.9	641.9	610.3	594.5	630.0	665.4	685.9	677.0	663.9	743.7	664.7	709.4	671.6	688.6	712.5	666.4
5	559.0	598.3	562.1	562.5	576.0	562.5	593.7	547.5	565.2	515.5	535.5	558.6	525.5	548.2	488.1	553.2
6	502.0	518.5	538.6	526.2	500.8	532.0	540.5	561.7	545.9	569.0	554.8	537.0	521.6	548.6	530.5	535.2
7	628.8	626.5	628.4	646.1	672.7	556.7	556.3	564.4	619.9	537.8	632.3	620.7	619.9	622.2	642.7	611.7
8	709.8	700.9	711.3	712.1	739.4	659.6	682.8	695.9	733.3	707.1	730.2	700.9	672.7	685.1	641.1	698.8
Mean	635.1	651.0	643.9	639.6	647.9	630.4	648.3	647.9	653.8	648.7	651.2	662.3	648.3	651.3	645.4	647.0
SD	75.40	70.62	71.69	72.55	78.03	70.94	74.24	77.14	72.92	93.92	72.98	82.79	88.14	76.64	96.10	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	738.1	737.3	729.8	732.4	717.7	733.0	
2	671.0	686.4	683.5	665.0	673.7	654.2	
3	663.1	675.1	688.2	717.1	741.9	757.4	
4	623.6	618.2	671.2	674.9	668.1	699.0	
5	560.6	580.4	555.0	579.4	530.5	553.4	
6	520.3	522.4	546.9	543.2	538.2	542.8	
7	628.6	636.3	560.6	588.1	626.1	621.5	
8	710.5	706.5	677.8	708.0	701.5	693.0	
Mean	639.5	645.3	639.1	651.0	649.7	656.8	646.9
SD	72.84	70.62	72.60	71.42	79.22	79.23	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	737.7	737.7	734.3	727.9	716.9	733.9	
2	680.5	677.0	683.0	665.6	670.4	657.5	
3	665.0	673.1	679.5	725.8	744.5	754.9	
4	639.4	602.4	675.6	670.4	687.0	680.1	
5	578.7	562.3	578.1	556.3	547.1	536.8	
6	510.2	532.4	536.3	553.8	545.9	535.1	
7	627.6	637.3	556.5	592.2	626.5	621.1	
8	705.3	711.7	671.2	714.6	715.5	678.9	
Mean	643.1	641.7	639.3	650.8	656.7	649.8	646.9
SD	72.46	71.87	71.81	73.69	76.62	81.65	

Maximum Rate of Force Development (RFD_{max}) (Ns^{-1})

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	10368	9264	7649	8584	7564	12748	11218	11133	10708	6884	7904	9264	10538	9349	10708	
2	11489	12183	9561	8790	8250	10101	11489	11334	10409	9947	10024	11180	11103	11103	6323	
3	6168	6862	6862	7094	6168	7942	5552	6631	6014	6631	7171	6091	5397	5937	4703	
4	6631	6091	5860	6940	4703	7402	6631	5552	5860	6014	7248	6323	8713	6477	8327	
5	7248	9870	7788	6708	4164	6091	6477	5706	6323	5783	5012	5166	5012	5320	4935	
6	6477	8019	8019	6708	8559	4781	6014	7788	7865	3624	6631	6554	5397	6862	8250	
7	6014	5629	6554	5089	4395	5320	4241	3316	4703	2930	8559	5937	4318	4241	4472	
8	4935	5166	5243	5243	6014	5397	7942	6323	6014	7479	7017	8559	6477	5629	6940	
Mean	7416	7885	7192	6894	6227	7473	7445	7223	7237	6161	7446	7384	7119	6865	6832	7120
SD	2284	2422	1360	1339	1744	2753	2628	2778	2225	2199	1463	2064	2639	2266	2179	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	9009	8924	11941	10963	9221	9306	
2	10525	10486	10718	10949	10563	11142	
3	6515	6978	7286	5783	6284	6014	
4	6246	6515	6477	6246	7980	6400	
5	7518	8289	5899	6400	5012	5243	
6	7248	7364	6284	6939	6014	6708	
7	6284	5359	4318	4472	6438	5089	
8	5089	5205	5860	6978	6747	7094	
Mean	7304	7390	7348	7341	7283	7124	7298
SD	1733	1796	2614	2366	1843	2088	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	9816	8116	11983	10921	8584	9944	
2	11836	9176	10795	10872	10602	11103	
3	6515	6978	6747	6323	6631	5667	
4	6361	6400	7017	5706	6785	7595	
5	8559	7248	6284	6014	5089	5166	
6	7248	7364	5397	7826	6592	6130	
7	5821	5821	4781	4009	7248	4279	
8	5050	5243	6670	6168	7788	6053	
Mean	7651	7043	7459	7230	7415	6992	7298
SD	2276	1253	2556	2489	1638	2392	

Average Rate of Force Development (RFD_{avg}) (Ns^{-1})

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
1	3644	2659	2852	3115	3349	3134	3033	3009	3595	3088	3141	3309	3230	3350	3541	
2	3840	3902	3675	3322	3298	3532	3365	3390	3022	3199	3348	3450	3587	3256	3412	
3	3428	2838	3377	3407	2818	3601	2854	2585	2692	3015	3501	3258	2766	3071	2470	
4	2562	2420	2401	2262	2533	2804	2525	2411	2542	2558	2762	2656	3654	2898	3237	
5	2439	3180	2921	2476	2815	2332	2464	2430	2683	2523	2612	2746	2689	2742	2411	
6	1729	1913	2224	2123	2123	1312	1824	1195	2327	1231	2417	2108	1909	2180	2196	
7	3410	3087	3629	3072	2523	2303	2782	1694	2198	2003	2841	2559	2576	1783	2170	
8	1563	1609	1544	1291	1586	1941	2097	1926	2187	2222	2084	1605	1602	1850	1539	
Mean	2827	2701	2828	2634	2631	2620	2618	2330	2656	2480	2838	2711	2752	2641	2622	2659
SD	879.9	730.3	743.2	729.3	585.5	797.1	499.6	709.3	473.5	658.4	477.3	634.5	737.6	622.9	704.4	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A**	**B**	**C**	**D**	**E**	**F**	
1	3248	2887	3072	3314	3186	3330	
2	3758	3612	3461	3194	3467	3353	
3	3403	3122	3093	2773	3134	3164	
4	2481	2341	2607	2533	3208	2777	
5	2680	2828	2381	2574	2650	2744	
6	1977	2018	1253	2075	2163	2144	
7	3520	3080	1998	2490	2708	2171	
8	1553	1450	1933	2142	1843	1728	
Mean	2827	2667	2475	2637	2795	2676	2680
SD	787.5	692.2	731.8	444.6	563.8	606.7	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A^1**	**B^1**	**C^1**	**D^1**	**E^1**	**F^1**	
1	3151	2984	3084	3302	3225	3290	
2	3871	3499	3449	3206	3399	3421	
3	3133	3392	3227	2638	3380	2918	
4	2491	2332	2664	2476	2709	3276	
5	2809	2699	2398	2557	2679	2715	
6	1821	2173	1568	1761	2262	2045	
7	3249	3351	2542	1946	2700	2179	
8	1586	1417	2019	2056	1844	1726	
Mean	2764	2731	2619	2493	2775	2696	2680
SD	765.3	724.2	632.0	562.4	548.5	643.4	

Force produced at 30 ms (F_{30}) (N)

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	130.5	156.0	155.1	152.6	162.3	99.44	62.47	117.7	136.0	118.6	106.7	103.7	174.2	150.9	99.01	
2	35.08	23.52	28.14	31.61	34.31	10.02	39.32	28.91	18.51	21.98	20.82	23.90	25.45	22.75	12.72	
3	22.48	39.32	28.53	22.75	22.48	26.99	20.05	15.04	31.61	31.61	41.64	28.91	27.37	22.75	9.64	
4	57.44	18.12	35.83	37.01	12.72	35.85	32.38	45.11	29.69	9.25	79.03	62.46	46.65	52.43	55.90	
5	31.23	14.65	32.38	10.02	22.36	21.98	12.34	22.36	24.67	34.70	12.72	11.18	17.73	15.42	24.29	
6	33.54	37.78	62.07	29.30	32.77	15.04	32.00	21.20	23.13	10.80	18.12	32.00	45.88	30.46	35.47	
7	42.02	39.71	44.72	36.24	57.09	57.09	50.89	28.14	27.76	45.11	45.11	27.76	20.82	43.95	20.82	
8	42.41	30.07	35.08	25.45	53.20	37.40	37.01	46.65	30.07	30.07	45.88	37.40	37.01	53.97	26.60	
Mean	49.33	44.89	52.73	43.12	49.66	37.97	35.81	40.64	40.18	37.76	46.25	40.91	49.39	49.07	35.56	43.55
SD	34.33	45.90	42.82	45.05	48.00	28.86	15.93	33.07	38.95	34.80	32.31	29.24	51.59	43.57	29.42	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	142.8	154.3	108.6	99.23	140.4	127.3	
2	31.61	27.57	19.47	28.91	23.13	23.32	
3	25.50	31.04	21.01	25.83	34.50	25.83	
4	46.64	27.57	40.48	31.03	62.84	57.44	
5	31.81	12.34	22.17	18.51	15.23	13.30	
6	47.81	33.54	18.12	27.57	32.00	31.23	
7	43.37	37.97	42.62	39.32	32.96	35.85	
8	38.75	27.76	42.02	33.54	41.44	45.69	
Mean	51.03	44.00	39.31	37.99	47.82	44.99	44.19
SD	37.90	45.16	29.97	25.46	39.94	35.93	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	143.2	153.8	80.95	126.8	105.2	162.5	
2	29.30	29.88	24.67	23.71	22.36	24.10	
3	30.90	25.64	23.52	23.32	35.28	25.06	
4	37.78	36.42	34.12	37.40	70.74	49.54	
5	22.94	21.20	17.16	23.52	11.95	16.58	
6	35.66	45.69	23.52	22.17	25.06	38.17	
7	40.87	40.48	53.99	27.95	36.43	32.38	
8	36.24	30.26	37.20	38.36	41.64	45.49	
Mean	47.11	47.92	36.89	40.41	43.58	49.23	44.19
SD	39.23	43.52	21.17	35.51	30.35	47.12	

Impulse produced over first 100 ms (I_{100}) (Ns)

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	19.95	21.01	20.54	20.34	22.83	16.71	17.03	18.40	19.97	18.19	16.79	18.72	22.86	21.49	19.12	
2	17.04	15.85	14.91	14.41	14.85	11.12	16.27	14.96	12.24	13.25	12.32	13.74	13.80	13.25	8.03	
3	10.09	12.41	11.43	9.86	10.09	12.96	9.19	13.85	7.88	13.85	15.22	12.30	10.47	11.18	5.62	
4	13.63	8.77	10.49	10.11	7.08	13.04	10.92	12.43	10.32	6.79	15.31	14.14	14.04	13.57	14.77	
5	10.50	5.41	11.97	5.54	9.92	8.39	6.46	9.57	10.39	11.14	7.32	5.77	8.45	6.32	9.13	
6	10.43	12.11	13.38	10.14	11.91	7.57	9.98	10.33	10.89	5.22	10.33	11.07	10.89	11.39	12.22	
7	14.06	12.86	13.81	9.60	12.94	12.94	12.43	7.42	7.40	13.69	13.69	9.90	6.34	8.62	6.34	
8	10.97	9.88	10.69	9.20	12.03	11.21	12.75	13.01	11.89	11.89	12.82	12.11	11.78	12.62	10.53	
Mean	13.33	12.28	13.40	11.15	12.71	11.74	11.88	12.50	11.37	11.75	12.97	12.22	12.33	12.30	10.72	12.18
SD	3.60	4.70	3.28	4.42	4.70	2.89	3.54	3.42	3.88	4.13	3.05	3.71	4.97	4.45	4.54	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	20.25	20.67	17.55	18.50	19.83	20.10	
2	15.97	15.13	13.04	14.25	13.06	13.49	
3	10.76	11.14	13.41	8.53	12.84	11.74	
4	12.06	9.44	12.73	10.62	14.68	13.86	
5	11.24	5.48	8.98	8.42	7.89	6.05	
6	11.90	11.12	8.95	10.44	10.61	11.23	
7	13.94	11.23	10.18	9.92	10.02	9.26	
8	10.83	9.54	12.11	12.32	12.30	12.36	
Mean	13.37	11.72	12.12	11.62	12.65	12.26	12.29
SD	3.30	4.50	2.83	3.38	3.58	4.04	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	20.48	20.44	16.87	19.18	17.75	22.17	
2	16.44	14.66	13.70	13.60	13.03	13.53	
3	11.25	10.65	11.08	10.86	13.76	10.83	
4	11.20	10.30	11.98	11.38	14.73	13.80	
5	7.96	8.76	7.42	9.98	6.55	7.39	
6	11.27	11.76	8.77	10.61	10.70	11.14	
7	13.46	11.70	12.69	7.41	11.80	7.48	
8	10.42	9.94	11.98	12.45	12.46	12.20	
Mean	12.81	12.28	11.81	11.93	12.60	12.32	12.29
SD	3.95	3.73	2.90	3.44	3.24	4.66	

Electromechanical Delay (EMD) (ms)

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	39.0	52.0	49.0	45.0	50.0	30.0	30.0	36.0	39.0	40.0	39.0	39.0	44.0	47.0	33.0	
2	24.0	32.0	22.0	15.0	22.0	39.0	24.0	21.0	24.0	24.0	26.0	25.0	22.0	16.0	21.0	
3	18.0	15.0	19.0	18.0	43.0	21.0	19.0	28.0	36.0	28.0	35.0	23.0	35.0	29.0	58.0	
4	20.0	24.0	19.0	15.0	13.0	23.0	21.0	25.0	14.0	14.0	29.0	27.0	21.0	29.0	22.0	
5	35.0	40.0	31.0	38.0	37.0	30.0	39.0	32.0	26.0	39.0	23.0	36.0	30.0	33.0	33.0	
6	33.0	31.0	32.0	30.0	35.0	23.0	32.0	26.0	24.0	27.0	31.0	35.0	32.0	31.0	30.0	
7	25.0	28.0	23.0	32.0	32.0	32.0	31.0	36.0	28.0	36.0	25.0	30.0	33.0	30.0	33.0	
8	37.0	26.0	27.0	28.0	32.0	37.0	28.0	27.0	32.0	32.0	32.0	27.0	30.0	40.0	24.0	
Mean	28.9	31.0	27.8	27.6	33.0	29.4	28.0	28.9	27.9	30.0	30.0	30.3	30.9	31.9	31.8	29.8
SD	8.10	11.1	9.92	11.0	11.5	6.65	6.50	5.36	7.86	8.67	5.37	5.78	7.30	9.01	11.8	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	44.0	48.5	33.0	34.5	41.5	43.0	
2	23.0	23.5	30.0	24.0	24.0	20.5	
3	18.5	16.5	24.5	27.5	35.0	26.0	
4	19.5	19.5	24.0	17.5	25.0	28.0	
5	33.0	39.0	31.0	32.5	26.5	34.5	
6	32.5	30.5	24.5	28.0	31.5	33.0	
7	24.0	30.0	34.0	29.5	29.0	30.0	
8	32.0	27.0	32.0	30.0	31.0	33.5	
Mean	28.3	29.3	29.1	27.9	30.4	31.1	29.4
SD	8.62	10.4	4.15	5.28	5.77	6.67	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	45.5	47.0	30.0	37.5	39.0	45.5	
2	28.0	18.5	31.5	22.5	25.5	19.0	
3	16.5	18.5	20.0	32.0	29.0	32.0	
4	22.0	17.0	22.0	19.5	28.0	25.0	
5	37.5	34.5	34.5	29.0	29.5	31.5	
6	32.0	31.0	27.5	25.0	33.0	31.5	
7	26.5	27.5	31.5	32.0	27.5	31.5	
8	31.5	27.5	32.5	29.5	29.5	35.0	
Mean	29.9	27.7	28.7	28.4	30.1	31.4	29.4
SD	8.99	10.10	5.18	5.80	4.17	7.62	

RMS Values (Arbitrary Units)
0-100 ms
Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
1	0.962	1.263	1.081	1.198	1.544	0.818	1.062	1.356	0.646	0.845	1.364	1.436	1.312	1.256	1.311	
2	1.669	1.632	1.781	1.624	1.826	1.308	1.742	1.734	1.673	1.579	1.655	1.576	1.785	1.804	1.443	
3	0.918	0.901	0.918	0.958	0.445	0.936	0.641	0.931	0.276	0.931	1.132	0.685	0.778	0.795	0.184	
4	1.401	1.112	1.191	0.871	1.249	1.291	1.525	1.388	1.367	0.948	1.607	1.205	1.548	1.434	1.383	
5	1.207	1.023	0.952	1.059	1.067	0.761	0.601	0.552	0.726	0.752	0.997	0.278	0.937	0.907	0.886	
6	1.302	0.826	1.491	1.363	1.324	0.894	1.100	0.863	1.092	0.450	1.200	1.133	0.839	1.217	1.083	
7	1.642	1.081	1.503	0.859	1.298	1.298	0.805	0.284	0.723	0.398	1.416	0.885	0.623	0.578	0.623	
8	1.162	1.130	0.745	0.946	0.849	1.052	1.258	1.200	1.194	1.194	1.321	1.195	1.050	1.154	0.905	
Mean	1.283	1.121	1.208	1.110	1.200	1.045	1.092	1.039	0.962	0.887	1.337	1.049	1.109	1.143	0.977	1.104
SD	0.280	0.247	0.354	0.270	0.422	0.227	0.408	0.475	0.451	0.383	0.226	0.420	0.404	0.385	0.426	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A**	**B**	**C**	**D**	**E**	**F**	
1	1.022	1.231	1.087	0.854	1.338	1.346	
2	1.725	1.628	1.521	1.708	1.720	1.690	
3	0.918	0.930	0.934	0.459	0.955	0.740	
4	1.296	0.992	1.340	1.446	1.578	1.320	
5	1.080	1.041	0.657	0.664	0.967	0.593	
6	1.397	1.095	0.879	1.096	1.020	1.175	
7	1.573	0.970	0.791	0.764	1.020	0.732	
8	0.954	1.038	1.126	1.226	1.186	1.175	
Mean	1.245	1.115	1.042	1.027	1.223	1.096	1.125
SD	0.301	0.226	0.287	0.420	0.295	0.376	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A^1**	**B^1**	**C^1**	**D^1**	**E^1**	**F^1**	
1	1.113	1.140	0.940	1.001	1.400	1.284	
2	1.651	1.703	1.525	1.704	1.616	1.795	
3	0.910	0.938	0.789	0.604	0.909	0.787	
4	1.257	1.031	1.408	1.378	1.406	1.491	
5	1.115	1.006	0.681	0.639	0.638	0.922	
6	1.064	1.427	0.997	0.978	1.167	1.028	
7	1.362	1.181	1.052	0.504	1.151	0.601	
8	1.146	0.846	1.155	1.197	1.258	1.102	
Mean	1.202	1.159	1.068	1.000	1.193	1.126	1.125
SD	0.225	0.282	0.288	0.416	0.308	0.387	

RMS Values (Arbitrary Units)
0-500 ms
Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
1	1.332	1.429	1.391	1.260	1.334	1.319	1.226	1.205	1.042	1.069	1.405	1.329	1.294	1.372	1.347	
2	1.749	1.778	1.647	1.614	1.566	1.712	1.630	1.579	1.649	1.667	1.792	1.695	1.648	1.756	1.586	
3	1.114	1.007	1.209	1.228	1.114	1.107	1.015	1.034	0.998	1.034	1.241	1.092	1.019	1.034	0.952	
4	1.372	1.357	1.338	1.305	1.487	1.526	1.644	1.562	1.493	1.592	1.648	1.497	1.524	1.547	1.731	
5	1.164	1.172	1.156	1.175	1.306	1.236	1.103	1.071	1.180	1.107	1.379	1.206	1.154	1.275	1.051	
6	1.223	1.016	1.356	1.258	1.143	0.791	0.915	0.875	1.036	0.859	1.156	1.178	0.936	1.182	1.219	
7	1.474	1.273	1.399	1.284	1.336	0.829	0.887	0.778	1.051	0.829	1.214	1.088	1.073	1.043	1.073	
8	1.283	1.184	1.194	1.160	1.285	1.202	1.308	1.061	1.273	1.273	1.627	1.442	1.308	1.364	1.182	
Mean	1.339	1.277	1.336	1.286	1.321	1.215	1.216	1.146	1.215	1.179	1.433	1.316	1.245	1.322	1.268	1.274
SD	0.202	0.251	0.157	0.142	0.153	0.315	0.296	0.292	0.241	0.312	0.232	0.216	0.248	0.247	0.272	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A**	**B**	**C**	**D**	**E**	**F**	
1	1.362	1.345	1.262	1.134	1.350	1.351	
2	1.698	1.696	1.646	1.640	1.720	1.726	
3	1.162	1.118	1.071	1.007	1.130	1.063	
4	1.355	1.331	1.544	1.569	1.586	1.522	
5	1.160	1.174	1.154	1.142	1.267	1.241	
6	1.290	1.137	0.833	0.976	1.046	1.180	
7	1.437	1.279	0.804	0.969	1.144	1.066	
8	1.239	1.172	1.132	1.291	1.468	1.403	
Mean	1.338	1.281	1.180	1.216	1.339	1.319	1.279
SD	0.175	0.189	0.301	0.263	0.238	0.230	

A[1] = Mean 1st and 2nd trials; B[1] = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A[1]**	**B[1]**	**C[1]**	**D[1]**	**E[1]**	**F[1]**	
1	1.381	1.326	1.273	1.124	1.367	1.333	
2	1.764	1.631	1.671	1.614	1.744	1.702	
3	1.061	1.219	1.061	1.016	1.167	1.027	
4	1.365	1.322	1.585	1.528	1.573	1.536	
5	1.168	1.166	1.170	1.126	1.293	1.215	
6	1.120	1.307	0.853	0.956	1.167	1.059	
7	1.374	1.342	0.858	0.915	1.151	1.058	
8	1.234	1.177	1.255	1.167	1.535	1.336	
Mean	1.308	1.311	1.216	1.180	1.374	1.283	1.279
SD	0.221	0.147	0.301	0.257	0.222	0.244	

RMS Values (Arbitrary Units)
500-1500 ms
Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	
1	1.403	1.467	1.442	1.373	1.308	1.352	1.450	1.342	1.155	1.283	1.338	1.337	1.286	1.420	1.403	
2	1.676	1.669	1.580	1.651	1.654	1.775	1.641	1.670	1.684	1.659	1.795	1.644	1.695	1.613	1.635	
3	1.172	1.232	1.308	1.185	1.172	1.244	1.189	1.221	1.155	1.221	1.346	1.292	1.228	1.295	1.189	
4	1.581	1.591	1.495	1.474	1.472	1.792	1.675	1.821	1.730	1.671	1.722	1.728	1.631	1.692	1.584	
5	1.242	1.153	1.207	1.160	1.184	1.380	1.286	1.323	1.190	1.127	1.284	1.251	1.187	1.186	1.216	
6	1.399	1.429	1.404	1.348	1.333	1.065	1.139	1.127	1.026	1.186	1.412	1.338	1.178	1.250	1.223	
7	1.471	1.319	1.284	1.336	1.338	1.205	1.263	1.223	1.210	1.093	1.205	1.064	1.093	1.218	1.244	
8	1.412	1.417	1.431	1.455	1.388	1.459	1.450	1.498	1.377	1.377	1.723	1.564	1.563	1.542	1.531	
Mean	1.420	1.410	1.394	1.373	1.356	1.409	1.387	1.403	1.316	1.327	1.478	1.402	1.358	1.402	1.378	1.387
SD	0.164	0.173	0.121	0.159	0.156	0.260	0.201	0.241	0.260	0.226	0.231	0.223	0.234	0.194	0.184	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A	B	C	D	E	F	
1	1.423	1.420	1.347	1.303	1.312	1.379	
2	1.628	1.660	1.723	1.663	1.745	1.629	
3	1.240	1.209	1.233	1.172	1.287	1.294	
4	1.538	1.533	1.807	1.703	1.677	1.710	
5	1.225	1.157	1.352	1.238	1.236	1.219	
6	1.402	1.389	1.096	1.083	1.295	1.294	
7	1.378	1.328	1.214	1.237	1.149	1.141	
8	1.422	1.436	1.479	1.414	1.643	1.553	
Mean	1.407	1.391	1.406	1.351	1.418	1.402	1.396
SD	0.136	0.164	0.249	0.226	0.231	0.205	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	A^1	B^1	C^1	D^1	E^1	F^1	
1	1.435	1.408	1.401	1.249	1.338	1.353	
2	1.673	1.616	1.708	1.677	1.720	1.654	
3	1.202	1.247	1.217	1.188	1.319	1.262	
4	1.586	1.485	1.734	1.776	1.725	1.662	
5	1.198	1.184	1.333	1.257	1.268	1.187	
6	1.414	1.376	1.102	1.077	1.375	1.214	
7	1.395	1.310	1.234	1.217	1.135	1.156	
8	1.415	1.443	1.455	1.438	1.644	1.553	
Mean	1.415	1.383	1.398	1.360	1.440	1.380	1.396
SD	0.164	0.138	0.228	0.249	0.225	0.212	

RMS Values (Arbitrary Units)
1500-2500 ms
Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
1	1.487	1.461	1.256	1.329	1.269	1.469	1.423	1.302	1.204	1.270	1.440	1.477	1.483	1.436	1.397	
2	1.755	1.687	1.703	1.711	1.659	1.803	1.633	1.737	1.769	1.676	1.711	1.761	1.677	1.596	1.639	
3	1.195	1.359	1.336	1.184	1.195	1.137	1.188	1.098	1.180	1.098	1.377	1.433	1.318	1.303	1.227	
4	1.625	1.617	1.602	1.548	1.695	1.968	1.937	2.050	2.051	1.881	1.811	1.855	1.847	1.839	1.727	
5	1.189	1.043	1.187	1.063	1.093	1.121	1.230	1.255	1.159	1.198	1.103	1.147	1.151	1.043	1.082	
6	1.463	1.473	1.466	1.403	1.311	1.168	1.206	1.230	1.195	1.208	1.461	1.358	1.338	1.303	1.335	
7	1.319	1.334	1.278	1.358	1.231	1.182	1.207	1.134	1.250	1.182	1.291	1.246	1.305	1.171	1.305	
8	1.520	1.469	1.503	1.450	1.586	1.572	1.585	1.466	1.481	1.481	1.714	1.704	1.663	1.600	1.572	
Mean	1.444	1.430	1.416	1.381	1.380	1.428	1.426	1.409	1.411	1.374	1.489	1.498	1.473	1.411	1.411	1.425
SD	0.200	0.196	0.181	0.202	0.232	0.330	0.273	0.330	0.333	0.278	0.241	0.254	0.237	0.259	0.219	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A**	**B**	**C**	**D**	**E**	**F**	
1	1.372	1.395	1.386	1.314	1.462	1.457	
2	1.729	1.699	1.770	1.701	1.694	1.679	
3	1.266	1.272	1.118	1.184	1.348	1.368	
4	1.614	1.583	2.009	1.994	1.829	1.847	
5	1.188	1.053	1.188	1.195	1.127	1.095	
6	1.465	1.438	1.199	1.201	1.400	1.331	
7	1.299	1.346	1.158	1.229	1.298	1.209	
8	1.512	1.460	1.519	1.533	1.689	1.652	
Mean	1.430	1.406	1.418	1.419	1.481	1.455	1.435
SD	0.184	0.195	0.326	0.299	0.237	0.255	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A^1**	**B^1**	**C^1**	**D^1**	**E^1**	**F^1**	
1	1.474	1.293	1.446	1.253	1.459	1.460	
2	1.721	1.707	1.718	1.753	1.736	1.637	
3	1.277	1.260	1.163	1.139	1.405	1.311	
4	1.621	1.575	1.953	2.051	1.833	1.843	
5	1.116	1.125	1.176	1.207	1.125	1.097	
6	1.468	1.435	1.187	1.213	1.410	1.321	
7	1.327	1.318	1.195	1.192	1.269	1.238	
8	1.495	1.477	1.579	1.474	1.709	1.632	
Mean	1.437	1.399	1.427	1.410	1.493	1.442	1.435
SD	0.193	0.187	0.300	0.329	0.246	0.247	

Median Frequency (MDF) (Hz)

Individual Trials

	DAY 1					DAY 2					DAY 3					
SUBJECT	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	
1	65.558	60.665	51.889	57.730	54.795	62.622	54.795	61.644	63.601	67.515	51.859	65.558	54.795	50.881	54.795	
2	61.644	68.493	61.644	61.644	61.644	57.730	55.773	54.795	55.773	55.773	55.773	59.687	57.730	55.773	59.687	
3	58.708	58.708	56.751	60.665	58.708	61.644	61.644	61.644	62.622	61.644	60.665	62.622	57.730	64.579	68.493	
4	59.687	63.601	63.601	66.536	65.558	65.558	64.579	65.558	61.644	59.687	64.579	60.665	63.601	66.536	63.601	
5	58.708	57.730	57.730	64.579	58.708	59.687	61.644	63.601	53.816	57.730	61.644	62.622	64.579	58.708	60.665	
6	51.859	49.902	52.838	53.816	49.902	50.881	48.924	59.687	59.687	55.773	55.773	46.967	48.924	60.665	52.838	
7	55.773	59.687	44.031	49.902	57.730	50.881	49.902	50.881	53.816	53.816	53.816	56.751	49.902	52.838	57.730	
8	52.838	58.708	58.708	57.730	57.730	51.859	52.838	52.838	54.795	54.795	55.773	51.859	53.816	53.816	52.838	
Mean	58.10	59.69	55.90	59.08	58.10	57.61	56.26	58.83	58.22	58.34	57.49	58.34	56.38	57.97	58.83	57.94
SD	4.53	5.28	6.22	5.48	4.59	5.76	5.80	5.34	4.12	4.53	4.34	6.21	5.73	5.65	5.47	

A = Mean 1st and 3rd trials; B = Mean 2nd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A**	**B**	**C**	**D**	**E**	**F**	
1	58.72	59.20	62.13	59.20	53.33	58.22	
2	61.64	65.07	56.26	55.77	56.75	57.73	
3	57.73	59.69	61.64	62.13	59.20	63.60	
4	61.64	65.07	65.56	63.11	64.09	63.60	
5	58.22	61.15	61.64	57.73	63.11	60.67	
6	52.35	51.86	55.28	54.31	52.35	53.82	
7	49.90	54.79	50.88	51.86	51.86	54.79	
8	55.77	58.22	52.35	53.82	54.79	52.84	
Mean	57.00	59.38	58.22	57.24	56.93	58.16	57.82
SD	4.17	4.58	5.26	4.03	4.76	4.21	

A^1 = Mean 1st and 2nd trials; B^1 = Mean 3rd and 4th trials

	DAY 1		DAY 2		DAY 3		
SUBJECT	**A^1**	**B^1**	**C^1**	**D^1**	**E^1**	**F^1**	
1	63.11	54.81	58.71	62.62	58.71	52.84	
2	65.07	61.64	56.75	55.28	57.73	56.75	
3	58.71	58.71	61.64	62.13	61.64	61.15	
4	61.64	65.07	65.07	63.60	62.62	65.07	
5	58.22	61.15	60.67	58.71	62.13	61.64	
6	50.88	53.33	49.90	59.69	51.37	54.79	
7	57.73	46.97	50.39	52.35	55.28	51.37	
8	55.77	58.22	52.35	53.82	53.82	53.82	
Mean	58.89	57.49	56.94	58.53	57.91	57.18	57.82
SD	4.46	5.67	5.59	4.27	4.16	4.90	

STUDY 1B

Maximum Voluntary Isometric Contraction Force (MVC) (N)

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	599.5	584.1	552.8	589.1	560.9	560.6	563.6	547.1	580.2	584.5	616.1	598.0	607.6	608.7
2	631.1	619.0	600.6	582.5	668.3	586.4	618.8	603.0	610.3	596.0	621.1	589.5	572.5	614.5
3	612.6	647.3	645.1	612.2	584.8	680.5	627.3	653.1	610.9	630.6	635.3	652.7	633.8	611.4
4	635.7	631.9	624.9	606.4	662.3	661.2	629.2	591.8	619.5	599.1	636.5	690.9	706.7	749.8
5	673.1	674.1	727.9	695.5	677.2	673.5	668.5	695.5	682.0	713.2	689.2	699.2	689.7	689.2
6	611.4	626.1	538.6	535.1	528.6	551.3	544.4	562.5	602.6	612.6	626.9	607.2	597.6	625.3
7	651.9	656.9	602.6	611.8	651.9	622.2	602.6	616.5	614.9	653.1	686.2	688.5	682.0	702.4
8	626.5	598.0	579.8	651.5	601.4	688.9	589.1	555.5	618.8	669.3	685.5	741.0	685.9	731.7

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	591.8	571.0	560.7	555.3	582.3	607.0	608.2	
2	625.0	591.6	627.3	610.9	603.2	605.3	593.5	
3	629.9	628.7	632.6	640.2	620.7	644.0	622.6	
4	633.8	615.7	661.8	610.5	609.3	663.7	728.3	
5	673.6	711.7	675.3	682.0	697.6	694.2	689.4	
6	618.8	536.8	539.9	553.4	607.6	617.0	611.4	
7	654.4	607.2	637.1	609.5	634.0	687.4	692.2	
8	612.2	615.7	645.2	572.3	644.0	713.2	708.8	
Mean	630.0	609.8	622.5	604.3	624.8	654.0	656.8	628.9
SD	25.19	50.67	47.53	43.82	35.01	42.05	53.08	

Maximum Rate of Force Development

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	7633	6631	6014	8327	6940	6940	7171	5860	7171	6323	9715	7865	6168	6631
2	5320	6246	3778	5397	4472	4395	4472	5783	4549	4781	4010	4010	3932	3932
3	9561	7479	8096	5475	5552	7633	6400	5706	5320	7325	7942	8327	6554	8019
4	7094	6862	5552	6168	7788	6477	5629	4472	10101	9484	11874	12799	8636	9638
5	4549	4858	4395	4395	4241	4626	5243	4087	5012	4852	5552	4549	4935	4164
6	5629	5475	5243	5552	4318	4858	4318	5706	6400	7633	5937	5397	3457	5552
7	5243	4858	6168	4626	6014	5629	4626	5783	4549	5706	5860	6323	6246	7402
8	6091	3778	4241	4935	5397	5397	4935	5166	3855	4781	6014	6014	4549	5783

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	7132	7171	6940	6515	6747	8790	6400	
2	5783	4588	4434	5128	4665	4010	3932	
3	8520	6785	6593	6053	6323	8135	7286	
4	6978	5860	7132	5050	9792	12337	9137	
5	4703	4395	4434	4665	4932	5050	4549	
6	5552	5397	4588	5012	7017	5667	4504	
7	5050	5397	5821	5205	5128	6091	6824	
8	4935	4588	5397	5050	4318	6014	5166	
Mean	6082	5523	5667	5335	6115	7012	5975	5958
SD	1336	1033	1129	619.2	1792	2654	1758	

Average Rate of Force Development

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	2824	2808	2486	3520	2935	3192	3145	2791	3181	3118	3568	3601	2826	3065
2	2604	3096	3145	2640	2702	2926	2337	2426	2252	2595	2745	2265	2792	2656
3	3414	3535	2746	2966	2726	3682	3192	3115	2884	2933	3626	3359	3350	3702
4	3801	3599	2813	3448	3200	2838	3285	2448	4150	2915	3319	4273	3718	4371
5	2347	2267	2213	2184	2067	2266	2371	2048	2247	2170	2338	2728	2557	2045
6	2855	2726	2670	2221	2632	2391	2478	2869	3097	2660	2878	2904	2287	2575
7	2251	2213	2262	2193	2415	1852	1855	2435	2445	2472	2673	2724	2646	3014
8	2668	2054	2088	2150	1840	2543	2757	2519	1932	2483	1894	2581	1976	2747

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	2816	3003	3064	2968	3150	3584	2945	
2	2850	2892	2814	2382	2423	2505	2724	
3	3474	2856	3204	3154	2908	3492	3526	
4	3700	3130	3019	2867	3532	3796	4044	
5	2307	2199	2166	2209	2208	2533	2301	
6	2790	2445	2512	2674	2879	2891	2431	
7	2232	2227	2133	2145	2459	2699	2830	
8	2361	2119	2192	2638	2207	2238	2362	
Mean	2816	2609	2638	2630	2721	2967	2895	2754
SD	537.7	405.2	442.3	362.6	476.0	580.1	610.3	

RMS Values (Arbitrary Units)
0-500 ms

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.520	1.320	1.453	1.466	1.357	1.186	1.427	1.351	1.346	1.140	1.639	1.279	1.446	1.264
2	0.914	0.962	0.998	0.973	1.114	1.072	1.087	1.070	1.068	0.984	0.809	0.809	1.030	1.030
3	1.681	1.382	1.541	1.576	1.611	1.643	1.717	1.669	1.611	1.529	1.718	1.727	1.707	1.730
4	1.221	1.215	1.169	1.285	1.288	1.130	1.122	0.879	1.281	1.477	1.188	1.397	1.236	1.257
5	1.167	0.978	1.066	0.956	1.091	1.226	1.370	1.042	1.259	1.259	1.494	1.417	1.311	1.168
6	1.596	1.703	1.648	1.440	1.587	1.587	1.442	1.557	1.740	1.682	1.481	1.684	1.540	1.761
7	1.730	1.778	1.677	1.724	1.775	1.702	1.584	1.771	1.674	1.732	1.690	1.833	1.697	1.822
8	1.385	1.227	1.244	1.357	1.362	1.426	1.404	1.162	1.698	1.293	1.224	1.340	1.222	1.313

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.420	1.460	1.272	1.389	1.243	1.459	1.355	
2	0.938	0.986	1.093	1.079	1.026	0.809	1.030	
3	1.532	1.559	1.627	1.693	1.570	1.723	1.719	
4	1.218	1.227	1.209	1.001	1.379	1.293	1.247	
5	1.073	1.011	1.159	1.206	1.259	1.456	1.240	
6	1.650	1.544	1.587	1.500	1.711	1.583	1.651	
7	1.754	1.701	1.739	1.678	1.703	1.762	1.760	
8	1.306	1.301	1.394	1.283	1.496	1.282	1.268	
Mean	1.361	1.348	1.385	1.353	1.423	1.421	1.408	1.386
SD	0.282	0.262	0.240	0.259	0.241	0.304	0.267	

RMS Values (Arbitrary Units)
500-1500 ms

SUBJECT	0		15		30		60		120		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.718	1.498	1.438	1.438	1.343	1.432	1.491	1.409	1.371	1.353	1.520	1.352	1.578	1.418
2	1.072	1.059	1.085	1.032	0.994	1.007	1.104	1.132	0.984	0.902	0.900	0.900	1.055	1.055
3	1.797	1.618	1.435	1.595	1.654	1.770	1.777	1.802	1.747	1.760	1.735	1.436	1.795	1.655
4	1.263	1.288	1.299	1.217	1.376	1.300	1.374	1.170	1.287	1.366	1.408	1.315	1.305	1.464
5	1.251	1.335	1.406	1.336	1.349	1.262	1.387	1.453	1.649	1.649	1.649	1.591	1.508	1.522
6	1.753	1.842	1.516	1.623	1.569	1.569	1.562	1.467	1.624	1.790	1.653	1.632	1.658	1.724
7	1.846	1.822	1.886	1.803	1.856	1.941	1.808	1.818	1.807	1.978	1.800	1.934	1.950	1.944
8	1.486	1.395	1.458	1.602	1.752	1.632	1.381	1.263	1.714	1.697	1.492	1.621	1.494	1.641

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.608	1.438	1.388	1.450	1.362	1.436	1.498	
2	1.066	1.059	1.001	1.118	0.943	0.900	1.055	
3	1.708	1.515	1.712	1.790	1.754	1.586	1.725	
4	1.276	1.258	1.338	1.272	1.327	1.362	1.385	
5	1.293	1.371	1.306	1.420	1.649	1.620	1.515	
6	1.798	1.570	1.569	1.515	1.707	1.643	1.691	
7	1.834	1.845	1.899	1.813	1.893	1.867	1.947	
8	1.441	1.530	1.692	1.322	1.706	1.557	1.568	
Mean	1.503	1.448	1.488	1.462	1.542	1.496	1.548	1.498
SD	0.278	0.232	0.285	0.242	0.310	0.284	0.263	

RMS Values (Arbitrary Units)
1500-2500 ms

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.731	1.544	1.420	1.519	1.534	1.471	1.409	1.332	1.352	1.352	1.669	1.484	1.454	1.560
2	1.020	0.992	0.982	1.049	0.908	1.082	0.993	1.041	1.023	0.958	0.903	0.903	1.004	1.004
3	1.749	1.783	1.493	1.687	1.611	1.611	1.777	1.763	1.712	1.622	1.643	1.446	1.718	1.668
4	1.397	1.131	1.224	1.376	1.354	1.371	1.293	1.246	1.305	1.345	1.296	1.388	1.408	1.280
5	1.405	1.367	1.548	1.474	1.482	1.457	1.533	1.579	1.831	1.831	1.657	1.698	1.568	1.571
6	1.809	1.887	1.685	1.607	1.633	1.633	1.595	1.651	1.797	1.807	1.763	1.528	1.728	1.786
7	1.867	1.869	1.838	1.808	1.963	1.936	1.900	2.015	1.862	1.910	1.821	1.832	1.863	1.931
8	1.772	1.700	1.682	1.719	1.596	1.618	1.596	1.521	1.914	1.807	1.612	1.722	1.771	1.691

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.638	1.470	1.503	1.371	1.352	1.577	1.507	
2	1.006	1.016	0.995	1.017	0.991	0.903	1.004	
3	1.766	1.590	1.611	1.770	1.667	1.545	1.693	
4	1.264	1.300	1.363	1.270	1.325	1.342	1.344	
5	1.386	1.511	1.470	1.556	1.831	1.678	1.570	
6	1.848	1.646	1.633	1.623	1.802	1.646	1.757	
7	1.868	1.823	1.950	1.958	1.886	1.827	1.897	
8	1.736	1.701	1.607	1.559	1.861	1.667	1.731	
Mean	1.564	1.507	1.516	1.515	1.589	1.523	1.563	1.540
SD	0.312	0.253	0.272	0.294	0.329	0.286	0.282	

Median Frequency (Hz)

SUBJECT	0 min		15 min		30 min		60 min		120 min		24 hrs		48 hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	60.67	55.77	56.75	53.82	50.88	51.86	51.86	59.69	47.95	58.71	57.73	55.77	58.71	54.80
2	54.80	65.56	59.69	53.82	63.60	57.73	56.75	55.77	54.80	57.73	53.82	53.82	49.90	49.90
3	64.58	67.52	68.49	71.43	65.56	69.47	71.43	65.56	60.67	64.58	64.58	67.52	66.54	62.62
4	54.80	50.88	48.92	58.71	58.71	51.86	57.73	59.69	54.80	53.82	59.69	55.77	55.77	55.77
5	60.66	64.58	66.54	58.71	65.56	56.75	56.75	61.64	57.73	57.73	59.69	61.64	59.69	63.60
6	60.67	60.67	59.69	55.77	65.56	65.56	57.73	64.58	56.75	54.80	59.69	60.67	58.71	56.75
7	40.12	47.95	50.88	45.01	39.14	48.92	40.12	40.12	48.92	42.07	49.90	40.12	42.07	46.95
8	72.41	66.54	62.62	70.45	69.47	65.56	63.60	63.60	66.54	66.54	67.52	64.58	71.43	63.60

SUBJECT	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	58.22	55.28	51.37	55.77	53.33	56.75	56.75	
2	60.18	56.75	60.67	56.26	56.26	53.82	49.90	
3	66.05	69.96	67.52	68.49	62.62	66.05	64.58	
4	52.84	53.82	55.28	58.71	54.31	57.73	55.77	
5	62.62	62.62	61.15	59.20	57.73	60.67	61.64	
6	60.67	57.73	65.56	61.15	55.77	60.18	57.73	
7	44.03	47.95	44.03	40.12	45.50	45.01	44.51	
8	69.47	66.54	67.52	63.60	66.54	66.05	67.52	
Mean	59.26	58.83	59.14	57.91	56.51	58.28	57.30	58.18
SD	7.92	7.17	8.38	8.29	6.28	6.85	7.53	

STUDY 1C

Forces elicited by Neuromuscular Electrical Stimulation
Absolute Force Values (N)

1 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	39.52	33.44	35.22	30.42	29.53	35.91	38.65	
2	21.09	19.45	19.74	17.52	21.84	21.57	18.06	
3	11.50	10.30	10.18	11.70	11.78	10.35	15.81	
4	36.01	28.55	27.39	27.66	33.64	37.86	34.04	
Mean	27.03	22.94	23.13	21.83	24.20	26.42	26.64	24.60
SD	13.08	10.23	10.70	8.74	9.61	12.94	11.40	

10 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	82.44	73.33	74.52	63.86	65.93	66.79	96.43	
2	41.59	36.48	35.67	39.03	38.94	52.12	38.66	
3	24.00	19.26	21.54	26.06	26.30	25.01	33.83	
4	96.78	76.38	77.33	72.06	97.25	110.16	72.34	
Mean	61.20	51.36	52.27	50.25	57.11	63.52	60.32	56.57
SD	34.09	28.05	27.95	21.38	31.46	35.59	29.55	

20 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	156.81	159.51	160.26	156.34	148.70	158.96	168.90	
2	104.29	100.84	98.92	105.35	106.67	109.21	104.68	
3	81.30	86.26	102.34	101.65	108.74	97.08	104.85	
4	184.11	161.20	159.22	144.98	183.66	183.10	154.08	
Mean	131.63	126.95	130.19	127.08	136.94	137.09	133.13	131.86
SD	47.15	39.03	34.16	27.66	36.66	40.72	33.30	

50 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	186.94	183.73	190.06	196.08	179.15	196.02	198.63	
2	146.72	140.63	136.13	149.26	145.52	153.90	143.66	
3	116.26	123.78	156.88	139.41	148.94	143.22	155.91	
4	257.15	244.68	248.78	209.67	260.68	245.07	231.26	
Mean	176.77	173.21	182.96	173.61	183.57	184.55	182.37	179.58
SD	60.91	53.92	49.18	34.49	53.58	46.34	40.22	

100 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	193.08	197.45	203.92	212.94	194.93	207.30	208.31	
2	159.02	154.72	148.51	161.99	156.91	167.49	155.21	
3	132.02	135.01	170.31	153.68	159.03	156.53	172.71	
4	280.43	284.03	284.49	242.30	282.71	280.07	253.22	
Mean	191.14	192.80	201.81	192.73	198.40	202.85	197.36	196.73
SD	64.56	66.17	59.65	42.17	58.85	55.91	43.30	

Values calculated from 100 Hz non-fatigued (fresh) muscle (%)

1 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	20.5	17.3	18.2	15.8	15.3	18.6	20.0	
2	13.3	12.2	12.4	11.0	13.7	13.6	11.4	
3	8.7	7.8	7.7	8.9	8.9	7.8	12.0	
4	12.8	10.2	9.8	9.9	12.0	13.5	12.1	
Mean	13.8	11.9	12.0	11.4	12.5	13.4	13.9	12.7
SD	4.9	4.1	4.6	3.0	2.7	4.4	4.1	

10 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	42.7	38.0	38.6	33.1	34.1	34.6	49.9	
2	26.2	22.9	22.4	24.5	24.5	32.8	24.3	
3	18.2	14.6	16.3	19.7	19.9	18.9	25.6	
4	34.5	27.2	27.6	25.7	34.7	39.3	25.8	
Mean	30.4	25.7	26.2	25.8	28.3	31.4	31.4	28.5
SD	10.6	9.7	9.4	5.5	7.3	8.7	12.4	

20 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	81.2	82.6	83.0	81.0	77.0	82.3	87.5	
2	65.6	63.4	62.2	66.2	67.1	68.7	65.8	
3	61.6	65.3	77.5	77.0	82.4	73.5	79.4	
4	65.7	57.5	56.8	51.7	65.5	65.3	54.9	
Mean	68.5	67.2	69.9	69.0	73.0	72.5	71.9	70.3
SD	8.7	10.8	12.4	13.1	8.1	7.4	14.4	

50 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	96.8	95.2	98.4	101.6	92.8	101.5	102.9	
2	92.3	88.4	85.6	93.9	91.5	96.8	90.3	
3	88.1	93.8	118.8	105.6	112.8	108.5	118.1	
4	91.7	87.3	88.7	74.8	93.0	87.4	82.5	
Mean	92.2	91.2	97.9	93.9	97.5	98.5	98.4	95.7
SD	3.6	3.9	15.0	13.7	10.2	8.9	15.6	

100 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs
1	100.0	102.3	105.6	110.3	101.0	107.4	107.9
2	100.0	97.3	93.4	101.9	98.7	105.3	97.6
3	100.0	102.3	129.0	116.4	120.5	118.6	130.8
4	100.0	101.3	101.4	86.4	100.8	99.9	90.3
Mean		100.8	107.4	103.7	105.2	107.8	106.7
SD		2.4	15.3	13.0	10.2	7.9	17.7

Percentage Decreases

1 Hz	15 min	30 min	60 min	120 min	24 hrs	48hrs
1	-15.4	-10.9	-23.0	-25.3	-9.1	-2.2
2	-7.8	-6.4	-16.9	3.6	2.3	-14.3
3	-10.4	-11.5	1.7	2.4	-10.0	37.5
4	-20.7	-23.9	-23.2	-6.6	5.1	-5.5
Mean	-13.6	-13.2	-15.3	-6.5	-2.9	3.9
SD	5.7	7.5	11.8	13.3	7.8	23.0

10 Hz	15 min	30 min	60 min	120 min	24 hrs	48hrs
1	-11.1	-9.6	-22.5	-20.0	-19.0	17.0
2	-12.3	-14.2	-6.2	-6.4	25.3	-7.0
3	-19.8	-10.3	8.6	9.6	4.2	41.0
4	-21.1	-20.1	-25.5	0.5	13.8	-25.3
Mean	-16.0	-13.5	-11.4	-4.1	6.1	6.4
SD	5.1	4.8	15.8	12.5	18.8	28.8

20 Hz	15 min	30 min	60 min	120 min	24 hrs	48hrs
1	1.7	2.2	-0.3	-5.2	1.4	7.7
2	-3.3	-5.1	1.0	2.3	4.7	0.4
3	6.1	25.9	25.0	33.8	19.4	29.0
4	-12.4	-13.5	-21.3	-0.2	-0.5	-16.3
Mean	-2.0	2.4	1.1	7.7	6.2	5.2
SD	8.0	16.9	18.9	17.7	9.0	18.8

50 Hz	15 min	30 min	60 min	120 min	24 hrs	48hrs
1	-1.7	1.7	4.9	-4.2	4.9	6.3
2	-4.2	-7.2	1.7	-0.8	4.9	-2.1
3	6.5	34.9	19.9	28.1	23.2	34.1
4	-4.8	-3.3	-18.5	1.4	-4.7	-10.1
Mean	-1.1	6.5	2.0	6.1	7.1	7.1
SD	5.2	19.3	15.8	14.8	11.7	19.2

100 Hz	15 min	30 min	60 min	120 min	24 hrs	48hrs
1	2.3	5.6	10.3	1.0	7.4	7.9
2	-2.7	-6.6	1.9	-1.3	5.3	-2.4
3	2.3	29.0	16.4	20.5	18.6	30.8
4	1.3	1.4	-13.6	0.8	-0.1	-9.7
Mean	0.8	7.4	3.7	5.2	7.8	6.7
SD	2.4	15.3	13.0	10.2	7.9	17.7

STUDY 1D

Maximum Voluntary Isometric Contraction Force (MVC) (N)

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	545.5	547.1	530.9	580.6	562.5	587.5	526.6	573.3	548.6	524.3	529.2	522.4	535.1	554.8	574.8	579.1
2	628.4	622.2	654.6	616.5	622.6	588.7	589.9	592.6	624.6	576.4	582.5	582.1	627.3	625.7	623.9	555.9
3	599.5	571.3	580.6	572.1	572.9	549.0	601.0	547.8	610.7	595.6	571.0	566.3	573.3	573.3	594.9	586.4
4	626.5	546.7	536.3	614.9	592.6	592.2	576.4	547.8	545.9	597.2	628.8	582.5	608.4	611.1	685.1	662.7
5	628.4	640.7	613.8	614.1	603.3	603.3	603.7	607.2	623.0	603.7	622.6	614.1	670.8	647.7	659.6	640.0
6	765.3	752.9	758.7	757.2	744.5	757.6	722.1	754.9	735.6	718.6	789.2	715.2	745.2	733.3	745.2	732.5
7	587.9	629.9	586.0	579.1	567.9	574.0	596.8	620.3	604.9	584.5	548.6	578.3	593.7	580.2	545.1	616.5

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	546.3	555.7	575.0	550.0	536.5	525.8	544.9	576.9	
2	625.3	635.5	605.7	591.2	600.5	582.3	626.5	589.9	
3	585.4	576.4	560.9	574.4	603.2	568.7	573.3	590.6	
4	586.6	575.6	592.4	562.1	571.5	605.7	609.7	673.9	
5	634.6	613.9	603.3	605.5	613.4	618.4	659.2	649.8	
6	759.1	757.9	751.0	738.5	727.1	752.2	739.2	738.9	
7	608.9	582.5	571.0	608.6	594.7	563.4	587.0	580.8	
Mean	620.9	613.9	608.5	604.3	606.7	602.3	620.0	628.7	613.2
SD	67.64	68.87	65.06	63.01	59.03	72.60	64.31	61.31	

Average Rate of Force Development (RFD_{avg}) ($N.s^{-1}$)

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	2093	2297	1959	2133	2416	2797	2174	2116	2607	2413	2535	1975	2432	2120	3023	2919
2	3347	2649	2701	3190	2963	2919	3406	2577	2551	3405	2726	3227	2875	3424	3396	2871
3	2929	2117	3003	1881	2663	2518	2311	2427	2731	1928	2525	2178	2464	2525	2379	2439
4	2668	2392	2054	2602	2770	2112	2195	2886	2430	2803	2611	2088	1894	2923	2476	2568
5	3766	3425	3787	3084	3583	3011	3275	3094	3061	3156	3441	3058	3671	3391	3784	3666
6	3807	4398	3932	3932	3825	3628	3984	3984	3865	3930	4133	3887	3683	3689	3535	3711
7	3660	3031	2957	2690	2979	2893	2605	2976	2696	2769	2478	3116	3300	2934	2839	3641

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	2195	2046	2607	2145	2510	2255	2276	2971	
2	2998	2945	2941	2991	2978	2977	3150	3134	
3	2523	2442	2591	2369	2329	2351	2494	2409	
4	2530	2328	2441	2541	2616	2350	2408	2522	
5	3595	3436	3297	3185	3108	3250	3531	3725	
6	4102	3932	3727	3984	3898	4010	3686	3623	
7	3346	2823	2936	2791	2732	2797	3117	3240	
Mean	3041	2850	2934	2858	2882	2856	2952	3089	2933
SD	679.9	659.4	452.5	611.6	521.1	629.3	563.1	502.1	

RMS Values (Arbitrary Units)
0-500 ms

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.266	1.397	1.067	1.386	1.325	1.496	1.311	1.403	1.562	1.314	1.543	1.260	1.306	1.005	1.518	1.416
2	1.026	0.878	1.061	1.172	1.062	1.132	0.839	0.991	0.974	1.024	1.203	1.020	1.164	1.037	0.836	1.006
3	1.413	1.219	1.317	1.347	1.298	1.171	1.722	1.369	1.574	1.336	1.537	1.456	1.191	1.404	1.085	1.025
4	1.183	0.986	1.123	1.385	1.158	1.102	1.088	1.120	1.120	1.264	1.190	1.190	1.165	1.218	1.800	1.800
5	1.703	1.663	1.764	1.591	1.710	1.411	1.610	1.721	1.687	1.687	1.736	1.670	1.638	1.638	1.589	1.695
6	1.607	1.478	1.344	1.624	1.527	1.410	1.385	1.575	1.484	1.672	1.556	1.441	1.428	1.505	1.329	1.361
7	1.582	1.542	1.556	1.476	1.543	1.479	1.499	1.514	1.648	1.569	1.545	1.608	1.500	1.422	1.494	1.561

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.332	1.227	1.411	1.357	1.438	1.402	1.156	1.467	
2	0.952	1.117	1.097	0.915	0.999	1.112	1.101	0.921	
3	1.316	1.332	1.235	1.546	1.455	1.497	1.298	1.055	
4	1.085	1.254	1.130	1.104	1.192	1.190	1.192	1.800	
5	1.683	1.678	1.561	1.666	1.687	1.703	1.638	1.642	
6	1.543	1.484	1.469	1.480	1.578	1.499	1.467	1.345	
7	1.562	1.516	1.511	1.507	1.609	1.577	1.461	1.528	
Mean	1.353	1.372	1.345	1.368	1.423	1.425	1.330	1.394	1.376
SD	0.266	0.195	0.189	0.267	0.246	0.210	0.197	0.314	

RMS Values (Arbitrary Units)
500-1500 ms

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.471	1.458	1.537	1.537	1.600	1.542	1.454	1.596	1.519	1.472	1.513	1.570	1.270	1.262	1.620	1.686
2	1.016	1.028	1.196	1.125	1.117	1.099	1.132	1.109	1.115	1.042	1.183	0.938	1.153	1.111	0.932	1.027
3	1.746	1.539	1.593	1.573	1.625	1.451	1.657	1.467	1.563	1.524	1.779	1.596	1.637	1.567	1.659	1.297
4	1.635	1.079	1.229	1.488	1.595	1.248	1.368	1.215	1.422	1.443	1.351	1.351	1.485	1.379	1.850	1.850
5	1.857	1.863	1.754	1.737	1.714	1.542	1.794	1.785	1.737	1.737	1.738	1.792	1.720	1.606	1.700	1.771
6	1.583	1.585	1.601	1.529	1.351	1.527	1.570	1.575	1.558	1.601	1.541	1.441	1.478	1.485	1.558	1.491
7	1.569	1.455	1.573	1.543	1.430	1.539	1.562	1.516	1.551	1.214	1.455	1.389	1.440	1.094	1.459	1.528

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.465	1.537	1.571	1.525	1.496	1.542	1.266	1.653	
2	1.022	1.161	1.108	1.121	1.079	1.061	1.132	0.980	
3	1.643	1.583	1.538	1.562	1.544	1.688	1.602	1.478	
4	1.357	1.359	1.422	1.292	1.433	1.351	1.432	1.850	
5	1.860	1.746	1.628	1.790	1.737	1.765	1.663	1.736	
6	1.584	1.565	1.439	1.573	1.580	1.491	1.482	1.525	
7	1.512	1.558	1.485	1.539	1.383	1.422	1.267	1.494	
Mean	1.492	1.501	1.456	1.486	1.464	1.474	1.406	1.531	1.476
SD	0.260	0.188	0.170	0.216	0.205	0.232	0.194	0.279	

RMS Values (Arbitrary Units)
1500-2500 ms

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	1.554	1.630	1.550	1.509	1.570	1.584	1.563	1.514	1.549	1.370	1.465	1.541	1.303	1.228	1.771	1.692
2	1.093	1.056	1.131	1.078	1.077	1.022	1.080	1.092	1.243	1.096	1.075	1.150	1.173	1.113	1.155	1.108
3	1.781	1.739	1.581	1.659	1.541	1.636	1.600	1.536	1.756	1.683	1.626	1.546	1.433	1.572	1.609	1.549
4	1.617	1.300	1.445	1.514	1.655	1.497	1.492	1.367	1.455	1.523	1.540	1.540	1.595	1.584	1.790	1.790
5	1.872	1.733	1.704	1.705	1.620	1.646	1.775	1.725	1.789	1.789	1.833	1.771	1.710	1.603	1.719	1.791
6	1.677	1.562	1.589	1.669	1.500	1.555	1.547	1.544	1.532	1.624	1.645	1.523	1.520	1.481	1.589	1.614
7	1.477	1.332	1.397	1.297	1.273	1.315	1.343	1.211	1.375	1.294	1.354	1.352	1.157	1.231	1.402	1.484

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	1.592	1.530	1.577	1.539	1.460	1.503	1.266	1.732	
2	1.075	1.105	1.050	1.086	1.170	1.113	1.143	1.132	
3	1.760	1.620	1.589	1.568	1.720	1.586	1.503	1.579	
4	1.459	1.480	1.576	1.430	1.489	1.540	1.590	1.790	
5	1.803	1.705	1.633	1.750	1.789	1.802	1.657	1.755	
6	1.620	1.629	1.528	1.546	1.578	1.584	1.501	1.602	
7	1.405	1.347	1.294	1.277	1.335	1.353	1.194	1.443	
Mean	1.530	1.488	1.464	1.456	1.506	1.497	1.407	1.576	1.491
SD	0.247	0.205	0.214	0.217	0.214	0.216	0.204	0.230	

Median Frequency (Hz)

SUBJECT	BASELINE		0min		15min		30min		60min		120min		24hrs		48hrs	
	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
1	49.90	50.88	53.82	61.64	56.75	51.86	50.88	50.88	49.90	50.88	48.92	53.82	61.64	47.95	44.03	49.90
2	52.84	54.80	48.92	57.73	58.71	58.71	59.69	58.71	51.86	52.84	53.82	53.82	53.82	52.84	55.77	54.80
3	56.75	52.84	57.73	54.80	52.84	56.75	55.75	55.75	51.86	57.73	51.86	49.90	50.88	53.82	54.80	53.82
4	62.62	59.69	64.58	62.62	61.64	58.71	63.60	66.54	59.69	58.71	61.64	57.73	59.69	61.64	62.62	60.67
5	63.60	67.52	57.73	60.67	60.67	60.67	58.71	60.67	64.58	62.62	61.66	57.73	57.73	65.56	62.62	60.67
6	59.69	55.77	61.64	57.73	60.67	55.77	59.69	58.71	60.67	56.75	57.73	58.71	59.69	60.67	53.82	59.69
7	63.60	63.60	57.73	48.92	55.77	56.75	56.75	51.86	69.47	55.77	55.77	61.64	57.73	56.75	56.75	54.80

SUBJECT	BASE	0 min	15 min	30 min	60 min	120 min	24hrs	48hrs	
1	50.39	57.73	54.31	50.88	50.39	51.37	54.79	46.97	
2	53.82	53.33	58.71	59.20	52.35	53.82	53.33	55.28	
3	54.79	56.26	54.79	55.75	54.79	50.88	52.35	54.31	
4	61.15	63.60	60.18	65.07	59.20	59.69	60.67	61.64	
5	65.56	59.20	60.67	59.69	63.60	59.70	61.64	61.64	
6	57.73	59.69	58.22	59.20	58.71	58.22	60.18	56.75	
7	63.60	53.33	56.26	54.31	62.62	58.71	57.24	55.77	
Mean	58.15	57.59	57.59	57.73	57.38	56.05	57.17	56.05	57.21
SD	5.54	3.68	2.52	4.56	5.03	3.91	3.76	4.99	

Forces elicited by Neuromuscular Electrical Stimulation (NMES)
Absolute Force Values (N)

20 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	121.54	111.43	109.59	131.16	127.20	135.91	155.31	
2	184.78	188.16	174.16	189.79	163.11	154.23	193.33	
3	174.04	150.18	132.22	152.71	151.07	178.15	201.30	
4	235.42	217.56	211.45	205.30	237.82	225.97	248.40	
5	155.51	151.38	156.38	159.89	150.93	184.90	206.22	
6	218.80	204.89	192.26	206.51	228.87	257.23	259.53	
7	205.72	189.39	176.14	184.59	190.97	259.70	210.50	
mean	185.11	173.28	164.60	175.71	178.57	199.44	210.66	183.91
SD	39.01	37.15	34.95	28.48	42.02	49.02	34.84	

50 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	169.16	156.30	155.06	200.70	193.08	186.35	195.62	
2	257.50	274.93	277.07	272.40	256.60	226.40	265.01	
3	242.99	228.96	215.05	240.14	228.24	240.57	269.77	
4	303.57	279.67	271.16	286.14	321.60	279.54	317.48	
5	231.67	235.40	256.53	260.27	263.05	254.10	277.31	
6	330.59	320.38	299.55	328.01	346.64	362.13	379.18	
7	321.62	307.72	282.14	325.39	342.74	336.45	296.68	
mean	265.30	257.62	250.94	273.29	278.85	269.36	285.86	268.75
SD	57.49	56.00	49.90	45.49	59.40	61.93	55.88	

100 Hz	0 min	15 min	30 min	60 min	120 min	24 hrs	48 hrs	
1	196.26	180.42	174.79	221.55	202.68	206.83	210.46	
2	275.15	283.81	284.20	283.10	280.99	240.46	282.42	
3	262.08	252.31	238.21	257.11	251.02	261.70	295.77	
4	324.05	309.84	297.97	308.57	340.51	298.14	334.79	
5	256.69	260.22	273.96	295.71	293.01	273.52	297.58	
6	356.24	346.21	319.96	339.82	347.42	387.02	413.04	
7	345.67	336.67	307.98	357.12	373.66	350.10	323.39	
mean	288.02	281.35	271.01	294.71	298.47	288.25	308.21	290.00
SD	57.03	57.10	50.01	46.59	59.97	62.60	61.12	

APPENDIX 7

RAW DATA: STUDY 2

Maximum Voluntary Isometric Contraction Force

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	769.3	635.3	648.5	655.1	755.7	760.8	837.2	1	-17.4	-15.7	-14.8	-1.8	-1.1	8.8
2	861.4	800.5	832.8	821.7	685.9	772.9	974.8	2	-7.1	-3.3	-4.6	-20.4	-10.3	13.2
3	574.0	497.3	466.8	491.8	490.0	580.2	551.6	3	-13.4	-18.7	-14.3	-14.6	1.1	-3.9
4	606.4	526.7	481.9	462.8	504.3	557.9	565.6	4	-13.2	-20.5	-23.7	-16.8	-8.0	-6.7
5	673.8	536.9	547.6	549.4	532.9	630.5	608.5	5	-20.3	-18.7	-18.5	-20.9	-6.4	-9.7
6	463.5	353.4	336.2	324.3	283.0	370.7	445.6	6	-23.8	-27.5	-30.0	-39.0	-20.0	-3.9
Mean	658.1	558.3	552.3	550.9	542.0	612.2	663.9	Mean	-15.8	-17.4	-17.7	-18.9	-7.5	-0.4
SD	142.5	149.5	171.4	171.4	165.9	148.7	199.8	SD	5.9	7.9	8.7	12.0	7.5	9.2

CON

SUBJECT	BASE	0	30	60	120	24hrs	48hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	744.3	690.7	697.3	681.9	706.9	727.8	792.4	1	-7.2	-6.3	-8.4	-5.0	-2.2	6.5
2	844.1	890.0	930.7	944.0	905.8	821.4	912.0	2	5.4	10.3	11.8	7.3	-2.7	8.0
3	588.7	608.5	612.9	612.9	597.1	604.8	596.0	3	3.4	4.1	4.1	1.4	2.7	1.2
4	571.1	608.1	563.7	569.2	568.1	573.8	563.0	4	6.5	-1.3	-0.3	-0.5	0.5	-1.4
5	720.4	682.6	677.5	686.7	652.9	669.1	670.5	5	-5.2	-6.0	-4.7	-9.4	-7.1	-6.9
6	480.4	450.3	422.8	456.6	411.1	440.4	417.3	6	-6.3	-12.0	-5.0	-14.4	-8.3	-13.1
Mean	658.2	655.1	650.8	658.5	640.3	639.5	658.5	Mean	-0.6	-1.9	-0.4	-3.4	-2.9	-1.0
SD	134.1	143.9	168.7	163.5	164.1	131.8	175.2	SD	6.3	8.0	7.4	7.8	4.3	8.1

DSE

SUBJECT	BASE	0	30	60	120	24hrs	48hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	727.1	650.3	670.2	679.0	693.3	717.9	757.9	1	-10.6	-7.8	-6.6	-4.6	-1.3	4.2
2	861.0	804.5	876.4	817.0	844.1	1005.6	1032.8	2	-6.6	1.8	-5.1	-2.0	16.8	19.9
3	599.0	534.0	554.6	532.9	528.1	644.5	605.6	3	-10.8	-7.4	-11.0	-11.8	7.6	1.1
4	580.8	463.9	436.0	389.8	427.6	566.7	581.7	4	-20.1	-24.9	-32.9	-26.4	-2.4	0.2
5	695.1	630.9	581.7	567.0	603.0	600.4	631.6	5	-9.2	-16.3	-18.4	-13.3	-13.6	-9.1
6	432.3	398.2	423.9	429.4	437.5	432.7	458.4	6	-7.9	-2.0	-0.7	1.2	0.1	6.0
Mean	649.2	580.3	590.5	569.2	588.9	661.3	678.0	Mean	-10.9	-9.4	-12.5	-9.5	1.2	3.7
SD	146.5	146.0	168.0	159.1	160.6	193.4	198.6	SD	4.4	8.9	10.7	9.1	9.3	8.7

Average Rate of Force Development

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	2900	2189	1624	2210	2395	2599	2928	1	-24.5	-44.0	-23.8	-17.4	-10.4	1.0
2	3067	2947	3117	2212	2050	3043	3510	2	-3.9	1.6	-27.9	-33.2	-0.8	14.4
3	1821	1691	1738	1533	928	2245	1831	3	-7.1	-4.6	-15.8	-49.0	23.3	0.5
4	3285	3021	2569	2529	2925	3148	3387	4	-8.0	-21.8	-23.0	-11.0	-4.2	3.1
5	2941	2372	1517	2201	1975	2754	2360	5	-19.4	-48.4	-25.2	-32.9	-6.4	-19.8
6	2740	2024	1685	1549	1552	1892	1826	6	-26.1	-38.5	-43.5	-43.4	-30.9	-33.4
Mean	2792	2374	2042	2039	1971	2613	2640	Mean	-14.8	-25.9	-26.5	-31.1	-4.9	-5.7
SD	509.5	523.3	648.6	405.7	686.9	478.9	747.4	SD	9.7	21.1	9.2	14.6	17.4	17.5

CON

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	3195	2725	2598	2519	2607	3060	3074	1	-14.7	-18.7	-21.1	-18.4	-4.2	-3.8
2	3596	3355	2980	3670	3553	2874	3457	2	-6.7	-17.1	2.1	-1.2	-20.1	-3.9
3	2191	1880	1826	1945	2159	2166	2532	3	-14.2	-16.6	-11.2	-1.5	-1.1	15.6
4	2735	2773	2597	2550	3051	2835	3098	4	1.4	-5.0	-6.8	11.6	3.6	13.3
5	3006	2564	2954	3120	2885	2999	3416	5	-14.7	-1.7	3.8	-4.0	-0.2	13.7
6	1718	1533	2010	1781	1740	2351	2028	6	-10.8	17.0	3.7	1.3	36.8	18.1
Mean	2740	2472	2494	2598	2666	2714	2934	Mean	-10.0	-7.0	-4.9	-2.0	2.5	8.8
SD	686.6	659.6	479.5	710.5	648.4	366.9	554.0	SD	6.4	13.7	10.1	9.7	18.7	9.9

DSE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	2571	2775	2262	1102	2347	3120	2902	1	7.9	-12.0	-57.1	-8.7	21.4	12.8
2	2928	2424	2447	2609	1724	3433	3287	2	-17.2	-16.4	-10.9	-41.1	17.2	12.3
3	2397	2003	2006	1761	1657	2588	2686	3	-16.4	-16.3	-26.5	-30.9	8.0	12.1
4	3325	2426	2200	1898	2083	3229	2895	4	-27.0	-33.8	-42.9	-37.4	-2.9	-12.9
5	2982	3028	2476	2225	2713	2709	2506	5	1.5	-17.0	-25.4	-9.0	-9.1	-16.0
6	1764	2275	2053	1685	1845	2235	2047	6	29.0	16.4	-4.4	4.6	26.8	16.0
Mean	2661	2489	2241	1880	2061	2886	2720	Mean	-3.7	-13.2	-27.9	-20.4	10.2	4.1
SD	547.5	364.1	195.0	511.4	407.8	450.5	420.9	SD	20.6	16.4	19.6	18.5	14.1	14.4

RMS Values: 0-500 ms

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.739	1.460	1.585	1.713	1.684	1.691	1.744	1	-16.1	-8.9	-1.5	-3.2	-2.8	0.3
2	1.527	1.315	1.391	1.398	1.236	1.535	1.634	2	-13.9	-8.9	-8.4	-19.0	0.5	7.0
3	0.968	0.825	0.695	0.864	0.792	1.037	0.805	3	-14.7	-28.2	-10.7	-18.1	7.1	-16.8
4	1.580	1.185	1.387	1.394	1.651	1.548	1.373	4	-25.0	-12.2	-11.8	4.5	-2.0	-13.1
5	1.731	1.625	1.596	1.626	1.575	1.642	1.470	5	-6.1	-7.8	-6.0	-9.0	-5.1	-15.1
6	1.552	1.356	1.437	1.543	1.210	1.348	1.604	6	-12.6	-7.4	-0.5	-22.0	-13.1	3.4
Mean	1.516	1.294	1.348	1.423	1.358	1.467	1.438	Mean	-14.7	-12.2	-6.5	-11.1	-2.6	-5.7
SD	0.284	0.273	0.333	0.301	0.345	0.241	0.336	SD	6.1	8.0	4.7	10.4	6.7	10.5

CON

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.910	1.858	1.805	1.947	1.891	1.886	1.865	1	-2.7	-5.5	1.9	-1.0	-1.3	-2.4
2	1.435	1.458	1.406	1.434	1.557	1.131	1.542	2	1.6	-2.0	0.0	8.5	-21.2	7.5
3	1.099	1.051	1.030	1.070	1.191	0.851	0.987	3	-4.4	-6.3	-2.7	8.3	-22.6	-10.2
4	1.474	1.452	1.352	1.442	1.579	1.464	1.400	4	-1.5	-8.3	-2.2	7.1	-0.7	-5.0
5	1.761	1.712	1.691	1.714	1.726	1.492	1.557	5	-2.8	-4.0	-2.7	-2.0	-15.3	-11.6
6	1.549	1.619	1.596	1.588	1.548	1.260	1.190	6	4.5	3.1	2.5	-0.1	-18.6	-23.2
Mean	1.538	1.525	1.480	1.532	1.582	1.347	1.423	Mean	-0.9	-3.8	-0.5	3.5	-13.3	-7.5
SD	0.281	0.279	0.279	0.297	0.233	0.354	0.307	SD	3.3	4.0	2.4	5.0	9.8	10.3

DSE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.651	1.673	1.668	1.485	1.531	1.663	1.619	1	1.3	1.0	-10.1	-7.3	0.7	-1.9
2	1.520	1.214	1.388	1.463	1.597	1.620	1.591	2	-20.1	-8.7	-3.7	5.1	6.6	4.7
3	1.113	1.093	1.169	1.152	1.298	1.262	1.107	3	-1.8	5.0	3.5	16.6	13.4	-0.5
4	1.441	1.253	1.178	1.132	1.213	1.593	1.536	4	-13.0	-18.3	-21.4	-15.8	10.5	6.6
5	1.737	1.658	1.554	1.585	1.656	1.604	1.703	5	-4.5	-10.5	-8.8	-4.6	-7.6	-1.9
6	1.594	1.611	1.746	1.608	1.583	1.519	1.504	6	1.1	9.6	0.9	-0.7	-4.7	-5.6
Mean	1.509	1.417	1.451	1.404	1.480	1.544	1.510	Mean	-6.2	-3.6	-6.6	-1.1	3.2	0.2
SD	0.219	0.259	0.246	0.211	0.180	0.146	0.209	SD	7.9	9.6	8.2	10.2	7.7	4.2

RMS Values: 500-1500 ms

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.835	1.726	1.756	1.796	1.849	1.773	1.910	1	-6.0	-4.3	-2.1	0.8	-3.4	4.1
2	1.698	1.511	1.612	1.606	1.630	1.721	1.619	2	-11.0	-5.1	-5.4	-4.0	1.4	-4.7
3	1.159	1.022	0.954	1.103	1.217	1.212	1.114	3	-11.8	-17.7	-4.8	5.0	4.6	-3.8
4	1.727	1.475	1.659	1.618	1.756	1.711	1.526	4	-14.6	-4.0	-6.3	1.7	-0.9	-11.6
5	1.749	1.702	1.648	1.684	1.655	1.687	1.535	5	-2.7	-5.7	-3.7	-5.4	-3.5	-12.2
6	1.673	1.580	1.525	1.642	1.237	1.587	1.735	6	-5.6	-8.8	-1.8	-26.0	-5.1	3.7
Mean	1.640	1.502	1.525	1.575	1.557	1.615	1.573	Mean	-8.6	-7.6	-4.0	-4.7	-1.2	-4.1
SD	0.242	0.256	0.290	0.241	0.268	0.207	0.267	SD	4.6	5.2	1.8	11.1	3.6	7.1

CON

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	2.044	1.936	1.975	1.908	1.899	1.860	1.899	1	-5.3	-3.4	-6.7	-7.1	-9.0	-7.1
2	1.546	1.341	1.641	1.660	1.529	1.346	1.741	2	-13.3	6.1	7.4	-1.1	-12.9	12.6
3	1.424	1.502	1.408	1.520	1.547	1.121	1.095	3	5.5	-1.1	6.7	8.6	-21.3	-23.1
4	1.607	1.569	1.480	1.671	1.693	1.523	1.507	4	-2.4	-7.9	4.0	5.4	-5.2	-6.2
5	1.723	1.745	1.691	1.698	1.731	1.639	1.593	5	1.2	-1.9	-1.5	0.5	-4.9	-7.6
6	1.711	1.771	1.632	1.732	1.772	1.396	1.285	6	3.5	-4.6	1.2	3.5	-18.4	-24.9
Mean	1.676	1.644	1.638	1.698	1.695	1.481	1.520	Mean	-1.8	-2.1	1.9	1.6	-12.0	-9.4
SD	0.212	0.214	0.197	0.126	0.140	0.255	0.295	SD	6.8	4.7	5.3	5.5	6.8	13.6

DSE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.788	1.772	1.833	1.752	1.759	1.737	1.705	1	-0.9	2.5	-2.0	-1.6	-2.9	-4.6
2	1.680	1.572	1.590	1.651	1.722	1.785	1.723	2	-6.4	-5.4	-1.7	2.5	6.2	2.6
3	1.396	1.371	1.453	1.480	1.614	1.468	1.468	3	-1.8	4.1	6.0	15.6	5.2	5.2
4	1.580	1.365	1.360	1.329	1.344	1.573	1.651	4	-13.6	-13.9	-15.9	-14.9	-0.4	4.5
5	1.718	1.714	1.626	1.653	1.671	1.665	1.653	5	-0.2	-5.4	-3.8	-2.7	-3.1	-3.8
6	1.817	1.764	1.736	1.774	1.765	1.689	1.701	6	-2.9	-4.5	-2.3	-2.8	-7.0	-6.4
Mean	1.663	1.593	1.600	1.607	1.646	1.653	1.650	Mean	-4.3	-3.7	-3.3	-0.7	-0.3	-0.4
SD	0.155	0.189	0.175	0.171	0.158	0.115	0.094	SD	4.6	5.9	6.5	9.0	4.7	4.6

RMS Values: 1500-2500 ms

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.884	1.671	1.791	1.805	1.891	1.812	1.931	1	-11.3	-4.9	-4.2	0.3	-3.8	2.5
2	1.731	1.534	1.531	1.531	1.555	1.635	1.759	2	-11.4	-11.5	-11.5	-10.2	-5.5	1.6
3	1.242	1.120	1.099	1.246	1.268	1.371	1.213	3	-9.9	-11.6	0.3	2.1	10.3	-2.3
4	1.687	1.460	1.666	1.726	1.818	1.803	1.595	4	-13.4	-1.2	2.3	7.8	6.9	-5.4
5	1.752	1.736	1.665	1.662	1.679	1.649	1.511	5	-0.9	-4.9	-5.1	-4.1	-5.9	-13.7
6	1.736	1.630	1.619	1.585	1.370	1.728	1.804	6	-6.1	-6.8	-8.7	-21.1	-0.5	3.9
Mean	1.672	1.525	1.562	1.592	1.597	1.666	1.635	Mean	-8.8	-6.8	-4.5	-4.2	0.3	-2.2
SD	0.221	0.222	0.242	0.196	0.246	0.163	0.255	SD	4.6	4.1	5.2	10.3	6.8	6.6

CON

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.922	2.005	1.940	1.899	1.966	1.935	1.950	1	4.3	0.9	-1.2	2.3	0.7	1.4
2	1.543	1.442	1.637	1.737	1.691	1.414	1.783	2	-6.5	6.1	12.6	9.6	-8.3	15.6
3	1.567	1.583	1.616	1.634	1.664	1.232	1.230	3	1.0	3.1	4.2	6.2	-21.4	-21.5
4	1.546	1.671	1.537	1.604	1.632	1.519	1.494	4	8.1	-0.6	3.7	5.6	-1.7	-3.4
5	1.743	1.663	1.718	1.669	1.749	1.632	1.618	5	-4.6	-1.4	-4.2	0.4	-6.4	-7.1
6	1.876	1.839	1.748	1.818	1.734	1.551	1.341	6	-2.0	-6.8	-3.1	-7.6	-17.3	-28.5
Mean	1.699	1.700	1.699	1.727	1.739	1.547	1.569	Mean	0.1	0.2	2.0	2.7	-9.1	-7.3
SD	0.172	0.197	0.140	0.114	0.119	0.235	0.270	SD	5.5	4.4	6.3	6.0	8.7	15.9

DSE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	1.929	1.734	1.887	1.816	1.775	1.615	1.748	1	-10.1	-2.2	-5.9	-8.0	-16.3	-9.4
2	1.768	1.608	1.681	1.718	1.701	1.898	1.786	2	-9.0	-4.9	-2.8	-3.8	7.4	1.0
3	1.545	1.353	1.494	1.523	1.698	1.512	1.517	3	-12.4	-3.3	-1.4	9.9	-2.1	-1.8
4	1.658	1.327	1.314	1.331	1.376	1.724	1.703	4	-19.9	-20.8	-19.7	-17.0	4.0	2.7
5	1.761	1.747	1.642	1.699	1.711	1.683	1.689	5	-0.8	-6.8	-3.5	-2.8	-4.5	-4.1
6	1.899	1.774	1.759	1.839	1.795	1.782	1.801	6	-6.6	-7.4	-3.2	-5.5	-6.2	-5.2
Mean	1.760	1.591	1.629	1.654	1.676	1.702	1.707	Mean	-9.8	-7.5	-6.1	-4.5	-2.9	-2.8
SD	0.145	0.202	0.202	0.194	0.152	0.134	0.103	SD	5.8	6.2	6.2	8.0	7.6	4.0

Median Frequency

HRE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	SUBJECT	0 min	30 min	60 min	120 min	24hrs	48hrs
1	60.18	63.11	59.69	61.64	55.28	60.67	58.71	1	4.9	-0.8	2.4	-8.1	0.8	-2.4
2	52.84	52.35	57.73	49.41	45.50	55.77	63.10	2	-0.9	9.3	-6.5	-13.9	5.6	19.4
3	66.54	76.32	79.75	72.90	68.00	67.51	62.62	3	14.7	19.9	9.6	2.2	1.5	-5.9
4	58.71	64.09	58.71	57.24	58.22	56.26	59.03	4	9.2	0.0	-2.5	-0.8	-4.2	0.6
5	57.73	56.75	63.60	59.69	54.79	59.20	59.69	5	-1.7	10.2	3.4	-5.1	2.5	3.4
6	45.99	61.64	60.67	54.79	43.05	55.77	58.38	6	34.0	31.9	19.1	-6.4	21.3	26.9
Mean	57.00	62.38	63.36	59.28	54.14	59.20	60.26	Mean	10.0	11.7	4.3	-5.4	4.6	7.0
SD	6.97	8.13	8.28	7.91	9.04	4.55	2.07	SD	13.3	12.5	9.1	5.6	8.8	13.1

CON

SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	SUBJECT	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	61.64	63.60	58.22	60.67	60.67	64.09	66.54	1	3.2	-5.6	-1.6	-1.6	4.0	7.9
2	62.13	62.62	61.64	66.54	63.60	52.84	62.13	2	0.8	-0.8	7.1	2.4	-15.0	0.0
3	67.03	65.56	69.96	68.49	66.05	76.81	85.63	3	-2.2	4.4	2.2	-1.5	14.6	27.8
4	58.22	58.22	57.73	58.71	57.24	54.14	58.06	4	0.0	-0.8	0.8	-1.7	-7.0	-0.3
5	55.28	56.26	61.15	62.62	57.73	59.69	54.31	5	1.8	10.6	13.3	4.4	8.0	-1.8
6	57.24	58.22	60.67	54.31	55.77	54.31	56.75	6	1.7	6.0	-5.1	-2.6	-5.1	-0.9
Mean	60.26	60.75	61.56	61.89	60.18	60.31	63.90	Mean	0.9	2.3	2.8	-0.1	-0.1	5.5
SD	4.22	3.68	4.41	5.19	4.01	9.13	11.48	SD	1.8	5.8	6.5	2.8	10.9	11.5

DSE

SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	66.05	62.14	60.19	52.35	64.09	64.58	63.60	1	-5.9	-8.9	-20.7	-3.0	-2.2	-3.7
2	55.28	58.71	62.62	58.71	58.71	53.82	50.88	2	6.2	13.3	6.2	6.2	-2.7	-8.0
3	66.05	87.57	75.34	72.90	62.62	73.39	72.41	3	32.6	14.1	10.4	-5.2	11.1	9.6
4	59.69	61.64	59.69	56.26	55.77	56.75	58.22	4	3.3	0.0	-5.7	-6.6	-4.9	-2.5
5	57.73	60.67	62.13	62.62	56.26	56.75	54.31	5	5.1	7.6	8.5	-2.5	-1.7	-5.9
6	54.31	59.20	56.75	58.71	56.75	54.79	58.71	6	9.0	4.5	8.1	4.5	0.9	8.1
Mean	59.85	64.99	62.79	60.26	59.03	60.01	59.69	Mean	8.4	5.1	1.1	-1.1	0.1	-0.4
SD	5.16	11.14	6.49	7.05	3.52	7.57	7.57	SD	11.8	7.9	11.1	4.8	5.2	6.8

Forces Elicited by Neuromuscular Electrical Stimulation

HRE														
20 Hz	**BASE**	**0 min**	**30 min**	**60 min**	**120 min**	**24 hrs**	**48 hrs**	**SUBJECT**	**0 min**	**30 min**	**60 min**	**120 min**	**24hrs**	**48hrs**
1	197.4	91.4	93.3	92.0	124.8	163.7	151.3	**1**	-53.7	-52.7	-53.4	-36.8	-17.1	-23.3
2	193.0	180.3	207.3	174.0	194.5	147.5	170.4	**2**	-6.6	7.4	-9.8	0.8	-23.6	-11.7
3	163.8	95.1	112.4	95.2	153.4	168.0	167.7	**3**	-42.0	-31.4	-41.9	-6.4	2.6	2.4
4	201.4	103.4	111.8	118.7	131.2	210.1	196.1	**4**	-48.7	-44.5	-41.1	-34.8	4.3	-2.6
5	256.9	137.8	140.0	178.6	178.8	215.8	239.2	**5**	-46.3	-45.5	-30.5	-30.4	-16.0	-6.9
6	144.5	75.0	77.6	87.4	94.4	138.4	154.3	**6**	-48.1	-46.3	-39.5	-34.7	-4.2	6.8
mean	192.8	113.8	123.7	124.3	146.2	173.9	179.8	**Mean**	-40.9	-35.5	-36.0	-23.7	-9.0	-5.9
SD	38.4	38.6	46.0	41.7	36.9	32.1	33.1	**SD**	17.2	22.1	14.8	16.5	11.5	10.7

CON														
20 Hz	**BASE**	**0**	**30**	**60**	**120**	**24 hrs**	**48 hrs**	**SUBJECT**	**0**	**30**	**60**	**120**	**24hrs**	**48hrs**
1	185.5	192.8	185.0	176.9	183.5	156.0	169.7	**1**	3.9	-0.3	-4.6	-1.1	-15.9	-8.5
2	223.5	215.9	203.8	214.2	245.8	181.1	163.6	**2**	-3.4	-8.8	-4.1	10.0	-19.0	-26.8
3	200.2	191.4	182.8	171.1	180.2	171.6	166.7	**3**	-4.4	-8.7	-14.6	-10.0	-14.3	-16.7
4	209.4	217.9	196.7	190.5	206.4	204.8	208.8	**4**	4.1	-6.1	-9.0	-1.4	-2.2	-0.3
5	254.6	246.8	283.4	252.8	290.9	243.1	248.2	**5**	-3.1	11.3	-0.7	14.2	-4.5	-2.5
6	158.2	160.2	160.1	156.9	143.5	157.8	186.0	**6**	1.3	1.2	-0.8	-9.3	-0.2	17.6
mean	205.2	204.2	202.0	193.7	208.4	185.7	190.5	**Mean**	-0.3	-1.9	-5.6	0.4	-9.3	-6.2
SD	32.9	29.6	42.6	34.8	52.6	33.3	32.9	**SD**	3.8	7.7	5.3	9.9	8.0	15.2

DSE														
20 Hz	**BASE**	**0**	**30**	**60**	**120**	**24 hrs**	**48 hrs**	**SUBJECT**	**0**	**30**	**60**	**120**	**24hrs**	**48hrs**
1	164.6	108.4	118.2	139.4	139.2	162.0	200.6	**1**	-34.2	-28.2	-15.3	-15.4	-1.6	21.8
2	181.1	118.9	158.2	142.0	167.1	169.2	187.6	**2**	-34.3	-12.6	-21.6	-7.7	-6.5	3.6
3	170.6	77.2	87.9	133.0	180.0	165.5	190.5	**3**	-54.7	-48.5	-22.0	5.5	-2.9	11.7
4	188.7	120.8	138.5	137.9	169.9	175.0	188.9	**4**	-36.0	-26.6	-26.9	-9.9	-7.2	0.1
5	270.3	151.2	170.1	182.1	238.6	195.0	244.0	**5**	-44.1	-37.1	-32.6	-11.7	-27.8	-9.7
6	169.5	116.8	134.7	128.7	139.7	146.5	200.4	**6**	-31.1	-20.5	-24.0	-17.6	-13.5	18.2
mean	190.8	115.5	134.6	143.9	172.4	168.9	202.0	**Mean**	-39.1	-28.9	-23.8	-9.5	-9.9	7.6
SD	39.9	23.8	29.3	19.3	36.5	16.0	21.3	**SD**	8.8	12.6	5.8	8.2	9.7	11.9

Forces Elicited by Neuromuscular Electrical Stimulation

HRE

100 Hz	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	382.1	230.3	253.8	264.1	326.1	327.7	291.8	1	-39.7	-33.6	-30.9	-14.7	-14.3	-23.6
2	361.2	368.5	390.4	373.1	297.7	279.2	354.3	2	2.0	8.1	3.3	-17.6	-22.7	-1.9
3	276.7	170.4	213.3	193.0	279.6	285.3	294.9	3	-38.4	-22.9	-30.2	1.1	3.1	6.6
4	280.5	163.0	195.6	204.7	226.4	338.5	284.0	4	-41.9	-30.3	-27.0	-19.3	20.7	1.2
5	367.5	244.4	253.5	306.7	309.7	339.2	351.5	5	-33.5	-31.0	-16.5	-15.7	-7.7	-4.4
6	255.1	168.4	198.9	197.3	219.5	233.6	230.4	6	-34.0	-22.0	-22.7	-13.9	-8.4	-9.7
Mean	320.5	224.2	250.9	256.5	276.5	300.6	301.1	Mean	-30.9	-22.0	-20.7	-13.4	-4.9	-5.3
SD	55.6	78.7	73.0	72.7	44.2	42.0	46.4	SD	16.5	15.4	12.9	7.3	15.1	10.5

CON

100 Hz	BASE	0	30	60	120	24 hrs	48 hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	360.6	386.5	352.5	347.2	384.6	325.5	350.8	1	7.2	-2.2	-3.7	6.6	-9.7	-2.7
2	367.1	322.2	304.8	320.0	354.8	311.6	293.2	2	-12.2	-17.0	-12.8	-3.3	-15.1	-20.1
3	316.9	309.6	302.2	279.5	311.0	305.1	286.5	3	-2.3	-4.6	-11.8	-1.8	-3.7	-9.6
4	291.9	305.4	286.3	291.2	292.2	310.0	287.8	4	4.6	-1.9	-0.3	0.1	6.2	-1.4
5	353.9	339.3	384.4	352.1	384.4	337.6	355.1	5	-4.1	8.6	-0.5	8.6	-4.6	0.4
6	274.7	262.2	262.9	268.0	268.6	251.8	276.8	6	-4.6	-4.3	-2.4	-2.2	-8.3	0.7
Mean	327.5	320.9	315.5	309.7	332.6	306.9	308.4	Mean	-1.9	-3.6	-5.3	1.3	-5.9	-5.5
SD	38.8	41.1	44.8	35.5	49.2	29.5	35.0	SD	7.0	8.2	5.6	5.1	7.2	8.1

DSE

100 Hz	BASE	0	30	60	120	24 hrs	48 hrs	SUBJECT	0	30	60	120	24hrs	48hrs
1	332.8	228.0	274.5	316.5	316.0	379.1	397.6	1	-31.5	-17.5	-4.9	-5.0	13.9	19.5
2	339.1	227.6	281.6	243.7	266.6	338.1	290.3	2	-32.9	-17.0	-28.1	-21.4	-0.3	-14.4
3	293.8	170.0	262.2	264.6	299.7	305.4	334.1	3	-42.2	-10.8	-10.0	2.0	3.9	13.7
4	264.2	179.1	209.7	212.5	251.5	262.2	266.5	4	-32.2	-20.6	-19.6	-4.8	-0.8	0.9
5	366.9	252.1	266.1	274.1	348.5	301.7	351.2	5	-31.3	-27.5	-25.3	-5.0	-17.8	-4.3
6	275.4	204.8	223.1	245.4	269.6	241.2	262.5	6	-25.6	-19.0	-10.9	-2.1	-12.4	-4.7
mean	312.0	210.3	252.9	259.5	292.0	304.6	317.0	Mean	-32.6	-18.7	-16.5	-6.1	-2.2	1.8
SD	40.3	31.6	29.3	35.1	36.4	50.0	53.3	SD	5.3	5.4	9.3	8.0	11.4	12.6

Lactic Acid

HRE

SUBJECT	BASE	0 min	30 min	120 min
1	0.8	8.7	1.6	0.6
2	1.3	4.4	1.0	0.6
3	0.6	4.9	1.1	0.9
4	0.6	4.2	0.5	0.4
5	0.9	11.1	3.6	1.0
6	0.7	3.5	1.2	0.8
Mean	0.8	6.1	1.5	0.7
SD	0.3	3.1	1.1	0.2

CON

SUBJECT	BASE	0 min	30 min	120 min
1	0.9	0.8	0.6	0.6
2	1.3	0.9	0.7	0.7
3	0.7	0.5	0.8	1.0
4	0.5	0.5	0.4	0.4
5	1.0	0.6	0.6	0.7
6	0.8	0.8	0.9	0.8
Mean	0.9	0.7	0.7	0.7
SD	0.3	0.2	0.1	0.2

DSE

SUBJECT	BASE	0 min	30 min	120 min
1	0.5	1.6	0.3	0.3
2	0.5	7.2	1.2	0.6
3	0.7	6.5	1.6	0.7
4	0.6	6.9	1.4	0.6
5	1.5	10.1	2.7	0.8
6	1.0	3.4	1.2	0.6
Mean	0.8	6.0	1.4	0.6
SD	0.4	3.0	0.8	0.2

Creatine Kinase
Heavy Resistance Exercise

SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs
1	164	206	185	194	493	411
2	105	213	213	206	173	130
3	116	141	142	152	227	199
4	81	88	88	98	115	94
5	1591	2081	1756	1706	1487	1045
6	235	261	248	245	430	271
Mean	382	498	439	434	488	358
SD	595	778	648	625	511	355

LOG

SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs
1	2.215	2.314	2.267	2.288	2.693	2.614
2	2.021	2.328	2.328	2.314	2.238	2.114
3	2.064	2.149	2.152	2.182	2.356	2.299
4	1.908	1.944	1.944	1.991	2.061	1.973
5	3.202	3.318	3.245	3.232	3.172	3.019
6	2.371	2.417	2.394	2.389	2.633	2.433
Mean	2.297	2.412	2.389	2.399	2.526	2.409
SD	0.472	0.474	0.448	0.431	0.396	0.375

% DIFF

SUBJECT	0 min	30 min	120 min	24 hrs	48 hrs
1	25.6	12.8	18.3	200.6	150.6
2	102.9	102.9	96.2	64.8	23.8
3	21.6	22.4	31.0	95.7	71.6
4	8.6	8.6	21.0	42.0	16.0
5	30.8	10.4	7.2	-6.5	-34.3
6	11.1	5.5	4.3	83.0	15.3
Mean	33.4	27.1	29.7	79.9	40.5
SD	35.1	37.6	34.0	69.2	63.6

Creatine Kinase
Control

SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs
1	251	253	256	244	465	592
2	117	119	120	125	124	142
3	352	344	349	335	204	175
4	224	225	228	218	239	239
5	355	360	365	380	414	668
6	216	216	218	206	186	163
Mean	253	253	256	251	272	330
SD	90	89	91	92	136	236

LOG

SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs
1	2.400	2.403	2.408	2.387	2.667	2.772
2	2.068	2.076	2.079	2.097	2.093	2.152
3	2.547	2.537	2.543	2.525	2.310	2.243
4	2.350	2.352	2.358	2.338	2.378	2.378
5	2.550	2.556	2.562	2.580	2.617	2.825
6	2.334	2.334	2.338	2.314	2.270	2.212
Mean	2.375	2.376	2.381	2.374	2.389	2.431
SD	0.177	0.174	0.175	0.171	0.218	0.295

% DIFF

SUBJECT	0 min	30 min	120 min	24 hrs	48 hrs
1	0.8	2.0	-2.8	85.3	135.9
2	1.7	2.6	6.8	6.0	21.4
3	-2.3	-0.9	-4.8	-42.0	-50.3
4	0.4	1.8	-2.7	6.7	6.7
5	1.4	2.8	7.0	16.6	88.2
6	0.0	0.9	-4.6	-13.9	-24.5
Mean	0.3	1.5	-0.2	9.8	29.5
SD	1.4	1.3	5.6	42.5	70.2

Creatine Kinase
Dynamic Strength Exercise

SUBJECT	BASE	0min	30min	120min	24hrs	48hrs
1	230	231	239	238	393	252
2	127	141	132	128	151	127
3	352	421	399	379	302	172
4	67	76	74	77	140	104
5	549	616	526	582	2223	1152
6	4420	4639	4356	4116	2127	967
Mean	958	1021	954	920	889	462
SD	1705	1784	1675	1576	1001	469

LOG

SUBJECT	BASE	0min	30min	120min	24hrs	48hrs
1	2.362	2.364	2.378	2.377	2.594	2.401
2	2.104	2.149	2.121	2.107	2.179	2.104
3	2.547	2.624	2.601	2.579	2.480	2.236
4	1.826	1.881	1.869	1.886	2.146	2.017
5	2.740	2.790	2.721	2.765	3.347	3.061
6	3.645	3.666	3.639	3.614	3.328	2.985
Mean	2.537	2.579	2.555	2.555	2.679	2.467
SD	0.631	0.624	0.616	0.608	0.538	0.450

% DIFF

SUBJECT	0min	30min	120min	24hrs	48hrs
1	0.4	3.9	3.5	70.9	9.6
2	11.0	3.9	0.8	18.9	0.0
3	19.6	13.4	7.7	-14.2	-51.1
4	13.4	10.4	14.9	109.0	55.2
5	12.2	-4.2	6.0	304.9	109.8
6	5.0	-1.4	-6.9	-51.9	-78.1
Mean	10.3	4.3	4.3	72.9	7.6
SD	6.7	6.7	7.3	127.4	68.7

Upper Leg Muscle Soreness - Heavy Resistance Exercise

Right Quadriceps: General Soreness

SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	72 HRS	96 HRS	120 HRS
1	0	0	0	0	0	0	0	0
2	0	0	5	8	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	3	5	1	0	0
5	0	0	0	3	0	0	0	0
6	0	0	2	2	7	1	0	0
Mean	0.0	0.0	1.2	2.7	2.0	0.3	0.0	0.0
SD	0.0	0.0	2.0	2.9	3.2	0.5	0.0	0.0

Left Quadriceps: General Soreness

SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	72 HRS	96 HRS	120 HRS
1	0	0	0	0	0	0	0	0
2	0	0	4	4	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	3	5	1	0	0
5	0	0	0	3	0	0	0	0
6	0	0	2	3	7	2	0	0
Mean	0.0	0.0	1.0	2.2	2.0	0.5	0.0	0.0
SD	0.0	0.0	1.7	1.7	3.2	0.8	0.0	0.0

Right Quadriceps: Leg Soreness

SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	72 HRS	96 HRS	120 HRS
1	0	0	0	0	0	0	0	0
2	0	0	4	8	0	0	0	0
3	0	0	0	3	7	0	0	0
4	0	0	3	11	13	5	3	0
5	0	0	0	9	7	3	0	0
6	0	0	2	4	12	3	1	1
Mean	0.0	0.0	1.5	5.8	6.5	1.8	0.7	0.2
SD	0.0	0.0	1.8	4.2	5.6	2.1	1.2	0.4

Left Quadriceps: Leg Soreness

SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	72 HRS	96 HRS	120 HRS
1	0	0	0	0	0	0	0	0
2	0	0	4	4	0	0	0	0
3	0	0	0	3	7	0	0	0
4	0	0	3	11	12	5	3	0
5	0	0	0	9	7	3	0	0
6	0	0	2	4	13	4	1	1
Mean	0.0	0.0	1.5	5.2	6.5	2.0	0.7	0.2
SD	0.0	0.0	1.8	4.1	5.6	2.3	1.2	0.4

Potassium

Heavy Resistance Exercise

SUBJECT	BASE	0 min	30 min	% DIFF 0 min	% DIFF 30 min
1	4.2	4.6	4.3	9.5	2.4
2	5.1	4.8	5.1	-5.9	0.0
3	4.2	4.2	4.7	0.0	11.9
4	4.7	4.3	4.7	-8.5	0.0
5	4.4	4.3	4.2	-2.3	-2.5
6	4.4	4.3	4.4	-2.5	0.2
Mean	4.5	4.4	4.6	-1.6	2.0
SD	0.4	0.2	0.3	6.2	5.1

Control

SUBJECT	BASE	0 min	30 min	% DIFF 0 min	% DIFF 30 min
1	4.3	5.0	4.4	16.3	2.3
2	5.1	5.2	5.3	2.0	3.9
3	4.5	4.2	4.3	-6.7	-4.4
4	5.1	5.2	4.6	2.0	-9.8
5	4.5	4.4	4.6	-2.5	2.2
6	3.7	4.0	4.6	7.0	23.1
Mean	4.5	4.7	4.6	3.0	2.9
SD	0.5	0.5	0.4	8.0	11.2

Dynamic Strength Exercise

SUBJECT	BASE	0 min	30 min	% DIFF 0	% DIFF 30
1	4.7	4.4	4.4	-6.4	-6.4
2	4.4	4.1	4.9	-6.8	11.4
3	4.1	3.8	4.3	-7.3	4.9
4	4.5	4.3	4.5	-4.4	0.0
5	4.3	3.4	4.3	-20.2	0.5
6	4.9	4.4	4.2	-8.6	-13.0
Mean	4.5	4.1	4.4	-9.0	-0.4
SD	0.3	0.4	0.2	5.7	8.5

Plasma Volume Changes

HRE

SUBJECT	0 MIN	30 MIN	120 MIN	24 HRS	48 HRS
1	-13.0	-1.5	-6.0	-4.8	2.9
2	-6.9	-1.9	0.7	1.2	3.7
3	2.4	6.8	3.6	9.3	14.9
4	-5.2	-7.5	-4.2	-10.4	-4.1
5	-15.7	-1.0	-6.4	4.5	5.3
6	-12.1	-5.6	-10.4	-4.2	-7.1
Mean	-8.4	-1.8	-3.8	-0.7	2.6
SD	6.6	4.9	5.1	7.1	7.7

CON

SUBJECT	0 MIN	30 MIN	120 MIN	24 HRS	48 HRS
1	-8.0	-5.9	-9.8	-6.5	-2.8
2	0.0	-7.2	-5.6	10.3	7.5
3	-7.6	-1.9	-17.7	1.5	-3.1
4	2.0	0.6	0.5	5.2	2.3
5	1.0	-1.3	2.2	-1.4	-8.3
6	1.8	-0.7	1.5	-0.5	-3.8
Mean	-1.8	-2.7	-4.8	1.4	-1.4
SD	4.7	3.1	7.9	5.8	5.5

DSE

SUBJECT	0 MIN	30 MIN	120 MIN	24 HRS	48 HRS
1	9.8	1.3	4.3	5.7	-2.9
2	-7.0	-5.6	-3.7	-7.6	-4.2
3	-5.2	-3.3	-4.9	0.3	0.0
4	-11.7	3.4	-10.0	-3.1	-5.6
5	-11.0	0.5	7.6	3.5	0.7
6	-3.9	2.5	7.8	6.4	0.2
Mean	-4.8	-0.2	0.2	0.9	-2.0
SD	7.8	3.5	7.4	5.5	2.6

Ratings of Perceived Exertion

Heavy Resistance Exercise

SUBJECT	SET 1	SET 2	SET 3	SET 4	SET 5
1	16	16	16	19	20
2	15	15	13	14	15
3	13	14	17	18	20
4	15	17	18	19	19
5	14	17	19	19	20
6	12	13	15	16	17
Mean	14.2	15.3	16.3	17.5	18.5
SD	1.5	1.6	2.2	2.1	2.1

Dynamic Strength Exercise

SUBJECT	SET 1	SET 2	SET 3	SET 4	SET 5
1	10	10	11	11	11
2	13	13	13	13	13
3	12	14	15	15	16
4	15	16	18	19	18
5	15	17	18	19	20
6	12	12	13	13	14
Mean	12.8	13.7	14.7	15.0	15.3
SD	1.94	2.58	2.88	3.35	3.33

APPENDIX 8

RAW DATA: STUDY 3

STUDY 3

TRAINING DATA

Heavy Resistance Exercise

MVC (N)

Subject	Pre-test	Test	+ 3 days	+ 10 days	% DIFF + 3 days	% DIFF + 10 days
1	497.3	475.3	497.3	476.4	4.6	0.2
2	750.2	722.6	883.0	824.3	22.2	14.1
3	794.6	685.2	667.6	652.2	-2.6	-4.8
4	507.2	525.6	481.5	453.6	-8.4	-13.7
5	623.6	620.6	652.5	612.5	5.1	-1.3
6	562.6	555.3	581.3	594.2	4.7	7.0
Mean	622.6	597.4	627.2	602.2	4.3	0.2
SD	125.3	95.7	146.9	134.1	10.3	9.6

RFD_{avg}

Subject	Pre-test	Test	+ 3 days	+ 10 days	% DIFF + 3 days	% DIFF + 10 days
1	1723	2013	1787	1815	-11.2	-9.8
2	3719	3097	4011	3933	29.5	27.0
3	4239	3673	4284	3966	16.6	8.0
4	2482	2922	2202	2159	-24.6	-26.1
5	3875	3957	3511	3407	-11.3	-13.9
6	2405	2376	3010	3175	26.7	33.6
Mean	3074	3006	3134	3076	4.3	3.1
SD	1004	741	993	903	22.8	23.8

1RM

Subject	Pre-test	Test	+ 3 days	DIFF (Kg)	DIFF %
1	120	120	140	20	16.7
2	110	110	165	55	50.0
3	140	150	180	30	20.0
4	120	120	155	35	29.2
5	180	180	230	50	27.8
6	140	145	195	50	34.5
Mean	135.0	137.5	177.5	40.0	29.7
SD	25.1	26.0	32.1	13.8	11.9

Dynamic Strength Exercise

MVC (N)

Subject	Pre-test	Test	+ 3 days	+ 10 days	% DIFF 3days	10days
1	611.1	635.7	698.4	691.8	9.9	8.8
2	611.8	597.0	679.7	629.1	13.9	5.4
3	563.4	561.9	619.9	639.3	10.3	13.8
4	648.5	575.5	681.5	636.8	18.4	10.7
5	417.3	395.3	465.0	410.3	17.6	3.8
6	692.6	741.0	748.0	689.6	0.9	-6.9
Mean	590.8	584.4	648.8	616.2	11.8	5.9
SD	95.3	112.8	98.9	104.5	6.4	7.2

RFD_{avg}

Subject	Pre-test	Test	+ 3 days	+ 10 days	% DIFF + 3 days	+ 10 days
1	3049.3	3102.6	3722.9	3517.2	19.99	13.36
2	3417.4	3442.1	3758.4	3998.1	9.19	16.15
3	3518.1	3294.0	3521.3	3232.4	6.90	-1.87
4	2288.1	2520.6	2801.1	2740.7	11.13	8.73
5	2601.8	2898.9	3593.0	2592.0	23.94	-10.59
6	3547.5	3418.1	3319.2	3681.7	-2.90	7.71
Mean	3070.4	3112.7	3452.6	3293.7	11.38	5.58
SD	525.5	355.3	355.9	547.5	9.60	10.04

1RM

Subject	Pre-test	Test	+ 3 days	DIFF (Kg)	DIFF %
1	120	140	145	5	3.6
2	140	180	180	0	0.0
3	140	140	155	15	10.7
4	135	135	170	35	25.9
5	150	155	170	15	9.7
6	150	150	175	25	16.7
Mean	**139.2**	**150.0**	**165.8**	**15.8**	**11.1**
SD	**11.1**	**16.4**	**13.2**	**12.8**	**9.3**

FATIGUE AND RECOVERY CHARACTERISTICS

Forces elicited by Neuromuscular electrical stimulation (N)

Heavy Resistance Exercise

Pre-training

20 Hz Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	134.297	99.229	118.818	121.178	133.348	135.874	84.322	-26.1	-11.5	-9.8	-0.7	1.2	-37.2
2	184.348	94.905	93.992	86.053	85.574	138.978	136.987	-48.5	-49.0	-53.3	-53.6	-24.6	-25.7
3	213.758	116.034	120.711	109.040	81.861	102.717	139.898	-45.7	-43.5	-49.0	-61.7	-51.9	-34.6
4	189.326	104.163	130.326	123.900	176.184	212.378	186.198	-45.0	-31.2	-34.6	-6.9	12.2	-1.7
5	200.228	138.828	137.342	140.354	122.089	151.416	223.726	-30.7	-31.4	-29.9	-39.0	-24.4	11.7
6	191.561	102.968	139.330	150.515	171.832	182.752	169.415	-46.2	-27.3	-21.4	-10.3	-4.6	-11.6
Mean	185.6	109.4	123.4	121.8	128.5	154.0	156.8	-40.4	-32.3	-33.0	-28.7	-15.4	-16.5
SD	27.17	16.08	16.67	22.87	40.58	38.54	47.82	9.5	13.1	16.5	26.1	23.0	19.4

Post-training

20 Hz Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	188.980	130.284	157.614	130.030	158.106	136.392	134.680	-31.1	-16.6	-31.2	-16.3	-27.8	-28.7
2	266.118	187.978	168.601	180.805	190.000	176.685	190.505	-29.4	-36.6	-32.1	-28.6	-33.6	-28.4
3	221.351	146.637	145.297	134.884	134.634	211.853	205.723	-33.8	-34.4	-39.1	-39.2	-4.3	-7.1
4	170.815	126.916	134.507	125.830	144.012	173.673	156.580	-25.7	-21.3	-26.3	-15.7	1.7	-8.3
5	267.919	188.251	195.430	220.995	242.198	280.142	320.747	-29.7	-27.1	-17.5	-9.6	4.6	19.7
6	205.004	152.806	172.275	190.113	200.841	264.953	222.958	-25.5	-16.0	-7.3	-2.0	29.2	8.8
Mean	220.031	155.479	162.287	163.776	178.299	207.283	205.199	-29.2	-25.3	-25.6	-18.6	-5.0	-7.3
SD	40.078	27.078	21.542	39.169	40.542	56.119	65.145	3.2	8.9	11.5	13.4	23.0	19.5

Heavy Resistance Exercise

Pre-training

100 Hz													
Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0	30 min	60 min	120 min	24hrs	48hrs
1	186.271	137.265	175.214	166.635	179.808	176.505	122.566	-26.3	-5.9	-10.5	-3.5	-5.2	-34.2
2	283.903	218.567	240.261	223.646	233.781	278.333	256.238	-23.0	-15.4	-21.2	-17.7	-2.0	-9.7
3	307.227	246.669	270.204	267.562	247.122	251.125	258.047	-19.7	-12.1	-12.9	-19.6	-18.3	-16.0
4	260.663	250.849	310.318	307.878	323.705	363.052	324.824	-3.8	19.0	18.1	24.2	39.3	24.6
5	296.724	234.792	239.041	232.398	166.563	243.619	314.415	-20.9	-19.4	-21.7	-43.9	-17.9	6.0
6	277.566	186.141	242.913	257.276	289.563	277.073	268.610	-32.9	-12.5	-7.3	4.3	-0.2	-3.2
Mean	268.7	212.4	246.3	242.6	240.1	265.0	257.5	-21.1	-7.7	-9.3	-9.3	-0.7	-5.4
SD	43.45	43.65	44.33	47.61	60.94	60.69	72.26	9.7	13.8	14.6	23.3	21.1	20.0

Post-training

100 Hz													
Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	204.879	174.065	213.510	184.763	175.579	183.675	174.658	-15.0	4.2	-9.8	-14.3	-10.3	-14.8
2	411.978	363.720	369.456	394.151	402.937	344.307	356.993	-11.7	-10.3	-4.3	-2.2	-16.4	-13.3
3	327.308	262.465	283.392	274.555	299.155	336.323	341.770	-19.8	-13.4	-16.1	-8.6	2.8	4.4
4	358.088	343.512	323.234	376.400	341.990	347.377	328.397	-4.1	-9.7	5.1	-4.5	-3.0	-8.3
5	376.280	308.237	312.000	342.661	354.932	392.546	432.321	-18.1	-17.1	-8.9	-5.7	4.3	14.9
6	340.637	259.200	299.633	322.793	321.141	375.301	370.260	-23.9	-12.0	-5.2	-5.7	10.2	8.7
Mean	336.528	285.2	300.204	315.887	315.956	329.922	334.067	-15.4	-9.7	-6.6	-6.8	-2.1	-1.4
SD	70.9523	68.7608	51.5057	76.7508	77.1718	74.7286	86.0141	6.9	7.3	7.1	4.2	9.9	12.4

Dynamic Strength Exercise

Pre-training

20 Hz Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	185.121	160.817	159.072	139.743	154.102	165.925	151.616	-13.1	-14.1	-24.5	-16.8	-10.4	-18.1
2	234.395	158.003	177.169	187.939	212.647	238.822	212.824	-32.6	-24.4	-19.8	-9.3	1.9	-9.2
3	165.769	101.861	128.031	133.352	135.263	194.973	190.834	-38.6	-22.8	-19.6	-18.4	17.6	15.1
4	187.457	95.584	124.965	135.837	126.643	173.124	214.075	-49.0	-33.3	-27.5	-32.4	-7.6	14.2
5	160.062	105.650	111.229	120.726	141.850	167.562	252.389	-34.0	-30.5	-24.6	-11.4	4.7	57.7
6	306.288	173.096	169.188	162.747	158.804	183.172	207.540	-43.5	-44.8	-46.9	-48.2	-40.2	-32.2
Mean	206.515	132.502	144.942	146.724	154.885	187.263	204.880	-35.1	-28.3	-27.1	-22.7	-5.7	4.6
SD	55.445	34.994	27.010	24.402	30.676	27.488	33.004	12.4	10.5	10.1	14.9	19.6	31.9

Post-training

20 Hz Subject	BASE	0	30	60	120	24 hrs	48 hrs	0	30	60	120	24hrs	48hrs
1	193.238	166.926	169.006	172.051	162.099	188.825	167.459	-13.6	-12.5	-11.0	-16.1	-2.3	-13.3
2	239.699	174.027	175.522	187.012	239.659	287.193	328.613	-27.4	-26.8	-22.0	0.0	19.8	37.1
3	234.154	148.635	172.412	188.198	195.134	234.354	253.606	-36.5	-26.4	-19.6	-16.7	0.1	8.3
4	194.517	139.816	165.623	143.605	188.543	187.141	201.265	-28.1	-14.9	-26.2	-3.1	-3.8	3.5
5	190.835	143.961	141.167	130.936	157.322	161.399	197.220	-24.6	-26.0	-31.4	-17.6	-15.4	3.3
6	316.548	200.217	219.593	228.324	254.770	307.929	282.989	-36.7	-30.6	-27.9	-19.5	-2.7	-10.6
Mean	228.165	162.264	173.887	175.021	199.588	227.807	238.525	-27.8	-22.9	-23.0	-12.2	-0.7	4.7
SD	48.427	22.914	25.521	34.922	39.961	59.283	60.770	8.6	7.3	7.2	8.4	11.4	18.0

Dynamic Strength Exercise

Pre-training

100 Hz Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	263.461	228.983	230.382	222.563	234.480	239.892	216.018	-13.1	-12.6	-15.5	-11.0	-8.9	-18.0
2	326.325	233.699	266.764	278.701	297.100	336.846	301.008	-28.4	-18.3	-14.6	-9.0	3.2	-7.8
3	239.445	173.031	209.249	229.404	233.076	292.621	281.833	-27.7	-12.6	-4.2	-2.7	22.2	17.7
4	275.271	181.350	245.629	297.516	276.715	293.541	340.136	-34.1	-10.8	8.1	0.5	6.6	23.6
5	324.134	209.292	235.828	277.805	282.977	312.783	418.289	-35.4	-27.2	-14.3	-12.7	-3.5	29.0
6	435.675	310.151	325.024	329.567	327.192	338.165	349.138	-28.8	-25.4	-24.4	-24.9	-22.4	-19.9
Mean	310.719	222.751	252.146	272.593	275.257	302.308	317.737	-27.9	-17.8	-10.8	-9.9	-0.5	4.1
SD	70.1532	49.3249	40.367	40.743	36.5461	36.4823	68.5772	7.9	7.1	11.2	8.9	15.1	21.9

Post-training

100 Hz Subject	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24hrs	48hrs
1	256.962	253.259	255.120	259.824	265.738	264.329	253.108	-1.4	-0.7	1.1	3.4	2.9	-1.5
2	328.416	257.345	252.915	283.463	320.925	383.594	426.947	-21.6	-23.0	-13.7	-2.3	16.8	30.0
3	318.669	217.013	258.882	293.925	293.633	341.290	365.104	-31.9	-18.8	-7.8	-7.9	7.1	14.6
4	325.636	230.182	281.520	250.243	306.195	293.700	323.177	-29.3	-13.5	-23.2	-6.0	-9.8	-0.8
5	358.444	280.905	284.254	259.197	268.512	267.290	335.926	-21.6	-20.7	-27.7	-25.1	-25.4	-6.3
6	400.857	319.992	349.506	383.797	408.342	493.660	428.137	-20.2	-12.8	-4.3	1.9	23.2	6.8
Mean	331.497	259.783	280.366	288.408	310.558	340.644	355.4	-21.0	-14.9	-12.6	-6.0	2.4	7.1
SD	47.5412	36.9466	36.4672	49.5598	52.4431	87.9404	66.9104	10.7	8.0	11.1	10.3	17.8	13.4

MVC (N)

Pre-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	475.3	428.7	414.4	469.8	440.4	488.5	481.5	-9.8	-12.8	-1.2	-7.3	2.8	1.3
2	722.6	673.5	643.4	599.7	631.3	637.1	712.7	-6.8	-11.0	-17.0	-12.6	-11.8	-1.4
3	685.2	466.8	474.9	520.4	476.4	419.5	401.9	-31.9	-30.7	-24.0	-30.5	-38.8	-41.3
4	525.6	398.9	418.8	433.8	394.9	457.3	396.4	-24.1	-20.3	-17.5	-24.9	-13.0	-24.6
5	620.6	556.4	524.8	507.2	469.4	582.4	588.7	-10.4	-15.4	-18.3	-24.4	-6.2	-5.1
6	555.3	425.0	437.1	521.5	503.5	512.7	517.9	-23.5	-21.3	-6.1	-9.3	-7.7	-6.7
Mean	597.4	491.5	485.6	508.7	486.0	516.3	516.5	-17.7	-18.6	-14.0	-18.2	-12.4	-13.0
SD	95.69	104.75	87.68	56.05	80.19	80.76	120.4	10.1	7.2	8.6	9.6	14.1	16.6

Post-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	476.4	433.8	444.1	428.7	460.2	505.7	544.6	-8.9	-6.8	-10.0	-3.4	6.2	14.3
2	824.3	792.7	714.6	808.5	724.1	735.5	852.6	-3.8	-13.3	-1.9	-12.2	-10.8	3.4
3	652.2	576.2	596.0	507.9	542.4	596.0	591.6	-11.6	-8.6	-22.1	-16.8	-8.6	-9.3
4	453.6	438.6	422.8	419.9	410.7	444.8	409.2	-3.3	-6.8	-7.4	-9.5	-1.9	-9.8
5	612.5	567.4	499.1	535.1	541.3	638.2	666.9	-7.4	-18.5	-12.6	-11.6	4.2	8.9
6	594.2	505.4	542.1	513.1	523.4	588.3	675.3	-14.9	-8.8	-13.7	-11.9	-1.0	13.7
Mean	602.2	552.4	536.4	535.5	533.7	584.8	623.4	-8.3	-10.5	-11.3	-10.9	-2.0	3.5
SD	134.1	132.5	107.8	141.8	106.8	101.5	148.5	4.5	4.6	6.8	4.4	6.7	10.9

MVC (N)

Pre-training

	DSE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	635.7	578.8	565.2	579.9	590.9	606.7	591.6	-8.9	-11.1	-8.8	-7.0	-4.6	-6.9
2	597.0	568.1	519.7	564.1	540.2	567.0	583.7	-4.8	-12.9	-5.5	-9.5	-5.0	-2.2
3	561.9	531.4	504.3	532.9	519.7	556.8	571.1	-5.4	-10.3	-5.2	-7.5	-0.9	1.6
4	575.5	517.1	528.1	584.7	559.0	644.5	589.8	-10.1	-8.2	1.6	-2.9	12.0	2.5
5	495.3	424.6	412.5	509.0	423.2	492.5	521.8	-14.3	-16.7	2.8	-14.6	-0.6	5.4
6	741.0	599.0	593.1	589.8	548.3	601.2	644.5	-19.2	-20.0	-20.4	-26.0	-18.9	-13.0
Mean	601.0	536.5	520.5	560.1	530.2	578.1	583.7	-10.5	-13.2	-5.9	-11.2	-3.0	-2.1
SD	82.68	62.63	62.05	32.37	57.46	52.26	39.45	5.5	4.4	8.4	8.2	9.9	6.8

Post-training

	DSE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24hrs	48hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	691.8	669.4	643.4	654.8	665.8	680.8	699.4	-3.2	-7.0	-5.4	-3.8	-1.6	1.1
2	629.1	528.5	504.3	511.6	539.9	560.8	625.0	-16.0	-19.8	-18.7	-14.2	-10.9	-0.6
3	639.3	586.5	585.4	624.7	576.9	561.5	577.7	-8.3	-8.4	-2.3	-9.8	-12.2	-9.6
4	636.8	566.7	546.5	514.6	560.1	630.9	550.2	-11.0	-14.2	-19.2	-12.0	-0.9	-13.6
5	410.3	444.5	391.6	399.7	426.5	434.5	466.1	8.3	-4.6	-2.6	3.9	5.9	13.6
6	689.6	690.4	647.0	658.8	644.1	722.6	717.1	0.1	-6.2	-4.5	-6.6	4.8	4.0
Mean	616.2	581.0	553.0	560.7	568.9	598.5	605.9	-5.0	-10.0	-8.8	-7.1	-2.5	-0.9
SD	104.5	91.01	96.46	103.0	85.22	102.9	94.79	8.6	5.8	8.0	6.6	7.6	9.8

MVS (N)

Pre-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	433.1	381.7	387.6	456.6	394.9	469.0	504.3	-11.9	-10.5	5.4	-8.8	8.3	16.4
2	694.4	590.9	665.0	615.8	588.7	656.2	714.2	-14.9	-4.2	-11.3	-15.2	-5.5	2.9
3	754.6	489.6	449.2	487.4	514.5	357.5	399.2	-35.1	-40.5	-35.4	-31.8	-52.6	-47.1
4	514.6	414.0	464.6	426.5	405.2	475.6	449.2	-19.5	-9.7	-17.1	-21.3	-7.6	-12.7
5	596.0	587.9	523.4	568.1	469.8	598.2	661.4	-1.4	-12.2	-4.7	-21.2	0.4	11.0
6	558.6	468.3	488.1	529.2	538.8	516.0	505.7	-16.2	-12.6	-5.3	-3.5	-7.6	-9.5
Mean	591.9	488.7	496.3	513.9	485.3	512.1	539.0	-16.5	-15.0	-11.4	-17.0	-10.8	-6.5
SD	117.7	86.88	94.14	71.00	76.46	105.2	122.9	11.0	12.9	14.0	10.1	21.4	22.9

Post-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	422.8	400.0	405.2	366.3	463.9	453.6	527.0	-5.4	-4.2	-13.4	9.7	7.3	24.7
2	844.1	799.1	745.0	806.0	747.2	780.3	871.3	-5.3	-11.7	-4.5	-11.5	-7.6	3.2
3	637.9	535.1	546.1	527.8	554.9	632.0	601.2	-16.1	-14.4	-17.3	-13.0	-0.9	-5.8
4	479.3	429.4	415.5	434.5	459.5	454.4	476.4	-10.4	-13.3	-9.3	-4.1	-5.2	-0.6
5	659.2	611.4	548.3	550.5	579.1	641.5	682.6	-7.2	-16.8	-16.5	-12.1	-2.7	3.6
6	640.8	550.5	564.5	579.1	568.9	662.8	685.6	-14.1	-11.9	-9.6	-11.2	3.4	7.0
Mean	614.0	554.3	537.4	544.0	562.3	604.1	640.7	-9.8	-12.1	-11.8	-7.0	-0.9	5.3
SD	149.0	143.5	123.6	150.8	104.7	127.8	140.3	4.6	4.3	4.9	8.8	5.5	10.4

MVS-MVC (%)

Pre-training

HRE SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	-8.9	-11.0	-6.5	-2.8	-10.3	-4.0	4.7
2	-3.9	-12.3	3.4	2.7	-6.7	3.0	0.2
3	10.1	4.9	-5.4	-6.3	8.0	-14.8	-0.7
4	-2.1	3.8	11.0	-1.7	2.6	4.0	13.3
5	-4.0	5.7	-0.3	12.0	0.1	2.7	12.3
6	0.6	10.2	11.7	1.5	7.0	0.6	-2.3
Mean	-1.4	0.2	2.3	0.9	0.1	-1.4	4.6
SD	6.4	9.4	7.8	6.3	7.4	7.1	6.8

Post-training

HRE SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	-11.2	-7.8	-8.8	-14.6	0.8	-10.3	-3.2
2	2.4	0.8	4.3	-0.3	3.2	6.1	2.2
3	-2.2	-7.1	-8.4	3.9	2.3	6.0	1.6
4	5.7	-2.1	-1.7	3.5	11.9	2.1	16.4
5	7.6	7.8	9.9	2.9	7.0	0.5	2.4
6	7.8	8.9	4.1	12.9	8.7	12.7	1.5
Mean	1.7	0.1	-0.1	1.4	5.6	2.9	3.5
SD	7.4	7.2	7.5	9.0	4.3	7.7	6.7

MVS (N)

Pre-training

DSE SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	615.8	601.2	557.1	574.0	541.0	581.3	579.1	-2.4	-9.5	-6.8	-12.2	-5.6	-6.0
2	587.2	568.9	524.8	559.3	537.3	595.3	604.8	-3.1	-10.6	-4.8	-8.5	1.4	3.0
3	596.0	550.5	596.5	590.2	561.5	596.8	588.7	-7.6	0.1	-1.0	-5.8	0.1	-1.2
4	575.5	532.9	557.1	557.9	558.6	632.0	590.2	-7.4	-3.2	-3.1	-2.9	9.8	2.6
5	485.2	448.5	448.5	484.5	440.4	510.1	534.4	-7.6	-7.6	-0.2	-9.2	5.1	10.1
6	787.6	709.8	627.6	642.3	636.4	656.2	681.9	-9.9	-20.3	-18.5	-19.2	-16.7	-13.4
Mean	607.9	568.6	551.9	568.0	545.9	595.3	596.5	-6.3	-8.5	-5.7	-9.6	-1.0	-0.8
SD	99.03	86.05	61.97	51.38	62.96	50.01	48.22	2.9	7.0	6.7	5.6	9.3	8.1

Post-training

DSE SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	638.6	649.6	619.5	638.6	657.0	690.7	692.2	1.7	-3.0	0.0	2.9	8.2	8.4
2	593.8	527.0	519.0	544.6	503.5	607.0	657.7	-11.2	-12.6	-8.3	-15.2	2.2	10.8
3	645.2	608.5	623.9	649.6	623.2	596.8	578.4	-5.7	-3.3	0.7	-3.4	-7.5	-10.4
4	621.7	602.6	541.0	540.2	547.6	616.6	598.2	-3.1	-13.0	-13.1	-11.9	-0.8	-3.8
5	434.5	433.1	458.0	417.7	444.8	474.2	466.1	-0.3	5.4	-3.9	2.4	9.1	7.3
6	743.6	721.5	631.3	669.4	643.7	742.8	753.1	-3.0	-15.1	-10.0	-13.4	-0.1	1.3
Mean	612.9	590.4	565.4	576.7	570.0	621.4	624.3	-3.6	-6.9	-5.8	-6.5	1.8	2.3
SD	101.0	100.0	70.67	95.29	85.34	91.72	100.1	4.5	8.0	5.6	8.1	6.2	8.1

MVS-MVC (%)

Pre-training

DSE SUBJECT	BASE	0	30	60	120	24hrs	48hrs
1	-3.1	3.9	-1.4	-1.0	-8.4	-4.2	-2.1
2	-1.6	0.1	1.0	-0.8	-0.5	5.0	3.6
3	6.1	3.6	18.3	10.7	8.1	7.2	3.1
4	0.0	3.1	5.5	-4.6	-0.1	-1.9	0.1
5	-2.0	5.6	8.7	-4.8	4.1	3.6	2.4
6	6.3	18.5	5.8	8.9	16.1	9.2	5.8
Mean	0.9	5.8	6.3	1.4	3.2	3.1	2.1
SD	4.2	6.5	6.9	6.8	8.4	5.2	2.8

Post-training

DSE SUBJECT	BASE	0	30	60	120	24hrs	48hrs
1	-7.7	-3.0	-3.7	-2.5	-1.3	1.5	-1.0
2	-5.6	-0.3	2.9	6.5	-6.7	8.2	5.2
3	0.9	3.8	6.6	4.0	8.0	6.3	0.1
4	-2.4	6.3	-1.0	5.0	-2.2	-2.3	8.7
5	5.9	-2.6	17.0	4.5	4.3	9.1	0.0
6	7.8	4.5	-2.4	1.6	-0.1	2.8	5.0
Mean	-0.2	1.5	3.2	3.2	0.3	4.3	3.0
SD	6.2	3.9	7.7	3.2	5.2	4.4	3.9

RFD_{avg} ($N.s^{-1}$)

Pre-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1823	1076	1326	1776	1453	1594	2396	-41.0	-27.3	-2.6	-20.3	-12.6	31.4
2	3097	2117	1556	1730	1663	2071	2369	-31.6	-49.8	-44.1	-46.3	-33.1	-23.5
3	3673	2897	3210	3629	3841	3796	1522	-21.1	-12.6	-1.2	4.6	3.4	-58.6
4	2922	2288	3065	2396	2853	2906	2162	-21.7	4.9	-18.0	-2.4	-0.5	-26.0
5	3957	3084	3209	3063	3077	3795	4032	-22.1	-18.9	-22.6	-22.2	-4.1	1.9
6	2376	1716	2388	2496	2292	2363	2028	-27.8	0.5	5.0	-3.5	-0.6	-14.6
Mean	2975	2196	2459	2515	2530	2754	2418	-27.6	-17.2	-13.9	-15.0	-7.9	-14.9
SD	794.2	745.7	848.4	737.2	904.6	912.0	852.0	7.8	19.9	18.2	18.6	13.5	30.1

Post-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1815	871	1239	961	1406	2368	2920	-52.0	-31.7	-47.1	-22.6	30.4	60.8
2	3933	3222	2653	2667	2990	3480	3969	-18.1	-32.6	-32.2	-24.0	-11.5	0.9
3	3966	3300	3973	2901	4090	3647	3686	-16.8	0.2	-26.9	3.1	-8.0	-7.1
4	2159	1994	2029	2411	2213	2316	3200	-7.6	-6.0	11.7	2.5	7.3	48.2
5	3407	2139	2164	2614	2203	2892	2727	-37.2	-36.5	-23.3	-35.4	-15.1	-19.9
6	3175	1172	2187	2349	2919	4227	4380	-63.1	-31.1	-26.0	-8.0	33.2	38.0
Mean	3076	2117	2374	2317	2637	3155	3480	-32.5	-23.0	-23.9	-14.1	6.0	20.2
SD	903.0	1008	907.7	693.0	916.3	760.3	640.4	22.0	15.8	19.4	15.7	21.4	33.1

RFD_{avg} ($N.s^{-1}$)

Pre-training

DSE													
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	3254	3067	2655	2858	3150	2985	3024	-5.7	-18.4	-12.1	-3.2	-8.3	-7.1
2	3442	2820	3025	3335	2584	3490	3917	-18.1	-12.1	-3.1	-24.9	1.4	13.8
3	3294	2690	3120	3340	3198	3304	3374	-18.3	-5.3	1.4	-2.9	0.3	2.4
4	2521	1996	2126	2231	2817	3030	2605	-20.8	-15.6	-11.5	11.8	20.2	3.4
5	3238	1940	1817	3252	2707	3043	2871	-40.1	-43.9	0.4	-16.4	-6.0	-11.3
6	3779	3418	3011	2859	3353	3790	3718	-9.6	-20.3	-24.4	-11.3	0.3	-1.6
Mean	3255	2655	2626	2979	2968	3274	3252	-18.8	-19.3	-8.2	-7.8	1.3	-0.1
SD	412.6	587.4	539.7	429.1	307.4	319.3	508.0	11.9	13.2	9.8	12.7	10.1	8.8

Post-training

DSE													
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	3176	3020	3169	3003	3190	3547	3446	-4.9	-0.2	-5.5	0.5	11.7	8.5
2	3998	3146	2436	2533	3051	2836	2839	-21.3	-39.1	-36.6	-23.7	-29.1	-29.0
3	3232	2630	3000	2846	2797	2991	2872	-18.6	-7.2	-12.0	-13.5	-7.5	-11.1
4	2741	1964	1932	1855	2480	2620	2833	-28.4	-29.5	-32.3	-9.5	-4.4	3.4
5	2592	1758	2071	2380	2336	2766	2723	-32.2	-20.1	-8.2	-9.9	6.7	5.1
6	3682	2812	2713	2638	3265	3217	3016	-23.6	-26.3	-28.3	-11.3	-12.6	-18.1
Mean	3237	2555	2553	2543	2853	2996	2955	-21.5	-20.4	-20.5	-11.2	-5.9	-6.9
SD	537.2	569.7	497.3	403.1	382.9	338.3	258.5	9.5	14.5	13.5	7.8	14.5	14.9

RMS Values (Arbitrary Units)
0-500 ms
Pre-training

	HRE											
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1.238	0.854	1.072	1.412	1.291	1.264	1.616	-31.0	-13.4	14.1	4.3	2.1	30.5
2	1.722	1.696	1.767	1.672	1.910	1.576	1.509	-1.5	2.6	-2.9	10.9	-8.5	-12.4
3	1.702	1.528	1.553	1.490	1.263	1.658	1.510	-10.2	-8.7	-12.5	-25.8	-2.6	-11.3
4	1.649	1.543	1.637	1.549	1.626	1.710	1.525	-6.4	-0.7	-6.0	-1.4	3.7	-7.5
5	1.859	1.708	1.692	1.818	1.712	1.910	1.707	-8.1	-9.0	-2.2	-7.9	2.8	-8.2
6	1.568	1.295	1.484	1.680	1.609	1.752	1.639	-17.4	-5.4	7.1	2.6	11.7	4.5
Mean	1.623	1.437	1.534	1.603	1.568	1.645	1.584	-12.4	-5.8	-0.4	-2.9	1.5	-0.7
SD	0.212	0.322	0.247	0.148	0.250	0.217	0.082	10.5	5.9	9.5	12.8	6.7	16.5

Post-training

	HRE											
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48hrs
1	1.022	0.560	0.670	0.754	0.822	1.267	1.167	-45.2	-34.4	-26.2	-19.6	23.9	14.2
2	1.521	1.501	1.386	1.519	1.525	1.523	1.505	-1.3	-8.9	-0.2	0.3	0.1	-1.1
3	2.127	1.960	2.147	1.966	2.037	2.133	2.063	-7.9	0.9	-7.6	-4.2	0.3	-3.0
4	1.544	1.387	1.343	1.538	1.447	1.503	1.340	-10.2	-13.0	-0.4	-6.3	-2.7	-13.2
5	1.927	1.803	1.812	1.927	1.793	1.942	2.007	-6.4	-6.0	0.0	-7.0	0.8	4.2
6	1.628	1.355	1.474	1.435	1.622	1.683	1.819	-16.7	-9.4	-11.8	-0.3	3.4	11.8
Mean	1.628	1.428	1.472	1.523	1.541	1.675	1.650	-14.6	-11.8	-7.7	-6.2	4.3	2.1
SD	0.381	0.488	0.498	0.438	0.410	0.316	0.368	15.8	12.0	10.3	7.2	9.8	10.1

500-1500 ms
Pre-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1.592	1.412	1.462	1.638	1.673	1.718	1.750	-11.3	-8.2	2.9	5.1	7.9	9.9
2	1.722	1.665	1.726	1.825	1.801	1.685	1.624	-3.3	0.3	6.0	4.6	-2.1	-5.7
3	1.713	1.438	1.660	1.590	1.286	1.681	1.641	-16.1	-3.1	-7.2	-24.9	-1.8	-4.2
4	1.961	1.791	1.769	1.820	1.634	1.916	1.862	-8.7	-9.8	-7.2	-16.7	-2.3	-5.0
5	1.833	1.746	1.717	1.725	1.679	1.877	1.744	-4.7	-6.3	-5.9	-8.4	2.4	-4.8
6	1.719	1.557	1.627	1.767	1.772	1.839	1.858	-9.4	-5.4	2.8	3.1	7.0	8.1
Mean	1.756	1.601	1.660	1.727	1.641	1.786	1.746	-8.9	-5.4	-1.4	-6.2	1.8	-0.3
SD	0.126	0.158	0.109	0.096	0.185	0.104	0.102	4.6	3.6	6.0	12.6	4.7	7.2

Post-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1.168	0.835	0.803	1.130	1.090	1.245	1.174	-28.5	-31.2	-3.2	-6.6	6.6	0.6
2	1.585	1.567	1.591	1.654	1.556	1.569	1.543	-1.1	0.4	4.4	-1.8	-1.0	-2.6
3	2.190	2.041	2.200	2.050	2.106	2.157	2.239	-6.8	0.5	-6.4	-3.8	-1.5	2.2
4	1.875	1.710	1.713	1.700	1.618	1.685	1.502	-8.8	-8.7	-9.3	-13.7	-10.1	-19.9
5	2.003	1.953	1.950	1.965	2.002	2.096	2.036	-2.5	-2.6	-1.9	0.0	4.6	1.6
6	1.811	1.544	1.645	1.679	1.683	1.724	1.762	-14.7	-9.2	-7.3	-7.1	-4.8	-2.7
Mean	1.772	1.608	1.650	1.696	1.676	1.746	1.709	-10.4	-8.5	-4.0	-5.5	-1.0	-3.5
SD	0.358	0.429	0.473	0.323	0.361	0.340	0.387	10.1	11.9	4.9	4.8	6.1	8.3

1500-2500 ms
Pre-training

HRE													
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	1.538	1.399	1.493	1.466	1.645	1.685	1.671	-9.0	-2.9	-4.7	6.9	9.6	8.6
2	1.769	1.706	1.775	1.863	1.905	1.796	1.781	-3.6	0.4	5.3	7.7	1.6	0.7
3	1.707	1.465	1.695	1.697	1.270	1.670	1.669	-14.2	-0.7	-0.6	-25.6	-2.1	-2.2
4	1.992	1.834	1.866	1.768	1.790	2.019	1.856	-7.9	-6.3	-11.2	-10.1	1.3	-6.8
5	1.844	1.735	1.635	1.825	1.575	1.884	1.752	-5.9	-11.3	-1.0	-14.6	2.2	-5.0
6	1.708	1.628	1.706	1.807	1.835	1.946	1.957	-4.7	-0.1	5.8	7.5	13.9	14.6
Mean	1.759	1.628	1.695	1.738	1.670	1.833	1.781	-7.5	-3.5	-1.1	-4.7	4.4	1.7
SD	0.152	0.167	0.127	0.145	0.231	0.141	0.112	3.8	4.6	6.4	14.1	6.0	8.3

Post-training

HRE													
SUBJECT	BASE	0	30	60	120	24hrs	48hrs	0	30	60	120	24hrs	48hrs
1	1.166	0.978	0.788	1.035	1.134	1.204	1.206	-16.1	-32.4	-11.2	-2.7	3.3	3.5
2	1.549	1.664	1.531	1.663	1.562	1.538	1.542	7.4	-1.2	7.3	0.8	-0.7	-0.5
3	2.163	2.081	2.092	2.011	2.115	2.223	2.134	-3.8	-3.3	-7.0	-2.2	2.8	-1.3
4	1.908	1.740	1.845	1.752	1.688	1.776	1.800	-8.8	-3.3	-8.2	-11.5	-6.9	-5.7
5	2.056	1.923	1.942	1.994	2.011	2.074	2.076	-6.5	-5.6	-3.0	-2.2	0.9	0.9
6	1.806	1.644	1.659	1.645	1.727	1.744	1.813	-9.0	-8.2	-8.9	-4.4	-3.4	0.4
Mean	1.775	1.672	1.643	1.683	1.706	1.760	1.762	-6.1	-9.0	-5.2	-3.7	-0.7	-0.4
SD	0.366	0.379	0.464	0.355	0.349	0.367	0.346	7.8	11.7	6.7	4.2	3.9	3.0

MDF (Hz)

Pre-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	53.33	54.79	53.82	57.24	53.33	53.33	54.80	2.8	0.9	7.3	0.0	0.0	2.8
2	61.64	69.47	65.07	64.58	63.11	62.62	56.67	12.7	5.6	4.8	2.4	1.6	-8.1
3	53.82	63.60	60.67	50.88	45.50	58.22	52.35	18.2	12.7	-5.5	-15.5	8.2	-2.7
4	55.77	60.67	58.22	57.73	51.37	57.73	58.22	8.8	4.4	3.5	-7.9	3.5	4.4
5	62.62	63.60	65.56	57.73	55.28	60.67	59.69	1.6	4.7	-7.8	-11.7	-3.1	-4.7
6	60.18	60.67	60.67	57.73	59.20	58.22	58.22	0.8	0.8	-4.1	-1.6	-3.3	-3.3
Mean	57.89	62.13	60.67	57.65	54.63	58.46	56.66	7.5	4.8	-0.3	-5.7	1.1	-1.9
SD	4.09	4.82	4.39	4.34	6.15	3.14	2.69	7.0	4.3	6.3	7.1	4.3	4.7

Post-training

	HRE												
SUBJECT	BASE	0 min	30 min	60 min	120 min	24 hrs	48 hrs	0 min	30 min	60 min	120 min	24 hrs	48 hrs
1	53.33	50.88	50.39	52.84	54.31	53.82	58.22	-4.6	-5.5	-0.9	1.8	0.9	9.2
2	74.85	68.00	67.52	66.54	61.15	78.15	75.15	-9.2	-9.8	-11.1	-18.3	4.4	0.4
3	45.99	54.31	41.10	48.92	45.99	56.75	47.95	18.1	-10.6	6.4	0.0	23.4	4.3
4	59.69	61.64	55.77	51.86	51.37	59.16	58.22	3.3	-6.6	-13.1	-13.9	-0.9	-2.5
5	58.71	65.07	62.62	58.71	57.73	55.77	55.77	10.8	6.7	0.0	-1.7	-5.0	-5.0
6	57.73	58.71	62.13	56.75	53.77	59.69	56.75	1.7	7.6	-1.7	-6.9	3.4	-1.7
Mean	58.38	59.77	56.59	55.94	54.05	60.56	58.68	3.4	-3.0	-3.4	-6.5	4.4	0.8
SD	9.52	6.47	9.65	6.26	5.22	8.89	8.94	10.0	8.1	7.4	8.1	9.9	5.2

Lactic Acid

Heavy Resistance Exercise

	Pre-Training				Post-training			
SUBJECT	BASE	0 min	30 min	120 min	BASE	0 min	30 min	120 min
1	0.7	1.5	0.7	0.5	0.5	1.4	0.9	0.6
2	1.1	5.5	1.1	0.9	0.7	4.1	1.1	0.6
3	0.7	11.1	2.1	1.5	1.5	10.8	2.7	0.7
4	1.2	2.2	1.0	0.8	0.8	2.5	1.0	0.7
5	1.5	9.0	2.5	1.1	2.3	9.5	2.5	1.0
6	0.9	7.2	1.4	0.7	0.8	6.2	0.9	0.6
Mean	1.0	6.1	1.5	0.9	1.1	5.7	1.5	0.7
SD	0.3	3.8	0.7	0.4	0.7	3.8	0.8	0.1

Dynamic Strength Exercise

	Pre-training				Post-training			
SUBJECT	BASE	0 min	30 min	120 min	BASE	0 min	30 min	120 min
1	0.7	1.3	0.8	0.5	0.7	1.1	0.5	0.5
2	1.4	5.3	1.2	0.9	1.0	7.4	1.3	1.0
3	0.7	4.9	0.6	0.6	0.5	6.2	0.8	0.5
4	0.8	5.0	1.2	1.2	1.5	4.8	1.0	0.7
5	0.6	2.6	0.7	0.6	1.2	2.4	0.9	0.5
6	0.8	5.8	1.4	0.6	0.9	7.6	1.5	0.5
Mean	0.8	4.2	1.0	0.7	1.0	4.9	1.0	0.6
SD	0.3	1.8	0.3	0.3	0.4	2.7	0.4	0.2

Creatine Kinase

Pre-training

	HRE										
SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	171	178	170	162	175	131	4.1	-0.6	-5.3	2.3	-23.4
2	125	151	137	176	256	207	20.8	9.6	40.8	104.8	65.6
3	202	238	216	326	3906	4369	17.8	6.9	61.4	1833.7	2062.9
4	153	167	180	191	426	273	9.2	17.6	24.8	178.4	78.4
5	250	292	276	279	305	229	16.8	10.4	11.6	22.0	-8.4
6	129	145	140	178	320	259	12.4	8.5	38.0	148.1	100.8
Mean	171.7	195.2	186.5	218.7	898.0	911.3	13.5	8.8	28.6	381.5	379.3
SD	47.8	57.9	52.5	67.2	1475.9	1694.6	6.2	5.9	23.5	714.7	826.2

Post-training

	HRE										
SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	112	112	116	114	109	141	0.0	3.6	1.8	-2.7	25.9
2	153	157	145	159	168	174	2.6	-5.2	3.9	9.8	13.7
3	183	220	200	228	270	230	20.2	9.3	24.6	47.5	25.7
4	115	120	116	119	145	131	4.3	0.9	3.5	26.1	13.9
5	589	669	628	609	373	282	13.6	6.6	3.4	-36.7	-52.1
6	452	500	475	524	475	343	10.6	5.1	15.9	5.1	-24.1
Mean	267.3	296.3	280.0	292.2	256.7	216.8	8.6	3.4	8.9	8.2	0.5
SD	202.5	232.7	218.0	218.0	143.9	84.0	7.6	5.1	9.3	28.3	31.7

Pre-training

	DSE										
SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	94	95	96	97	87	114	1.1	2.1	3.2	-7.4	21.3
2	209	234	212	223	303	326	12.0	1.4	6.7	45.0	56.0
3	64	77	75	79	149	101	20.3	17.2	23.4	132.8	57.8
4	521	574	554	603	350	314	10.2	6.3	15.7	-32.8	-39.7
5	243	255	240	230	199	204	4.9	-1.2	-5.3	-18.1	-16.0
6	169	195	192	231	980	434	15.4	13.6	36.7	479.9	156.8
Mean	216.7	238.3	228.2	243.8	344.7	248.8	10.6	6.6	13.4	99.9	39.3
SD	163.7	179.7	172.5	189.0	326.0	131.6	7.0	7.3	15.2	195.7	69.4

Post-training

	DSE										
SUBJECT	BASE	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	101	98	97	101	96	80	-3.0	-4.0	0.0	-5.0	-20.8
2	142	150	144	152	271	262	5.6	1.4	7.0	90.8	84.5
3	70	44	73	78	92	95	-37.1	4.3	11.4	31.4	35.7
4	240	254	240	242	157	251	5.8	0.0	0.8	-34.6	4.6
5	124	123	128	122	127	124	-0.8	3.2	-1.6	2.4	0.0
6	118	134	131	173	301	333	13.6	11.0	46.6	155.1	182.2
Mean	133	134	136	145	174	191	-2.6	2.7	10.7	40.0	47.7
SD	58	70	57	59	90	105	17.9	5.0	18.3	70.6	75.4

Upper Leg Muscle Soreness
Heavy Resistance Exercise

General Soreness – Left Quadriceps

	Pre-training					Post-training				
SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	BEFORE	IMMED	2 HRS	24 HRS	48 HRS
1	0	0	2	7	3	0	0	0	0	3
2	0	0	0	0	0	0	0	0	0	0
3	0	3	3	11	14	0	0	0	0	0
4	0	1	2	7	4	0	6	2	2	1
5	0	0	0	3	3	0	0	0	0	0
6	0	3	3	7	7	0	3	7	6	4
Mean	0.0	1.2	1.7	5.8	5.2	0.0	1.5	1.5	1.3	1.3
SD	0.0	1.5	1.4	3.8	4.9	0.0	2.5	2.8	2.4	1.8

Leg Soreness – Left Quadriceps

	Pre-training					Post-training				
SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	BEFORE	IMMED	2 HRS	24 HRS	48 HRS
1	0	0	2	7	3	0	0	0	0	3
2	0	0	0	4	4	0	0	0	0	0
3	0	7	3	11	14	0	0	0	3	0
4	0	2	3	8	5	0	6	2	2	1
5	0	0	0	11	7	0	0	0	0	0
6	0	7	6	7	7	0	5	9	6	5
Mean	0.0	2.7	2.3	8.0	6.7	0.0	1.8	1.8	1.8	1.5
SD	0.0	3.4	2.3	2.7	3.9	0.0	2.9	3.6	2.4	2.1

Dynamic Strength Exercise

General Soreness – Left Quadriceps

	Pre-training					Post-training				
SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	BEFORE	IMMED	2 HRS	24 HRS	48 HRS
1	0	0	3	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1	0
3	0	3	0	3	3	0	0	0	0	0
4	0	0	0	11	3	0	0	0	0	0
5	0	0	0	0	0	0	0	3	1	2
6	0	0	0	4	2	0	0	0	1	0
Mean	0.0	0.5	0.5	3.0	1.3	0.0	0.0	0.5	0.5	0.3
SD	0.0	1.2	1.2	4.3	1.5	0.0	0.0	1.2	0.5	0.8

Leg Soreness – Left Quadriceps

	Pre-training					Post-training				
SUBJECT	BEFORE	IMMED	2 HRS	24 HRS	48 HRS	BEFORE	IMMED	2 HRS	24 HRS	48 HRS
1	0	0	3	0	0	0	0	0	0	0
2	0	0	0	1	0	0	0	0	1	0
3	0	3	3	7	11	0	0	0	0	0
4	0	0	0	11	3	0	0	0	3	0
5	0	0	0	2	0	0	0	3	1	2
6	0	0	0	6	5	0	0	0	2	0
Mean	0.0	0.5	1.0	4.5	3.2	0.0	0.0	0.5	1.2	0.3
SD	0.0	1.2	1.5	4.2	4.4	0.0	0.0	1.2	1.2	0.8

Potassium

Dynamic Strength Exercise

Pre-Training				% DIFF	
SUBJECT	BASE	0 min	30 min	0 min	30 min
1	4.3	4.2	4.2	-2.3	-2.3
2	4.1	3.8	4.1	-7.3	0.0
3	4.7	4.7	4.7	0.0	0.00
4	4.3	3.8	4.2	-11.6	-2.3
5	4.4	4.1	4.1	-6.8	-6.8
6	4.2	3.8	4.2	-9.5	0.0
Mean	4.3	4.1	4.3	-6.3	-1.9
SD	0.2	0.4	0.2	4.4	2.7

Dynamic Strength Exercise

Post-training				% DIFF	
SUBJECT	BASE	0 min	30 min	0 min	30 min
1	4.2	3.9	4.2	-7.1	0.0
2	4.4	3.7	4.2	-15.9	-4.5
3	4.9	4.3	4.6	-12.2	-6.1
4	4.7	4.3	4.5	-8.5	-4.3
5	4.4	4.1	4.3	-6.8	-2.3
6	4.4	3.8	4.5	-13.6	2.3
Mean	4.5	4.0	4.4	-10.7	-2.5
SD	0.3	0.3	0.2	3.8	3.1

Plasma Volume Changes

Heavy Resistance Exercise

	Pre-training					Post-training				
SUBJECT	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	-8.0	-5.9	-13.4	-10.2	-1.5	-5.4	-4.1	-2.5	0.9	8.4
2	-6.4	-3.1	-1.1	3.7	15.1	-2.3	7.5	3.3	2.1	22.0
3	-15.7	2.3	-0.8	-7.2	-7.2	-24.2	-15.2	-14.0	-14.0	-9.0
4	-2.9	1.5	-6.5	-7.4	-8.6	-3.7	-2.2	-6.9	-0.7	-0.7
5	-15.0	-5.5	-3.8	-7.7	0.4	-9.1	5.3	3.7	-0.5	2.0
6	-3.4	12.6	3.2	5.2	10.9	0.5	10.1	4.9	-5.7	2.7
Mean	-8.6	0.3	-3.7	-3.9	1.5	-7.4	0.2	-1.9	-3.0	4.2
SD	5.6	6.9	5.7	6.6	9.6	8.8	9.3	7.4	6.0	10.4

Dynamic Strength Exercise

	Pre-training					Post-training				
SUBJECT	0 min	30 min	120 min	24 hrs	48 hrs	0 min	30 min	120 min	24 hrs	48 hrs
1	-6.1	3.0	-4.0	-1.4	-2.8	-1.0	-1.3	-6.3	-1.3	-0.7
2	-1.8	-1.8	-0.7	-4.2	6.0	-1.2	16.5	10.1	-2.5	5.0
3	-7.8	2.9	4.8	-0.7	0.1	-3.6	10.7	4.3	5.4	7.2
4	-7.9	-1.1	1.7	-0.2	-3.6	1.3	8.2	0.6	8.0	11.5
5	-5.2	0.5	-4.3	-5.5	-2.2	10.2	4.3	9.3	8.3	7.9
6	-13.4	-2.9	-2.3	10.7	-0.9	-4.5	3.2	-2.1	-8.1	-6.6
Mean	-7.0	0.1	-0.8	-0.2	-0.6	0.2	6.9	2.7	1.6	4.0
SD	3.8	2.5	3.5	5.8	3.5	5.3	6.3	6.5	6.6	6.6

RPE

Heavy Resistance Exercise

	Pre-training					Post-training				
SUBJECT	SET 1	SET 2	SET 3	SET 4	SET 5	SET 1	SET 2	SET 3	SET 4	SET 5
1	13	14	15	15	15	13	13	15	15	15
2	13	15	16	17	18	10	11	11	11	11
3	13	14	15	16	18	12	12	12	13	14
4	12	15	16	17	17	13	13	14	15	15
5	13	15	17	17	18	12	13	13	14	15
6	15	18	18	19	20	13	15	16	16	17
Mean	13.2	15.2	16.2	16.8	17.7	12.2	12.8	13.5	14.0	14.5
SD	1.0	1.5	1.2	1.3	1.6	1.17	1.33	1.87	1.79	1.97

Dynamic Strength Exercise

	Pre-training						Post-training				
SUBJECT	SET 1	SET 2	SET 3	SET 4	SET 5	SUBJECT	SET 1	SET 2	SET 3	SET 4	SET 5
1	12	12	13	13	13	1	11	11	12	12	12
2	9	9	10	10	11	2	8	9	9	10	10
3	14	14	13	14	13	3	10	11	10	11	12
4	16	16	16	17	18	4	11	11	12	12	13
5	6	8	10	11	13	5	9	11	11	11	11
6	15	16	15	17	16	6	10	12	13	13	15
Mean	12.0	12.5	12.8	13.7	14.0	mean	9.8	10.8	11.2	11.5	12.2
SD	3.8	3.4	2.5	2.9	2.5	SD	1.17	0.98	1.47	1.05	1.72