DOCTOR OF PHILOSOPHY

Symptoms of exercise-induced muscle damage in boys and men following eccentric exercise

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Award date:
2003

Awarding institution:
Bangor University

SYMPTOMS OF EXERCISE-INDUCED MUSCLE DAMAGE IN BOYS AND MEN FOLLOWING ECCENTRIC EXERCISE

PhD THESIS

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CONTENTS

Acknowledgements

I would like to express my sincere thanks to a number people for their help, support and patients.

Firstly I would like to thank my supervisor, Professor Roger Eston, you have been a true friend as well as first class mentor. There are few supervisors who would lose their shirt without complaint!! To Dr Gaynor Parfitt, thank you for your good humour and patience, both you and Roger were excellent at putting the pieces back together when things went wrong. You were my friend as well as my thesis chair, even though I never sat on you!

Secondly I would like to thank my friends, Pat, Sarah, Vanessa and Sam for listening to my anxieties and ideas. A very special thanks to Dr Ann Rowlands and my office mate, Dr Elaine Rose for always being there, you kept me sane and your honesty while, not always wanted, was very much appreciated. I consider you two of my best friends.

Additionally I would like say thank you to the people who took part in my studies, who in the case of the men, suffered a lot in the name of science.

Last but not least, I would like to thank my husband Andy and my parents who were always there for both the good and bad times, thank you for your love and support.

SUMMARY

Painful muscles are a familiar sensation following unaccustomed exercise. While this phenomenon is well documented in adults, research on delayed-onset muscle soreness and exercise-induced muscle damage (EIMD) in children is limited. It is well documented that a prior bout of eccentric exercise attenuates symptoms of exercise-induced muscle damage following a second bout of damaging exercise. This is commonly known as the repeated bout effect. However, there is no research on the repeated bout effect in children. This thesis comprises of four studies on the symptoms of exercise-induced muscle damage in boys and men.

Study 1

The first study compared the relationship between soreness and isometric strength in boys and men and also explored the face validity of a visual analogue scale (VAS) to assess muscle soreness in children. Following a high and a low repetition hopping protocol, strength decrements were lower than baseline at all time points after exercise ($P< 0.01$) and there were no differences between groups. Men reported higher levels of soreness, (1.8 cf. 0.75). In boys soreness was higher than baseline at all time points after the high repetition protocol and only at 24 and 48 h after the low repetition protocol. Soreness in men was higher than baseline at all time points after the high repetition protocol only. Differences in soreness between the high and low repetition protocols provided support for the face validity of the VAS. Although strength loss was similar in both groups, soreness was lower in boys following the high repetition protocol.

Study 2

The second study investigated differences in the torque-joint angle relationship of the quadriceps muscle in children and adults on an isokinetic dynamometer. Data were expressed as a percentage of peak torque (relative torque). Both groups demonstrated an expected increase in relative torque as the joint angle increased ($P<0.05$). Men produced higher relative torque at 20°; 40° and 60 ° knee flexion. Peak torque was attained at 80° in men and decreased significantly ($P<0.05$) at 90° and 100°. For boys, peak torque was attained at joint angles of 80° and 90°. There were no group differences at 80° and 90°. The reduction in peak torque at 100° was not significant, but the relative torque at this angle was lower in men compared to boys (77.9 $\pm$ 13.7 cf. 87.1 $\pm$ 10.4%; P <.0.05). It was concluded that the torque-joint angle relationship appears to be different in children

Study 3

The third study investigated the severity of the symptoms of EIMD in boys and men after unaccustomed exercise. Following eighty plyometric jumps, children experienced less soreness (0.8 cf. 3.6) ($P< 0.05$), less overall strength loss (expressed as a percentage of baseline values)(2.0 cf. 15.9%) ($P<0.05$) and lower decrements in jump height (expressed as a percentage of baseline values)(3.8 cf. 10.3%) ($P<0.05$). Average power output during the plyometric protocol (adjusted for lean thigh volume) was higher in adults. These findings may be explained by the lower power output per lean leg volume in boys during the plyometric jumps, suggesting a possible lower strain per unit muscle area. A further factor which may account for less severe symptoms of EIMD in boys may be the higher muscle compliance in boys as indicated by greater hip extension values (38° c.f. 23.8°).

Study 4

The fourth study investigated the repeated bout effect in children and adults. Following two bouts of eighty plyometric jumps, both groups experienced less soreness following bout two, compared to the first bout, although boys experienced less soreness than men after both bouts of exercise. Soreness in boys recovered faster following both bouts ($P<0.05$). There was a repeated bout effect for men only for the percentage of maximal squat jump height (%SJ) ($P<0.05$). However, a repeated bout effect was observed for both groups for the percentage of maximal counter movement jump ($P<0.05$)(%CMJ). Boys experienced less of a decline in %CMJ and %SJ following both bouts of exercise ($P<0.05$). There was a repeated bout effect for strength in men only. Strength was higher in boys after both bouts ($P<0.05$). The findings confirmed that the severity of the symptoms of EIMD is lower in boys and that a prior bout of plyometric exercise attenuates all symptoms of EIMD in men. In boys, a repeated bout effect was observed for soreness and %CMJ height.

CHAPTER 1

INTRODUCTION

1.1 Exercise - Induced Muscle Damage

1.2 Markers of Exercise - Induced Muscle Damage

- **1.2.1 Direct and Indirect Markers**
- **1.2.2 Ultrastructural Changes**
- **1.2.3 Strength Loss**
- **1.2.4 Delayed-onset Muscle Soreness and Tenderness**
- **1.2.5 Muscle Stiffness and Swelling**
- **1.2.6 Muscle Protein Release**
- **1.2.7 Summary of Markers of Exercise - Induced Muscle Damage**

1.1 Exercise - Induced Muscle Damage

Sore, aching muscles are a familiar sensation for most adults following unaccustomed exercise, or an increase in training intensity. This phenomenon is known as exercise-induced muscle damage (EIMD) (Armstrong, 1984; Cleak and Eston, 1992; Clarkson and Newham, 1995; Byrne and Eston, 1998; Morgan and Allen, 1999; Proske and Morgan 2001). Exercise that involves high frequencies of eccentric contractions, where the muscle lengthens (e.g. walking down stairs, jumping, lowering a weight) is associated with greater levels of EIMD in comparison to concentric muscle actions, where the muscle shortens (e.g. climbing stairs, pushing off the side of a swimming pool, lifting a weight) (Newham et al., 1983a,b; Tesch et al., 1990; Fitzgerald et al., 1991; Gleeson et al., 1995; McHugh et al., 2000; 2001). Both concentric and eccentric muscle actions are an integral part of everyday life and sporting activities.

1.2 Markers of Exercise – Induced Muscle Damage

1.2.1 Direct and indirect markers

In the research setting, the severity of EIMD is commonly quantified by direct or indirect markers. Direct quantification is achieved via histological verification following a muscle biopsy, to assess the ultrastructural changes, and is considered the gold standard (Jones and Round, 1990; Salmons, 1997). Indirect quantification is achieved via the variety of symptoms associated with muscle damage in the days that follow. These symptoms include: strength loss; delayed-onset muscle soreness; tenderness; stiffness; swelling; increased protein release (Armstrong, 1984; Ebbeling and Clarkson, 1989; Clarkson et al., 1992; Warren et al., 1999).

1.2.2 Ultrastructural Changes

Ultrastructural changes have been observed following needle biopsy in the days that follow eccentric exercise (Newham et al., 1983a; Jones et al., 1986, 1997; Lieber and Friden, 1988; Friden and Lieber, 1992; Talbot and Morgan, 1996). Histological changes are not consistent throughout the muscle fibre. Focal points of damage are observed, with damage increasing over the days that follow (Meltzer et al., 1976; Newham et al., 1983a; Armstrong, 1984; Friden and Lieber, 1992). Characteristic changes include Z-line streaming, and broadening, where the Z-line becomes disrupted and is said to "stream" across the sarcomere (figure 2.1, chapter 2, p 16), A-band disruption, misalignment and occasionally complete break down of myofibrils (Ebbeling and Clarkson, 1989; Newham et al., 1983a; Jones et al., 1986, 1997). Disruption seems to increase over the days that follow, with minimal changes observed in the first few days (Ebbeling and Clarkson 1989; Jones et al., 1986). For example, Newham et al. (1983a) reported that immediately following eccentric exercise, 16% of the total number of fibres showed focal changes, 16% showed extensive changes and 8% showed very extensive changes. The proportion of extensive and very extensive changes had increased to 23% and 28% respectively 30 hours later. Additional findings provided by Talbot and Morgan, (1996) and Jones et al. (1997) have demonstrated that the actin and myosin filaments in damaged muscle appear pulled apart. This can involve the whole sarcomere or half the sarcomere with the adjacent undamaged whole or half sarcomeres appearing to shorten. Greater ultrastructural changes have been observed in older participants of both genders following eccentric exercise, in comparison to younger participants (Manfredi et al., 1991; Roth et al., 2000). However, one is forced to assume that the sample of muscle tissue obtained in the biopsy is representative of the whole muscle. Problems with damage occurring as a result of the biopsy procedure itself should be considered when interpreting data (Malm, 2001).

1.2.3 Strength Loss

Maximal voluntary isometric contractions are commonly used as an indicator of muscle damage (Ebbeling and Clarkson, 1990; Cleak and Eston, 1992; Warren, 1999). An immediate and prolonged reduction in strength is observed following eccentric exercise (Child et al., 1998; McHugh et al., 1999; Byrne et al., 2001; Nosaka et al., 2001; Byrne and Eston, 2002a and b). The muscle feels weak directly following exercise when strength loss is at its greatest. Recovery can take up to 7-12 days (Ebbeling and Clarkson, 1989; Clarkson et al., 1992; Jones and Round, 1990; Child et al., 1998; McHugh et al., 1999; Byrne et al., 2001; Nosaka and Sakamoto, 2001; Byrne and Eston, 2002 a,b).

Ultrasructural changes appear to be unrelated to decrements in strength. As indicated above, strength loss is at it greatest immediately following damaging exercise, while histological changes are minimal and increase over the days that follow (Newham et al., 1983a; Jones et al., 1986). Strength shows a progressive recovery while the ultrastructural changes increase in severity and the affected fibres break down and regenerate. It has also been suggested that pain may inhibit muscle performance (Armstrong, 1984; Clarkson et al., 1992). However, there is no pain evident when strength loss is at its greatest (immediately after exercise). Pain is not usually noticeable until approximately eight hours after exercise, peaking at 24-48 hours (Jones and Round, 1990), which suggests little or no relationship.

1.2.4 Delayed-onset Muscle Soreness and Tenderness

Delayed-onset muscle soreness is the most commonly used marker of muscle damage (Warren et al., 1999) and can be evaluated via objective and subjective means. Objective measures have been achieved via a strain gauge algometer (Edwards et al., 1996; Baker et al., 1997). This measure is known as tenderness, and is defined as pain or discomfort upon palpation (Jones and Round, 1990). Tenderness is greatest towards the distal portion or myotendous junction of the muscle (Armstrong, 1984; Baker et al., 1997). Subjective measures of soreness are achieved via use of a visual analog scale (Liggins and Dip, 1982; Neely et al., 1992; O'Connor and Cook, 1999; Warren et al., 1999) and are often defined as pain upon movement of the affected muscle or muscle group (Jones and Round, 1990).

Both soreness and tenderness become evident approximately eight hours after the cessation of exercise and peak 24-28 hours after exercise and recover within seven days (Armstrong, 1984; Jones et al., 1986; 1987; Cleak and Eston, 1991; Child et al., 1998; McHugh et al., 1999; Nosaka and Sakamoto, 2001).

Although the delay in the appearance of soreness is poorly understood, inflammation and additional pressure from swelling are considered to be likely candidates (Stauber et al., 1990; Clarkson et al., 1992; Clarkson and Newham, 1995). Releases of substances such as bradykinin, histamines and prostaglandins from the break down of muscle fibres are thought to sensitize pain receptors (Proske and Morgan, 2001).

1.2.5 Muscle Stiffness and Swelling

Swelling and stiffness is a common sensation following muscle damage and is normally evaluated in the forearm flexors. Swelling is commonly assessed via arm circumference and it tends to peak 4-5 days after exercise and recovers within 10 days (Clarkson et al., 1992; Saxton and Donnelly, 1996; Jones et al., 1987; Eston and Peters, 1999; Nosaka and Sakamoto, 2001; Nosaka et al., 2001; Gleeson et al, 2002). Following muscle damage, changes in both passive (relaxed arm angle) and active (flexed arm angle) range of motion are observed (Clarkson and Tremblay, 1988; Donnelly et al., 1992; Saxton and Donnelly, 1996; Nosaka and Clarkson, 1995; Jones et al., 1987; Eston and Peters, 1999; Nosaka and Sakamoto, 2001; Nosaka et al., 2001; Nosaka and Newton, 2002; Gleeson et al, 2003). Changes in passive or relaxed arm angle are evident immediately after exercise and tend to peak 3-4 days after damage has been incurred. Changes in active or flexed arm angle are greatest immediately after exercise and recover within 5 days.

Spontaneous shortening of the muscle (changes in relaxed arm angle) has been suggested to occur as a result of a shortening in the connective tissues and calcium efflux (Clarkson et al., 1992). However, the absence of EMG activity (Jones et al., 1987) suggests that calcium efflux plays little to no part in the spontaneous shortening of the muscle. Jones et al. (1987) suggested that the similar time course of changes in flexed arm angle and strength loss could be a result of a shortening of adjacent, undamaged sarcomeres, which are pulled apart and become non-functional. This limits strength via a reduction in the number of available cross bridges in the damaged non functional sarcomeres (Gordon et al., 1966b; Morgan et al., 1991). Furthermore, an increase in pressure from Z-lines causes deformation of the actin and myosin cross-bridges (Gordon et al., 1966b; Rassier et al., 1999) and as a result, the remaining functional adjacent, undamaged sarcomeres become temporarily shorter. This effects the force-length characteristics of the muscle (torque-joint angle relationship) by increasing the length at which a given force can be exerted. This theory (the popping sarcomere theory) will be discussed in full in chapter 2.

1.2.6 Muscle Protein Release

Release of muscle proteins and enzymes are frequently observed following muscle damage (Clarkson and Newham, 1995; Ebbeling and Clarkson, 1987; Warren et al., 1999). The most commonly measured variable is creatine kinase (CK), but others include myoglobin, lactate dehydrogenase, myosin heavy chains and glutaminic oxaloacetic transaminase (Clarkson and Tremblay, 1988; Nosaka and Clarkson, 1995; Warren et al., 1999). Measures of CK are thought to represent both the release into and clearance out of the circulation and are found exclusively in cardiac and skeletal muscle (Hortobagyi and Denahan, 1989; Clarkson and Newham, 1995; Warren et al., 1999). Males tend to have higher resting levels of CK (Hortobagyi and Denahan, 1989; Kendall and Eston, 2002) and adults have higher values than children (Webber et al., 1989; Soares et al., 1996).

The temporal pattern of CK differs depending on the muscle group that has been damaged. Following muscle damage there is typically a delay before CK is released with peak values being observed 1-3 days after damaging exercise (downhill running and squatting with weights) in the quadriceps muscle (Webber et al., 1989; Thompson et al., 1998; Byrne et al., 2001; Byrne and Eston, 2002a, b). In contrast, CK values peak 4-7 days following damage to the elbow flexors (Nosaka and Clarkson, 1997; Linnama et al., 2000; Nosaka and Sakamoto, 2001). The variability of CK measures between subjects has been highlighted as being problematic (Hortobagyi and Denahan, 1989; Warren et al., 1999). This led Warren and co-workers to call for more functional measures following EIMD, as they were considered to be more reliable by these investigators.

1.2.7 Summary of Markers of Exercise – Induced Muscle Damage

In summary, the extent of EIMD is assessed via a number of direct and indirect markers. The most common evaluation of EIMD is achieved via the measurement of the indirect markers listed above. The subjective nature of soreness and the large variability of CK measures, have led Warren et al. (1999) to recommend the use of more functional measures in order to evaluate the severity of muscle damage. Additionally, the majority of research on EIMD has been conducted on adults. There is limited, but equivocal data on EIMD in children. The symptoms of EIMD following high intensity, eccentric exercise, in children and adults will be the focus of this thesis. The first study compared muscle soreness and strength loss in boys and men following eccentric exercise. Study two evaluated differences in the torque-joint angle relationship in the quadriceps muscle in boys and men. Study three evaluated symptoms of EIMD in boys and men. The last study examined the repeated bout protective effect in boys and men.

CHAPTER 2

REVIEW OF LITERATURE

2.7 Summary

2.1 Exercise - Induced Muscle Damage in Children

Sore, stiff muscles are a familiar sensation following unaccustomed exercise. While this phenomenon is well documented in adults, research on delayed-onset muscle soreness (DOMS) and exercise-induced muscle damage in children is sparse and equivocal. Only three studies have focused on symptoms of EIMD in the paediatric population (Webber et al., 1989; Soares et al., 1996; Duarte et al., 1999). Webber et al. (1989) observed no significant difference in soreness and serum creatine kinase (CK) activity, using weight as the covariate, in children (girls and boys, aged 10 years) and adults (men and women, aged 27 years). This suggested that the severity of EIMD was similar in children and adults following a downhill running protocol. In a later study, Soares et al. (1996) reported that children (boys aged 12 years) appeared to suffer less damage compared to adults (men aged 18 years), following a weight training protocol, based on measurements of soreness, CK and isometric strength. More recently, Duarte et al. (1999) reported that symptoms of EIMD were greater in children (boys aged 13 years) when the duration of the eccentric contraction was doubled, in a stepping protocol. No adult group was included in that study for comparison. Therefore, one study suggests that symptoms of EIMD are similar in adults and children, one study suggests that children experience fewer symptoms of EIMD. The third study did not include an adult group for comparison. The above studies did not offer any explanation as to why children should or should not experience similar symptoms of EIMD. This thesis will focus on symptoms of EIMD in children and adults and offer theoretical explanations for differences between the groups

2.2 Mechanical Factors Associated with Exercise - Induced Muscle Damage

2.1.1 *Force*

The ability of the muscle to produce significantly higher forces during eccentric contractions relative to concentric and isometric contractions has been suggested as an explanatory mechanism for the consistent observation that eccentric exercise results in greater EIMD (Newham et al., 1983 a,b; Tesch et al., 1990; Styf et al., 1995; Kellis and Baltzopoulos, 1998). As the muscle lengthens, cross-bridges detach mechanically, making the muscle action metabolically more economic. The force generating capacity of the muscle during an eccentric contraction has been reported to be up to 70% greater than an isometric contraction (Warren et al, 2000). Additionally, lower EMG amplitudes have been consistently reported (Tesch et al., 1990; Kellis and Baltzopoulos, 1998; McHugh et al., 2000, 2001, 2002; Warren et al., 2000). Tesch et al. (1990) reported the EMG/force ratio during an eccentric muscle action to be five times higher than that of concentric muscle action. Cumulatively, this would result in greater mechanical strain and a higher force per fibre during eccentric muscle actions, possible leading to greater EIMD.

2.1.2 Popping Sarcomere Theory

It has been proposed that during a bout of damaging eccentric exercise, weaker sarcomeres become overextended as the muscle lengthens (Morgan 1990). Failure of overextended full, or half sarcomeres to reinterdigitate causes the affected sarcomeres to become non-functional. As the exercise continues, other weaker sarcomeres become overextended. One of the consequences of EIMD is a change in the joint angle at which peak torque occurs. After EIMD, peak torque often occurs at longer muscle lengths, which results in a shift of the torque joint-angle curve to the right (Wood et al., 1993; Morgan 1990; Morgan and Allen, 1999). The greatest decrement in force tends to occur at short muscle lengths following eccentric exercise (Saxton and Donnelly, 1995; 1996; Jones et al., 1997; Bryne et al., 2000). This has been attributed to the possible shortening of the undamaged sarcomeres that are adjacent to overextended sarcomeres that have failed to reinterdigitate.

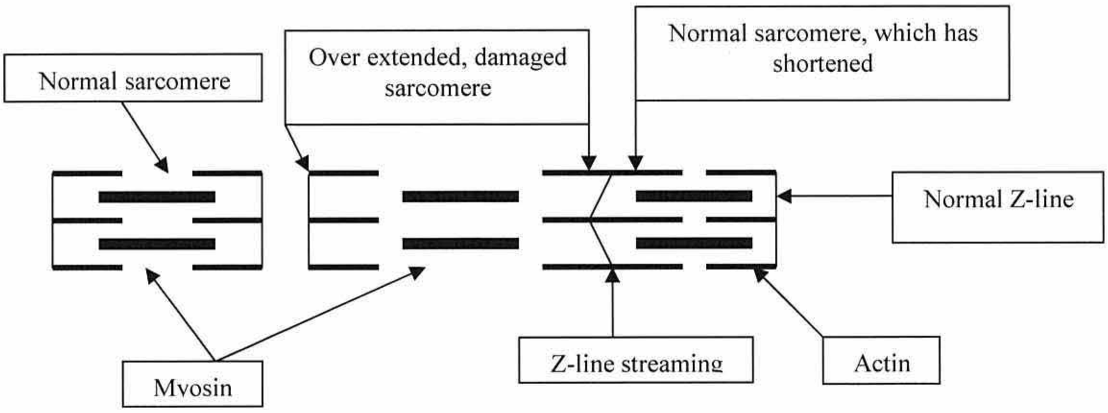


Figure 2.1: Diagram of Morgan's (1990) popping sarcomere theory

2.1.3 *The Role of Muscle Length*

Muscle length is known to play an important role in the amount of EIMD incurred during exercise (Newham., et al 1988; Wood et al., 1993; Talbot and Morgan 1996; Child et al., 1998; Nosaka and Sakamoto, 2001) and the amount of strength loss following EIMD (Saxton and Donnelly, 1995, 1996; Jones et al., 1997; Byrne et al., 2001).

The observed increase in EIMD following exercise at longer muscle lengths supports Morgan's (1990) prediction than when the muscle functions at lengths which correspond to the descending portion of the length-tension curve (longer lengths), a greater number of weaker sarcomeres throughout the muscle will be uncontrollably over extended.

The disproportionate decrease in strength is frequently observed at shorter muscle lengths following EIMD (Saxton and Donnelly, 1995, 1996; Jones et al., 1997; Byrne et al., 2001) is consistent with Morgan's (1990) popping sarcomere theory. Following EIMD, shortening of undamaged sarcomeres, which are adjacent to overextended, non-functional sarcomeres, results in an increase in compliance and a rightward shift of the torque-joint angle relationship towards longer muscle lengths (Morgan and Allan, 1999; Proske and Morgan, 2001). That is to say, if the functional sarcomeres are shorter, than there will be an increase in resistance from Z-lines causing greater deformation of the actin and myosin filaments and a possible increase in osmotic pressure (Gordon *et al.*, 1966b; Rassier *et al.*, 1999) as well as an overall decrease in the number of functional cross-bridges (Gordon et al., 1966b; Morgan *et al.*, 1991). The functional outcome is a disproportionate decrease in strength at short muscle lengths.

2.1.3 The Role of Muscle Compliance

In this thesis the term muscle compliance is taken in the context of greater levels of give or stretch in the muscle i.e. lower stiffness. Griffiths (1991) reported that the tendon in cat gastrocnemius muscle stretched as muscle fibres shortened, until the force generated by the muscle fibres could no longer stretch the tendon. The unload characteristics (when force is removed) of the muscle, demonstrated a recoiling of the tendon with little change in fibre length at first, followed by a slow stretch of the muscle fibre.

McHugh et al. (1999) observed greater symptoms of EIMD in subjects with stiffer hamstring muscles. They postulated that there might be a greater elongation in the aponeurosis in a more compliant musculotendinous unit during eccentric exercise, which provides a mechanism by which less sarcomere overextension occurs. In other words there would be a greater amount of stretch in the non-contractile component of the muscle. Thus, theoretically, a greater number of sarcomeres would function at lengths corresponding to the ascending portion of the torque-joint angle curve, which is associated with less sarcomere overextension (Morgan, 1990; Morgan and Allan, 1999).

It is well documented that flexibility, which is correlated with muscle stiffness (Gleim & McHugh, 1997), decreases with age (Alter, 1996). Therefore, if children have greater muscle compliance, the mechanisms postulated by McHugh et al., (1999) would suggest that children would suffer less severe symptoms of EIMD. Additionally, a greater lengthening of the tendon and aponeurosis (series elastic component) would require a greater shortening of the contractile component of the muscle to accommodate the stretch in the series-elastic component. This might manifest itself in a rightward shift of the torque-joint angle relationship towards longer muscle lengths in children. It has been suggested that greater stiffness is more favorable for the translation of force from the muscle to the bone (Wilson et al., 1994; Walshe et al., 1996; Kawakami & Lieber, 2000).

2.3 Neural Factors Associated with Exercise - Induced Muscle Damage

2.3.1 Selective Damage to Type II Muscle Fibres

Studies on ultrastructural changes of the muscle following eccentric exercise have reported that disruption is more prevalent in the fast twitch muscle fibre (Friden, 1984; Jones et al., 1986; Leiber and Friden, 1988, 1992). Friden (1984) reported a ratio of 4:1 of damage to the fast twitch fibre. Decreases in EMG median frequency following eccentric exercise have been taken to indicate preferential damage to fast twitch fibres (Linnamo et al., 2000). Byrne et al. (2002b) also concluded that decreases in power output and fatigue following EIMD could be explained by damage to fast twitch fibres. Higher EMG median frequencies during sub-maximal eccentric muscle actions also provide evidence of selective recruitment of fast twitch fibres (McHugh et al., 2000, 2001, 2002) and thus explain the greater incidence of disruption to this fibre type following EIMD. However, these findings have not been confirmed during maximal eccentric contractions (Tesch et al., 1990; Komi et al., 2000).

2.3.2 Proportion of Type II Muscle Fibres in Children

Children have a lower proportion of fast twitch fibres, which increase to adult proportions during adolescence (Bell et al., 1989; Armstrong and Welsman, 1996). As indicated above, EIMD is more prevalent in fast twitch fibres (Friden and Leiber, 1988; 1992; Jones et al., 1996; Byrne and Eston, 2002b). Therefore, if children are less able to recruit fast twitch fibres during exercise, which are known to be more susceptible to damage, symptoms of EIMD in children would be expected to be fewer than those reported by adults.

2.4 Functional Markers of Exercise - Induced Muscle Damage

2.4.1 Isometric Strength

As indicated in chapter 1, isometric strength is commonly used as an indicator of muscle damage and is considered to be a more reliable marker when compared to soreness and CK (Warren et al., 1999). An immediate and prolonged reduction in strength is observed following eccentric exercise (Child et al., 1998; McHugh et al., 1999; Byrne et al., 2001; Nosaka and Sakamoto, 2001; Byrne and Eston, 2002a, b) with recovery occurring by 7-12 days (Ebbeling and Clarkson, 1989; Clarkson et al., 1992; Jones and Round, 1990; Child et al., 1998; McHugh et al., 1999; Byrne et al., 2001; Nosaka and Sakamoto, 2001; Byrne and Eston, 2002 a, b).

2.4.2 Explosive Strength

Recently, research on the effect of EIMD on explosive strength measures, such as jump height, has been conducted in adults (Mair et al., 1995; Chambers et al., 1998; Horita et al., 1999; Byrne and Eston, 2002a). The evaluation of jump height provides a convenient model in which to study jump parameters with and without the use of the stretch shortening cycle. This type of muscle action, where an eccentric muscle action precedes a concentric muscle action is frequently observed in the sporting context (Horita et al., 1999) and could be considerd a more ecologically valid variable to study following EIMD. The enhanced muscle performance, which follows an eccentric muscle action, has been consistently demonstrated (Komi, 1984; Finni et al., 2000) and is thought to result from a mixture of elastic strain energy (Cavagna et al., 1965; 1968; Cavagna, 1970; Anderson and Pandy, 1993; Finni et al., 2000) and neural reflexes (Bobbert et al., 1986;Walshe et al., 1998; Bobbert and Zandwijk, 1999; Bosco, 1999;

Komi et al., 2000). Comparison of squat jump versus counter movement jump might provide valuable insight into the amount of damage incurred within the contractile (sarcomere) or non-contractile component of the muscle (series and parallel elastic component). This also has implications for sporting activities that are reliant upon use of the stretch-shortening cycle.

2.4.3 Motor Control

A recent growing area of interest is the effect that EIMD has on the dysfunction of the motor control system (Saxton et al., 1995; Brocket et al., 1997; Pearce et al., 1998; Leger, 2001). The majority of research has focused on the elbow flexors (Saxton et al., 1995; Brocket et al., 1997; Pearce et al., 1998) and wrist (Leger and Milner, 2001). The effects of EIMD include impairment in position sense (Saxton et al., 1995), force-matching tasks, where subjects consistently undershot the target value (Brocket et al., 1997; Leger and Milner, 2001), increased tremor (Saxton et al., 1995), and increased error during a tracking task (Pearce et al., 1998; Leger and Milner, 2001). Brocket et al. (1997) observed that participants tended to hold their arm in more extended position, suggesting a perception that the muscle was shorter. These authors postulated that disruption to the muscle receptors, muscle spindles and golgi tendon organs could be responsible for impaired motor function.

2.4.4 Functional Markers of Exercise - Induced Muscle Damage in Children

Of the three studies on EIMD in children, two included measures of isometric strength (Soares et al., 1996; Duarte et al., 1998). No measures of explosive strength have been investigated in children following eccentric exercise. Exercise that includes the use of the stretch shortening cycle (e.g. jumping, hopping) is probably a more ecologically valid activity for children, being a fundamental characteristic of children's play activities.

2.5 The Repeated Bout Effect

2.5.1 Direct and Indirect Markers of Exercise - Induced Muscle Damage Following a Repeated Bout

Following a prior bout of EIMD all markers of damage are dramatically reduced. Histological evidence obtained from an electron microscope, has demonstrated that reductions in damage can be as much as 16-45% (Friden et al., 1993; Hortobagyi et al., 1998). Similarly, indirect markers of EIMD (soreness, strength, stiffness, swelling and CK) have been observed to be significantly less severe and recover faster following a prior bout of eccentric exercise (Armstrong 1983; Ebbeling and Clarkson, 1989; Morgan, 1990; Clarkson and Nosaka, 1992; McHugh et al., 1999; Proske and Morgan 2001). This phenomenon is commonly referred to as 'the repeated bout effect' and is attained even if the symptoms associated with EIMD after the first bout are mild (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethy, 2001). The repeated bout effect has been reported to last between 6-10 weeks (Byrnes et al, 1985; Nosaka et al., 1991) and up to 6 months for creatine kinase following damage to the elbow flexor muscles (Nosaka et al., 2001), but not in the quadriceps muscles (Lun et al., 1998). The repeated bout effect has been explained by a number of theories, which include neural, cellular and mechanical changes within the muscle (McHugh et al., 1999), which are described in more detail in the following section.

2.5.2 The Repeated Bout Effect in Children

While the repeated bout effect is well documented in adults, there is no research on this phenomenon in children. It is therefore unknown if children's muscle adapts following a prior bout of eccentric exercise. It is anticipated that this will be the case as, mild symptoms associated with EIMD observed in adults have resulted in a repeated bout effect (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethly, 2001).

2.6 Mechanism of the Repeated Bout Effect

2.6.1 Neural Theory

A number of studies have discussed the possibility of a neural adaptation in order to explain the repeated bout effect. This theory suggests a change in the recruitment and or an increases the synchronization of firing neurons (Pierrynowski et al., 1987; Hortobagyi et al., 1998; Warren et al., 2000; Nosaka et al., 2001). Changes in the neural firing pattern may distribute the work-load more effectively among fibres reducing myofibrillar strain (Nosaka and Clarkson, 1995; Nosaka et al., 2001). Pierrynowski et al. (1987) was one of the first studies to suggest that the repeated bout effect resulted from a motor learning effect where the neurons would fire faster and be more synchronised. Warren et al. (1999) observed a lower EMG median frequency during a second bout of eccentric exercise. This lead them to suggest that greater reliance of slow twitch motor units could be responsible for less EIMD following a second bout of eccentric exercise. However, McHugh et al. (2001) tested this theory and reported no increase in the synchrony of motor units or a shift towards a greater recruitment of slow twitch motor units. Further study is needed in this area.

2.6.2 Mechanical Theory

Newham et al. (1987) attributed pain and stiffness to shortening of the non-contractile component (connective tissue) following eccentric exercise. They suggested that adaptation of connective tissue might be a possible mechanism for a reduction in pain and stiffness following a second bout of damaging exercise. However, there is little to no supporting evidence to support this theory.

2.6.3 Cellular Theory

Cellular adaptations include removal of weaker sarcomeres (Armstrong et al., 1983; Newham et al., 1987; Foley et al., 1999) and/or an increase in strength of the sarcolemma (Ebbeling and Clarkson, 1989) and the longitudinal addition of sarcomeres (Friden et al., 1983; Lynn and Morgan, 1994; Lynn et al., 1998; Proske and Morgan, 2001; Brockett et al., 2001).

The removal of stress-susceptible sarcomeres has been supported by the lack of additional EIMD when additional eccentric exercise is performed before recovery has accrued (Ebbeling and Clarkson 1989; Newham et al., 1987; Mair et al., 1994; Smith et al., 1994; Nosaka and Clarkson, 1995; Chen and Hsien, 2000; Paddon-Jones et al., 2000). However, this theory is limited by the fact that mild symptoms of EIMD also result in a repeated bout effect (Schwane and Armstrong 1983; Clarkson and Tremblay, 1988; Brown et al., 1997; Paddon-Jones et al., 2001; McHugh et al., 1999). Clarkson and Tremblay, (1988) suggested that an adaptation where there is an increase in the strength of the cell membrane which might result in reduction in calcium efflux and subsequent cell necrosis. However, this is a very difficult hypothesis to test.

One of the more popular hypotheses is the addition of sarcomeres (Friden et al., 1983; Lynn and Morgan, 1994; Lynn et al., 1998; Proske and Morgan, 2001; Brockett et al., 2001). Friden et al. (1983) observed a longitudinal increase in the number of sarcomeres following EIMD in rats. Later, Morgan (1990) suggested that the addition of sarcomeres would result in a greater number of sarcomeres functioning at lengths that correspond to the ascending portion of the torque-joint angle relationship. Thus for any given joint angle sarcomeres will be shorter. Similarly, the longitudinal addition of sarcomeres has been observed in rats following downhill running (Lynn and Morgan, 1994; Lynn et al., 1998) with decreases in sarcomere numbers also reported following uphill running. Greater symptoms of EIMD have been reported for humans following a concentric training programme. This is postulated to be due to a reduction in sarcomere numbers (Whitehead et al., 1998; Ploutz-Snyder et al., 1998; Gleeson et al., 2002). The most compelling evidence in support of this theory has been provided by Brockett et al. (2001), who reported a prolonged rightward shift of the torque-joint angle relationship in the hamstring following EIMD, which would result in the muscle functioning on the ascending portion of the length-tension curve where less EIMD is thought to occur.

2.7 Research Implications

At present, the research on EIMD in children is limited and equivocal. Additionally, it is unknown if children's muscles adapt in a similar way to adults following a prior bout of eccentric exercise. Greater muscle compliance and a lower proportion of fast twitch muscle fibres in children (Bell et al., 1989; Armstrong and Welsman, 1996), where EIMD is more prevalent (Friden and Leiber, 1988; 1992; Jones et al., 1996; Byrne and Eston, 2002b), provide a good theoretical basis for lower EIMD in children. As

Soares et al. (1996) pointed out there is anecdotal evidence to suggest that children suffer less muscle soreness following unaccustomed exercise.

Recent research has included additional measures of muscle function in the form of jump height in adults (Mair et al., 1995; Chambers et al., 1998; Horita et al., 1999; Byrne and Eston, 2002a) in answer to the call made by Warren et al. (1999) to conduct more studies to evaluate the impact of EIMD on performance variables. However, previous studies on EIMD in children (Webber et al., 1989; Soares et al., 1996; Duarte et al., 1999) have not included measures of jump height following eccentric exercise. Jump height might be a more ecologically valid variable to measure following EIMD, in both adults and children, as the stretch shortening cycle is an integral part of both sporting and play activities.

The following sections comprise four studies which explore the phenomenon of eccentric exercise-induced muscle damage in children.

CHAPTER 3

A comparison between soreness and isometric strength loss in boys and men following eccentric exercise.

Data from this study were presented at North American Society for Pediatric Exercise Medicine, Aspen, Colorado, August, 2000 and published as an abstract:

Marginson, V.F., Eston, R.G. and Parfitt, C.G. (2001) The relationship between soreness and muscle function in children and adults following eccentric exercise. *Pediatric Exercise Science*, 13, 89P

3.1 ABSTRACT

Delayed onset muscle soreness (DOMS) after a bout of eccentric or unaccustomed exercise is a well-documented phenomenon in adults. However, research on DOMS in children is limited. The aim of this study was to investigate the utility of an illustrated visual analogue scale (VAS) to measure DOMS and to compare the relationship between DOMS and isometric strength in children and adults after eccentric exercise. Ten boys, aged 8-11 y and ten men, aged 20-44 y performed two hopping protocols: a high repetition protocol, (6 x 10 hops) and a low repetition protocol, (2 x 10 hops for distance). Isometric strength and DOMS were recorded before, 15 min, 24 and 48 h after exercise. Significant strength losses were observed following both protocols. Overall mean values for strength retention were 83.9 cf. 87.4 % following the high and low protocols respectively. Strength decrements were significantly lower than baseline at all time points after exercise. There were no differences between groups. Men reported higher levels of soreness, 1.8 cf. 0.75. The higher repetition protocol elicited higher levels of soreness in both groups. Overall mean values were 1.1 cf. 0.44 and 4.5 cf. 0.66 for boys and men, respectively ($P < 0.01$). In boys, soreness was significantly higher than baseline at all time points after the high repetition protocol and only at 24 and 48 h after the low repetition protocol. However, soreness in men was significantly higher than baseline at all time points after the high repetition protocol only. In conclusion, differences in soreness between the high and low repetition protocols provide support for the construct validity of the VAS. Although strength loss was similar in both groups, soreness was lower in boys. These results have implications for exercise and training that contain high frequencies of eccentric contractions in children.

3.2 INTRODUCTION

Delayed onset muscle soreness (DOMS) is a familiar sensation following unaccustomed exercise. While this phenomenon is well documented in adults, research on DOMS and exercise-induced muscle damage in children is sparse and has yielded inconsistent results. Only three studies have focused on DOMS in the paediatric population (Webber et al., 1989; Soares et al., 1996; Duarte et al., 1999). Webber et al. (1989) observed no significant difference in soreness and serum creatine kinase (CK) activity, when this was corrected for weight, in children (girls and boys, aged 10 years) and adults (men and women, aged 27 years). This suggested that the extent of muscle damage and DOMS was similar in children and adults following a downhill running protocol. In a later study, Soares et al. (1996) reported that children (boys aged 12 years) appeared to suffer less damage compared to adults (men aged 18 years), following a weight training protocol, based on measurements of soreness, CK and strength. More recently, Duarte et al. (1999) reported that children (boys aged 13 years) experienced greater symptoms of muscle damage, when the duration of the eccentric contraction was doubled, in a stepping protocol. No adult group was included in that study for comparison.

Several measures are used to evaluate the symptoms of DOMS and exercise-induced muscle damage in the experimental setting. Histological verification is the direct method of assessing muscle damage and is considered the gold standard (Salmons, 1997). Indirect measures include: dynamic and isometric strength; stiffness or reduced range of motion; tenderness; soreness; and enzymatic activity (e.g., CK). One of the most popular methods of evaluating muscle damage is perceived soreness (Warren, 1999). This involves asking the participants to subjectively evaluate pain or discomfort in the affected muscle or muscle group upon active movement of the limb.

Numerous psychophysical scales have evolved in an attempt to produce valid, reliable estimates of the severity of pain or discomfort. Scales include: simple descriptive scales; numerical rating scales and visual analogue scales. Simple descriptive scales use four or five descriptive categories (e.g. no pain, mild pain, moderate pain, severe pain, and very severe pain). The wording may differ slightly from scale to scale to fit the specifics of the setting (clinical or experimental). However, these types of scales have been criticized for their limited scope, as they lack the sensitivity needed for detecting small changes (Downie et al., 1978; Liggins & Dip, 1982). Numerical rating scales typically consist of a 10 or 20-point scale (Liggins & Dip, 1982; Neely et al., 1992; O'Connor & Cook, 1999). The participant is asked to assign a number between 0-10 or 0-20, which they feel reflects the magnitude of the pain or discomfort experienced. This scale is thought to be more effective in discriminating between small changes over time. The visual analogue scale conventionally uses a vertical or horizontal straight line, which typically consists of a 0-10 or 20-point scale. The two ends of the line are indicated with the two extremes of the symptoms (e.g. no pain and unbearable pain) (Liggins & Dip, 1982; Neely et al., 1992; O'Connor & Cook, 1999). The participant is asked to mark a point anywhere along this continuum to indicate their perception of pain or discomfort.

Recently, several authors have suggested that the use of pictorial scales to assess effort perception in children may enhance their understanding of the scale and hence its validity (Eston & Lamb, 2000; Eston et al., 2000; Robertson et al., 2000). It is likely that similar problems exist with pain scales and children. Adding pictures, which include facial expressions, in addition to descriptors, may enhance childrens' understanding and improve the construct validity of the scale. Therefore, the first aim of this study was to evaluate the ability of a visual analogue scale, which included pictures of facial expressions as well as descriptors, to discriminate between muscle soreness after two hopping protocols that varied in their severity.

Muscle weakness is common following a bout of muscle damaging exercise and is considered a more reliable marker of muscle damage (Warren et al., 1999). Many investigators have used Morgan's (1990) 'popping sarcomere' theory to explain the prolonged reduction in muscle strength. It is hypothesized that during eccentric exercise, where the muscle lengthens under tension, weaker sarcomeres are extended beyond the point of overlap. While most sarcomeres or half sarcomeres will re-interdigitate, some fail to re-interdigitate upon relaxation. As the exercise continues, more and more sarcomeres become 'popped', starting with the weakest sarcomeres and then progressing on to the next weakest sarcomere. This renders the sarcomere non-functional and reduces muscle strength (Morgan and Allen, 1999; Proske and Morgan, 2001). While muscle function (strength) is considered to be a more reliable marker of muscle damage, the perception of soreness is still of interest. Soreness may serve to reduce the likelihood of activities that would result in excessive overload and possible muscle injury following damage. If the muscle is weak with no pain to inhibit the movement, other structures such as the tendon-bone complex may have to accommodate the stress that is normally absorbed by the muscle. This could be particularly problematic in children due to the presence of growth plates. For example Osgood-Schlatter's disease arises from high forces placed on the bone-tendon complex, leading to micro-avulsion fractures of the ossification centre of the tibial tuberosity (Kujala et al., 1985; Tansey, et al., 1998). Additionally, osteochondritis dessicans arises from high compressive forces, leading to portions of the joint surface becoming avascular and an eventual separation of the affected area to form a loose body (Singer, 1986; Ellenbecker and Mattalino, 1997). Therefore, the second aim of this study was to explore the relationship between soreness and strength in boys and men after two eccentric exercise protocols that varied in their severity.

McHugh et al. (1999) reported that muscle compliance or passive muscle stiffness is an important moderating factor in muscle damage. A more compliant muscle experiences fewer symptoms of damage relative to its stiffer counterpart. It is well documented that flexibility decreases as age increases (Alter, 1996). It is therefore, possible that children may experience lower levels of delayed onset muscle soreness and muscle damage following eccentric exercise, as a result higher of levels of muscle compliance. It was therefore expected that children would experience less soreness and lower strength decrements following unaccustomed, eccentric exercise.

3.3 METHODS

3.3.1 Participants

Ten boys (age 9.5 ± .85 y, ht 137.6 ± 5.3 cm, mass 32.7 ± 6.7 kg) and ten men (age 21.4 ± 10.0 y, ht 179.5 ± 9.5 cm, mass 79.2 ± 9.7 kg) volunteered to participate in this study. All participants gave written informed consent. In the case of the children, parents/guardians gave written consent and children gave verbal assent to participate in the study, which had been previously approved by the Ethics Committee of the School of Sport, Health and Exercise Sciences. Prior to any participation in this study, all participants completed health questionnaires in order to screen for any potential health risk. Participants who reported any history of knee pain or injury were excluded from the study. At the onset of the study, participants attended the laboratory for a familiarization training session one day prior to testing. During this session, participants were given the opportunity to become familiar with the demands of the proposed eccentric protocols (three trials per leg at a sub-maximal level), the strength test, soreness scale, and to ask any additional questions. This period also served to obtain target values that the participant was encouraged to exceed the following day during testing. None of the participants had taken part in any weight training during the six months prior to taking part in this study.

3.3.2 Hopping exercise for inducing muscle damage

Participants were asked to perform two hopping protocols, which were performed on the same day. A high repetition protocol of 6 x 10 ten hops for distance and a low repetition protocol of 2 x 10 hops for distance (Figure 3.1). Each set of ten hops was separated by a one-minute rest period and the two protocols were separated by a five minutes rest. Participants were asked to try and hop as far as possible and to maintain that distance throughout the protocol, each hop was separated by a ten second rest preiod. Both protocols were randomly assigned to the dominant or non-dominant leg (as designated by baseline isometric strength and asking the subject to kick a football). Participants were free to stop at any time without reason or prejudice.

Figure 3.1 - Hopping for distance

3.3.3 Perceived Muscle Soreness

Perceived muscle soreness was evaluated using an illustrated visual analogue scale, with a sliding pointer, numbered from 0-10 on the reverse side facing the experimenter (Figures 3.2a, & b). The words "*my muscles don't feel sore at all*" corresponded with the number zero. At the other end of the scale the words "*my muscles feel so sore that I don't want to move them*", corresponded with number ten. Participants were asked to stand in an upright position with their legs apart, with more weight on one leg and their hand on their hips facing the investigator. Following a slow knee bend, to a 90° knee flexion angle, participants moved the sliding pointer along the scale to indicate the sensation of soreness in their thigh. This was repeated on the contralateral leg.

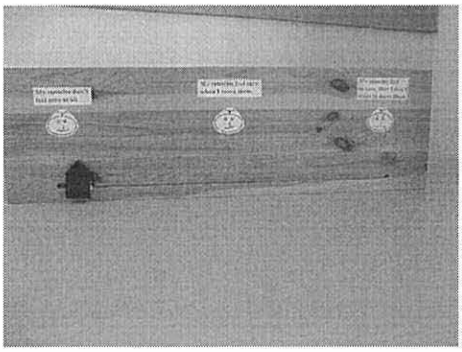


Figure 3.2 a – Participant's view of scale.

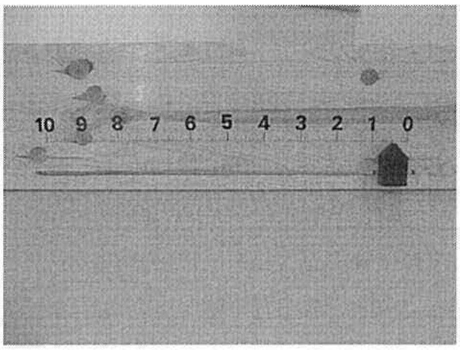


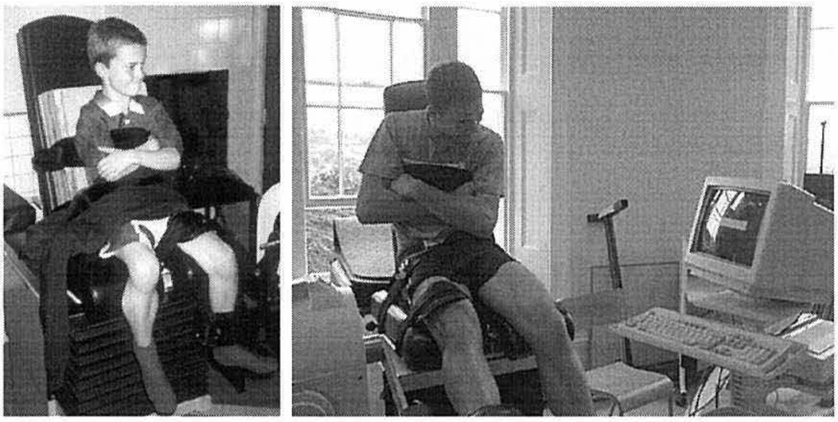
Figure 3.2 b – Experimenter's view of scale.

3.3.4 Isometric Strength

Isometric strength was assessed using a Kin Com (500H, Chattecx, Chattanooga, TN, USA) isokinetic dynamometer with the knee flexed to 80° (0° = full extension). Wooden boards were place behind the participant to ensure that the angle between the thigh and the torso was the same for all participants, as muscle length is known to affect force (Williams & Stutzman, 1959; Rassier et al., 1999). The number of boards varied depending on the length of the femur. The axis of rotation was aligned with the lateral condyle of the femur and restraining straps were used at the hip, thigh and chest to prevent any extraneous movement. The pad of the lever arm was positioned proximal to the malleoli (Figures 3.3a & b). The dynamometer lever arm length and horizontal and vertical positions were recorded for each participant in order to ensure that the testing position was the same across all testing days.

Following a warm-up, participants performed two, 3-second, maximal isometric contractions separated by a one-minute rest. A computer visual display unit, which displayed force in real time, was used to encourage maximal efforts.

Previous research has demonstrated that visual feedback enhances maximum voluntary torque during isokinetic tests (Baltzopoulos et al., 1991). Participants were also encouraged to exceed target values, based on values attained during the familiarisation session. The mean force for each 3-second contraction was recorded and the mean of the two contractions was used as the performance measure, as lower coefficients of variation and higher intra-class correlations have been reported for mean torque (Gleeson and Mercer, 1996).



Figures 3.3a & b - Placement of participants on the isokinetic dynamometer.

3.3.5 ANALYSIS

Isometric strength data were expressed as a percentage of baseline measures in order to remove baseline differences and analysed using a 3-factor (Group (2) x Time (4), pre, 15 minutes, 24 h and 48 h post) x Protocol (2)) analysis of variance (ANOVA). Soreness data were analysed using 4 separate (Group (2) x Time (4) and Time (4) x protocol (2)) 2-factor ANOVAs with alpha set at 0.05. The sphericity assumption was tested using Mauchly's Test of Sphericity. In the event of any violation of this assumption, Greenhouse-Geisser ($_{GG}$) corrections were applied. This method reduces the degrees of freedom and thereby increases the critical value of the F statistic, making the test more conservative. Significant results were followed up using an adapted Tukeys post hoc analysis for repeated measures (Stevens, 1996). A series of Pearson's product moment correlations were performed to investigate the relationship between peak soreness and peak isometric strength for boys and men.

3.4.1 RESULTS

3.4.2 *Perceived Soreness*

The higher eccentric protocol (60 hops) elicited higher levels of perceived soreness for both boys ($F_{1,9} = 7.59$, $P < 0.01$) and men($F_{1,9} = 11.67$, $P < 0.01$). Men also reported significantly higher levels of soreness than boys following 60 hops ($F_{1,18} = 5.8$, $P < 0.05$). There was no difference in soreness between boys and men following 20 hops. A significant time by protocol interaction for boys ($F_{1.8,16.5} = 4.97$, $P < 0.05)_{GG}$ indicated that boy's soreness was higher than baseline at all time points after 60 hops and at 15 min after 20 hops. Men's soreness was higher than baseline at all time points after 60 hops but, soreness following 20 hops was not higher than baseline at any time point ($F_{1.3,11.4} = 4.7$, $P < 0.05)_{GG}$. Boy's soreness was higher at 24 and 48 h when compared to the low repetition protocol. Men reported lower levels of soreness at all time points following 20 hops compared to 60.

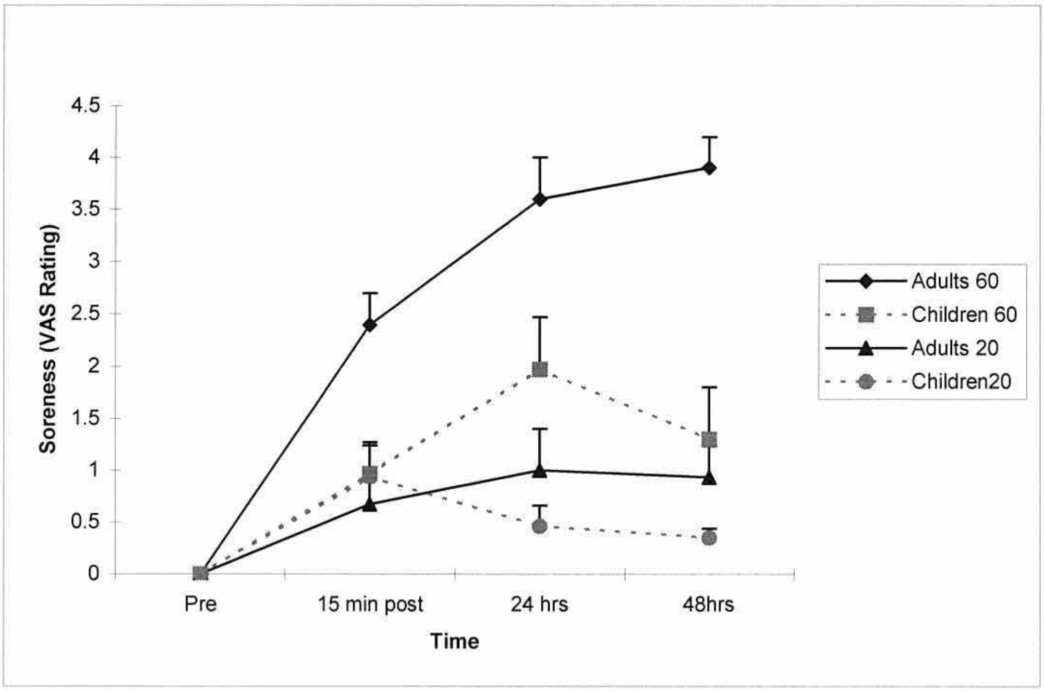


Figure 3.4 – Comparison of perceived muscle soreness in boys and men following a high and low repetition eccentric protocol of the quadriceps. Values are means ± S.E.M.

3.4.2 Isometric strength

Strength was significantly lower than baseline at all time points after exercise ($F_{2.2,39.6} = 22.4$, $P < 0.01)_{GG}$. The higher eccentric overload resulted in greater reductions in strength ($F1_{,18} = 5.99$, $P < 0.05$) in both groups. Both boys and men experienced similar reductions in strength follow eccentric exercise.

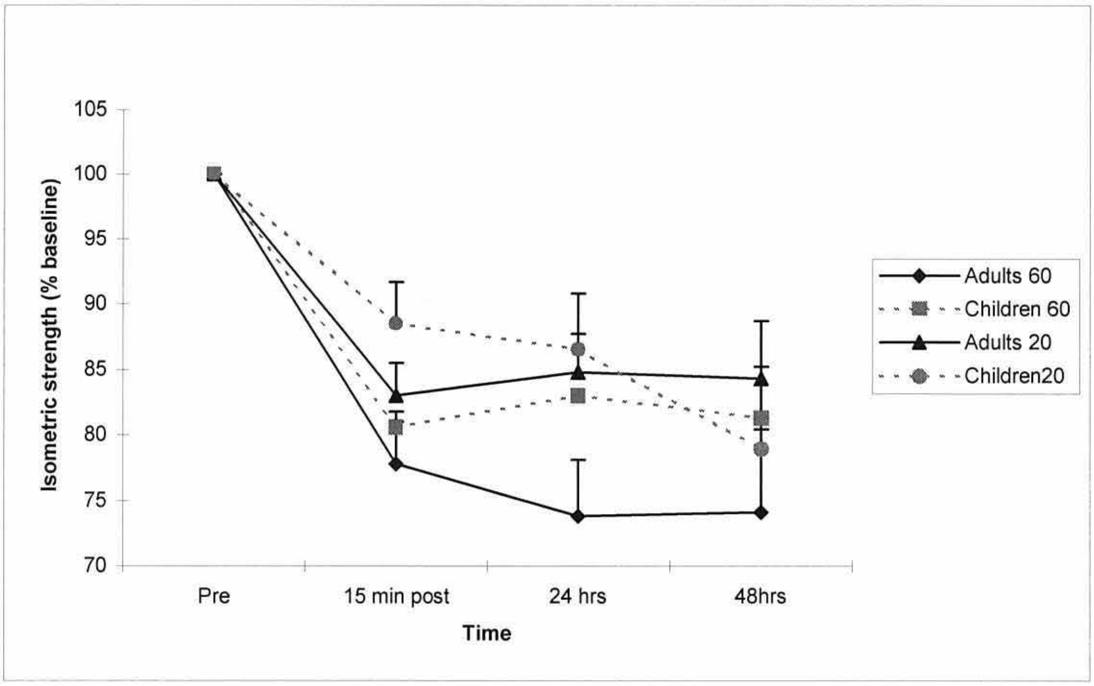


Figure 3.5 – Comparison of isometric strength (values are expressed as a percentage of baseline) in boys and men following a high and low repetition eccentric protocol of the quadriceps. Values are means ± S.E.M.

3.4.3 Relationship between peak isometric strength retention, and peak muscle soreness

Perceived soreness was negatively related to the percentage of maximal isometric strength retention in men following 60 hops (*r* = - 0.71, P < 0.05). This finding indicated that strength retention was low when soreness was high in men. No other significant correlations were observed.

3.5 DISCUSSION

3.5.1 Perceived muscle soreness

The hypothesis that boys would experience lower levels of muscle soreness than men was supported following the high repetition protocol only. However, the hypothesis that the higher eccentric overload (60 hops) would result in higher levels of soreness than the lower one (20 hops) was supported. In general, boys' soreness scores did not exceed 2 ± 1.6, compared to scores of 3.9 ± 3.7 for men. The expected differences in soreness between high and low repetition protocols and the changes in soreness over time demonstrate that the visual analogue scale was sensitive to differences in soreness over time and the extent of the higher eccentric overload. These findings provide preliminary support for the construct validity of the visual analogue scale with this subject population.

As expected, the greater eccentric overload elicited higher levels of muscle soreness. The difference in soreness resulting from a higher eccentric overload in boys concurs with previously reported findings (Duarte et al., 1999). It was not possible for Duarte et al. (1999) to evaluate differences in the response of children and adults to the varying eccentric overloads, as they did not include an adult group for comparison. However, it is well documented that a greater eccentric overload will lead to an increase in the severity of soreness and strength loss in adults (Brown et al., 1997; Tiidus and Ianuzzo, 1983). The lower eccentric overload was not sufficient to elicit any change in perceived soreness in men.

The time at which peak soreness was experienced was different in boys and men. Peak soreness following the higher repetition protocol occurred at 24 h for boys and 48 h for men. After both protocols, boys seemed to experience peak soreness 24 h earlier than men. The patterns of soreness for the heavy and light protocols were similar to those observed previously (Tiidus and Ianuzzo, 1983; Brown et al., 1997; Duarte et al., 1999), with higher eccentric overloads inducing greater levels of muscle soreness. Duarte et al. (1999) also observed that the time of peak soreness was influenced by the intensity of the eccentric protocol. In their study on 12 year old boys, the heavier eccentric protocol elicited peak soreness at 48 h compared to 24 h for the lighter protocol. The differences in the timing of peak soreness may possibly be attributed to differences in the extent of the muscle damage between protocols and the possibility that children sustain lower levels of muscle damage compared to adults. In contrast, however, Soares et al. (1996) did not observe differences in the timing of peak soreness. In their study, both boys and men experienced peak soreness at 24 h. Differences may be due to the fast explosive nature of the hopping protocol employed in this study. This protocol was chosen for its ecological validity in the sporting context, compared to the weight training protocol used by Soares et al. (1996) and the downhill running protocol used by Webber et al. (1989).

It is notable that there was a significant increase in soreness 15 min after the 60-hop protocol. Duarte et al. (1999) also observed increased pain immediately after exercise and postulated that this was due to fatigue. It is likely that fatigue may account for some of the post exercise discomfort in this study. Although participants received a 15 min rest period, it is possible that muscle lactate may still have been elevated, as hopping contains both concentric and eccentric muscle actions. As a general guide, 25 minutes of rest-recovery are required for the removal of fifty percent of the muscle lactate in adults (Fox et al., 1993). These results differ from those of Soares et al. (1996) who reported no post-exercise discomfort, in boys and men, following a weight training protocol to volitional exhaustion. Soreness measures in their study were taken immediately post exercise, which may explain the differences. Normally soreness is first apparent approximately eight hours after the cessation of exercise and peaks 24 hours after exercise (Armstrong, 1984; Cleak & Eston, 1992; Jones and Round, 1990; Byrne & Eston, 1998; Proske and Morgan 2001).

The similarities in soreness between boys and men following the light eccentric protocol may be attributed to minimal damage occurring

3.5.2 Isometric strength

The hypothesis that a greater eccentric overload would induce greater strength decrements was supported. However, the hypothesis that boys would demonstrate lower strength decrements than men was not supported. Both boys and men demonstrated similar reductions in isometric strength, which was reduced at 15 min, 24 h and 48 h after exercise relative to baseline. Strength decrements increased across time (with overall mean strength retention values of 82.5%, 82.1%, 79.7% at 15 minutes, 24 and 48 h, respectively), with the greatest reductions in strength occurring at 48 h. Normally strength is at its lowest immediately after exercise and then shows a gradual recovery over the days that follow (MacIntyre et al., 1995; Soares et al., 1996; Byrne & Eston, 1998). These may be due to some recovery during the 15 min rest period, which was used to minimise the effects of fatigue. Duarte et al. (1999) observed similar reductions in isometric strength, where greater muscle weakness was observed following a higher eccentric overload. In their study, strength decrements were greatest immediately after exercise, but some recovery was observed 1 hour later.

Soares et al. (1996) observed a significant reduction in strength following a weight training protocol in adults, but no changes were observed in children. Although the children in the present study generally demonstrated higher strength retention than adults, with the exception of 48 h following 20 hops (78.9 cf. 84.9), these differences were not statistically significant.

The similar strength reductions in the boys and men following the eccentric exercise protocol were unexpected. It may possibly be accounted for by the angle at which the isometric strength test was conducted and the resulting differences in the muscle length-tension relationship between children and adults. It is known that flexibility decreases as age increases (Alter, 1996). Therefore, at any given muscle length (which is manipulated in-vivo by altering the joint angle), a sarcomere in a more compliant muscle may, theoretically, be shorter. This in turn may shift the length tension curve in children further to the right in comparison to adults. Thus, the optimal joint angle that elicits peak force in children would be expected to be greater due to higher muscle compliance (full extension = 0^{O}). Disproportional reductions in strength have been observed at shorter muscle lengths following eccentric exercise (Jones et al., 1997; Saxton & Donnelly, 1996;Wood et al., 1993; Byrne et al., 2000). An explanation for this phenomenon may be based on Morgan's (1990) 'popping sarcomere' theory. As weaker sarcomeres are overextended and fail to re-interdigitate, adjacent sarcomeres get shorter and this consequently limits the number of available cross-bridges. This has the effect of inducing a rightward shift of the length-tension relationship (Brocket et al., 2001; Proske and Morgan, 2001). Therefore, as strength for boys and men was assessed at 80^O, strength measures for the boys in this study may well have been assessed at a relatively shorter length, i.e., not at the optimal angle that elicits peak torque. Theoretically, any rightward shift of the length-tension curve, assuming that the shift was the same for both groups, may have exacerbated strength loss in boys removing the expected differences in strength (see Figure 3.6). Further research is needed to investigate differences in the length-tension relationship in children and adults.

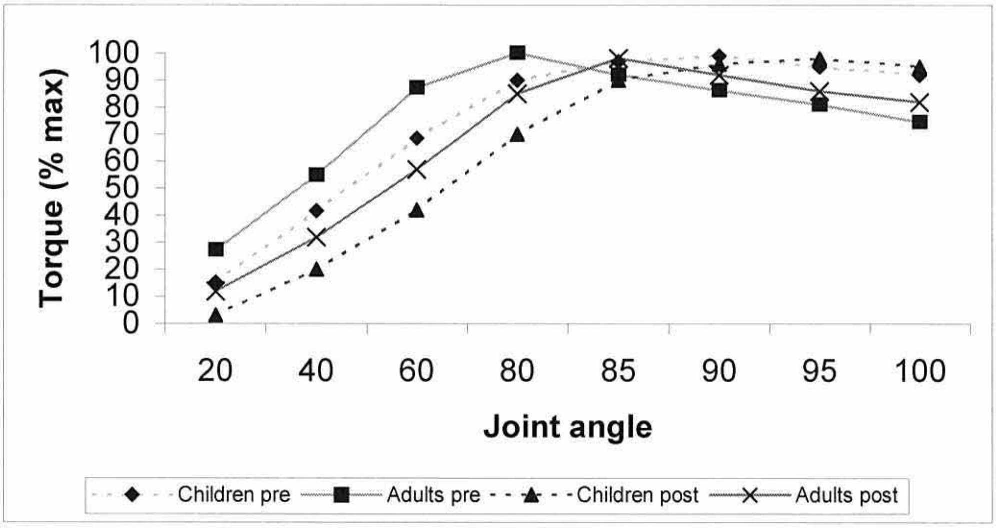


Figure 3.6 - Theoretical differences in the torque-joint angle relationship in boys and men before and after muscle damage.

At 80° degrees of knee flexion assuming the rightward shift is the same in both groups, strength loss is approximately 15 % for men and 20 % for boys. At the optimal angle that elicits peak torque in boys the strength loss is approximately 4%. Additionally, differences in the loading characteristics may have been greater in men.

Further studies may consider scaling for lean leg volume in order to evaluate this relationship.

McHugh et al., (1999) have observed that higher levels of muscle compliance are associated with lower levels of muscle damage and soreness following eccentric exercise. It appears that a more compliant musculotendinous unit is more able to accommodate contractions that involve the muscle lengthening. Therefore, it is possible that children's muscles may experience less damage following eccentric exercise.

3.5.3 Relationship between muscle soreness and strength loss

It has been postulated that reductions in strength may be due to pain inhibition (Byrne & Eston, 1999), but others have argued that pain and strength loss are unrelated (MacIntyre et al., 1995; Armstrong, 1984). In this study, soreness may have played a prominent role in reductions in strength values in the adults following 60 hops, as the largest reductions in strength coincided with the highest soreness scores. This was not the case following 20 hops. After this protocol, peak soreness in adults did not coincide with the greatest strength decrements. It was also interesting to note that the reductions in isometric strength were at their greatest when soreness was at its lowest in the children (24 h). This highlights that soreness alone cannot account for reductions in strength in this study.

Muscle weakness in the absence of discomfort may be particularly problematic for children due to the presence of growth plates. If the child is uninhibited during play or sporting activities, the forces that are normally accommodated by the muscle may have to be dissipated by the other structures, such as the tendon bone-complex, possibly increasing the risk of injuries such as Osgood-Schlatter's or Osteochondritis dessicans which both arise from high forces on the joint (Ellenbecker and Mattalino, 1997; Singer, 1986; Kujala et al., 1985; Tansey, 1998).

3.5.4 Summary

In summary, both boys and men experienced greater soreness and strength loss following the higher eccentric overload. Boys reported lower levels of soreness, but similar reductions in strength were observed. If children have a greater level of compliance, then the optimal joint angle that elicits peak torque in children may occur at longer muscle lengths. Evaluating strength at 80° of knee flexion may have magnified reductions in strength in the boys as consequence of the muscle performing at a relatively shorter length in comparison to the men. This phenomenon may have reduced the possibility of observing differences in muscle strength in this study. Further research is needed to investigate differences in the optimal angle that elicits peak torque between adults and children and any effects that eccentric exercise may have on the length-tension relationship of muscle contraction. The largest strength decrements coincided with lower soreness scores in boys. This observation has implications for exercise and training in children. Further research is needed to establish the functional consequences of exercise, which contains a high eccentric component in this population.

CHAPTER 4

The relationship between torque and joint angle during knee extension in boys and men.

4.1 Abstract

4.2 Introduction

4.3 Methods

  4.3.1 Participants

  4.3.2 Torque-joint angle relationship

  4.3.3 Analysis

4.4 Results

4.5 Discussion

4.6 Summary

Data from this study were presented at the British Association of Sport and Exercise Sciences, Liverpool, September, 2000, with the following publications arising from it:

Marginson, V.F. and Eston, R.G. 2001. A study to investigate the torque-joint angle relationship of muscle contraction in the quadriceps muscle of boys and men: implications for studies on strength and exercise-induced muscle damage. *Journal of Sports Sciences*. 19, 875-880.

Marginson, V.F. and Eston, R.G. (2001) A study to investigate the torque-joint angle relationship of muscle contraction in children and adults. *Journal of Sports Sciences,* 19, 30-31P.

4.1 ABSTRACT

The length-tension relationship of muscle contraction is well documented in adults. However, research on this relationship in children is sparse. The aim of this study was to compare differences in the torque-joint angle relationship of the quadriceps muscle in children and adults. Eight boys (aged 8 - 10 y) and eight men (aged 20 - 26 y) performed two maximal voluntary isometric contractions, at six joint angles (20°, 40°, 60°, 80°, 90°, 100°). The mean of the two trials was used as the performance measure. Both groups demonstrated an expected increase in relative torque as the joint angle increased ($P<0.05$). Men produced higher relative torque at 20°; 40° and 60 ° knee flexion. The percentage of maximal torque at these angles for the men and boys respectively were: 35.2 ± 4.3 cf. 15.2 ± 12%, 63.6 ± 9.1 cf. 51.8 ± 16.8% and 93.6 ± 6.5 cf. 84.4 ± 14.4%. Peak torque was attained at 80° in men and decreased significantly ($P<0.05$) at 90° and 100°. For boys, peak torque was attained at joint angles of 80° and 90°. There were no group differences at 80° and 90°. The reduction peak torque at 100° was not statistically significant, but the relative torque at this angle was lower in men compared to boys (77.9 ± 13.7 cf. 87.1 ± 10.4%; $P <.0.05$). In conclusion, the torque-joint angle relationship appears to be different in children.

4.2 INTRODUCTION

The change in torque as a result of changes in muscle length is well documented both in-vivo and in-vitro (Williams and Stutzman, 1959; Gordon *et al.*, 1966a,b; Edman and Reggiani, 1984; Rassier *et al.*, 1999) and is referred to as the length-tension relationship of muscle contraction. In the in-vivo experimental setting, muscle length is manipulated by making alterations to the joint angle. Data are plotted to produce a strength curve, which is defined as the muscle's ability to produce maximal torque as a function of joint angle (Kulig *et al.*, 1984). Therefore, in this study, the length-tension relationship will be referred to as the torque-joint angle relationship of muscle contraction. As the joint angle is manipulated to lengthen the muscle, torque increases until an optimal angle is achieved, beyond which torque successively decreases as the muscle is lengthened (Charteris and Goslin, 1986).

The torque-joint angle phenomenon is commonly explained by the 'sliding filament' theory. At short muscle lengths, torque reductions might result from deformation of the actin and myosin cross-bridges, which occurs because of resistance from the Z-lines (Gordon *et al.*, 1966b; Rassier *et al.*, 1999). Additionally, possible increases in osmotic pressure at shorter muscle lengths might oppose active sarcomere force (Rassier *et al.,* 1999). At muscle lengths beyond optimal sarcomere length, force is thought to decrease due to a reduction in the number of available actin-myosin cross-bridges, as it has been postulated that cross bridges function as independent force generators and that force is directly proportional to the number of available cross bridges (Gordon et al., 1966b; Morgan *et al.*, 1991). Support for the notion that there is a non-uniform distribution of sarcomeres throughout the myofibril has been provided by in-vitro studies on single frog muscle fibre (Gordon *et al.*, 1966a). Sarcomeres, which are situated toward the ends of the muscle fibre, are shorter relative to those situated in the middle of the fibres. During stimulated isometric tetiny, where fibre length is controlled, a redistribution of sarcomere length occurs (Edman and Reggiani, 1984). In their study, sarcomeres situated towards the ends of the fibre demonstrated a greater amount of shortening, relative to those situated in the mid region of the fibre.

Evidence that the tendon elongates as the muscle fibres shortened during isometric contractions has been provided from in-vivo cat medial gastrocnemius (Griffiths, 1990), in-vitro frog semitendinousus (Kawakami and Lieber, 2000) and in-vivo human tibialis anterior muscle (Ito et al., 1998). Kawakami and Lieber (2000) demonstrated that the presence of a series elastic component shifted the force-length curve towards longer muscle lengths in isolated muscle. Therefore, differences in the compliance of a musculotendinous unit might change the characteristics of the in-vivo torque-joint angle relationship. It is acknowledged that in-vivo assessments are influenced by biomechanical factors so in-vivo torque-joint angle characteristics might not necessarily reflect the characteristics of isolated muscle.

Flexibility, which is correlated with muscle stiffness (Gleim & McHugh, 1997), decreases with age. Increase in muscle stiffness (passive torque) with age might alter the characteristics of the torque-joint angle relationship in children and adults. Although, not all research has found increases in stiffness with increasing age (Brown et al., 1999).

Griffiths (1990) reported that the tendon in cat gastrocnemius muscle stretched as muscle fibres shortened, until the force generated by the muscle fibres could no longer stretch the tendon further. The unload characteristics of the muscle, demonstrated a recoiling of the tendon with little change in fibre length at first, followed by a slow stretch of the muscle fibre. It has been suggested that greater stiffness is more favorable for the translation of force from the muscle to the bone (Wilson et al., 1994; Walshe et al., 1996; Kawakami & Lieber, 2000). A greater lengthening of the tendon and aponeurosis (series elastic component) would require a greater shortening of the contractile component of the muscle to accommodate the stretch in the series-elastic component. This might alter the characteristics of the torque-joint angle curve, whereby the angle that elicits peak torque is shifted towards longer muscle lengths.

Theoretically, sarcomeres in a stiff musculotendinous unit will be longer at any given muscle length in comparison to a less stiff unit (Wilson et al., 1994; Walshe et al., 1996). Therefore, the optimal joint angle, for eliciting peak torque in a stiff muscle might occur at shorter muscle lengths in a stiffer musculotendinous unit. This would have an effect of shifting the torque-joint angle relationship of a stiffer musculotendinous unit to the left. That is, on the ascending limb of the torque-joint angle relationship, the proportion of maximal torque attained would be greater for adults, and the optimal torque would be achieved at a lower joint angle. Beyond optimal length (descending limb of the torque-joint angle relationship) it might be expected that children would attain higher levels of the proportion of maximal torque in relation to adults.

Asai and Aoki (1996) observed that electromechanical delay, which is the delay between the appearance of an EMG signal and the development of force, in children was higher. This might have been due to differences in biochemical factors or compliance of the musculotendinous unit between adults and children. Paasuke et al. (2001) noted a lower rate of force development in children. A lower rate of force development has been associated with lower levels of stiffness (Wilson et al., 1994; Walshe et al., 1996). If the optimal angle for eliciting peak torque is different in children and adults, this will influence the measurement of strength at any given joint angle.

Similarly the sliding filament theory has been employed in the development of the popping sarcomere theory following exercise-induced muscle damage (Morgan, 1990). Following damaging exercise, the number of functional sarcomeres and thus the number of cross bridges is reduced leading to reductions in the force producing capacity of the muscle. Additionally, % peak torque occurs at slightly longer muscle lengths, as over-extended sarcomeres cause adjacent sarcomeres, which are not over-extended, to shorten (Morgan & Allen, 1999).

In the previous study (chapter 3), it was observed that children experienced less muscle soreness following exercise that is known to elicit muscle damage. It was hypothesized that the children in this study would experience less soreness due to lower levels of muscle stiffness. While the children did experience less muscle soreness, the amount of muscle weakness, which is another indirect marker of muscle damage, was not significantly different from the adults in this study. It was postulated that perhaps the children in this study might have experienced similar muscle weakness as a result of differences in the torque-joint angle relationship. Disproportional reductions in strength have been observed at shorter muscle lengths following a bout of exercise-induced muscle damage (Wood et al., 1993; Saxton & Donnelly, 1996; Jones et al., 1997; Byrne et al., 2000). If the optimal angle for eliciting peak torque is different in children and adults, disproportional reductions in strength in the children, may have removed differences in muscle weakness in chapter 3.

The aim of this study was to investigate differences in the torque-joint angle relationship of muscle contraction and to identify the optimal joint angle for eliciting peak muscular torque in children and adults.

4.3 METHODS

4.3.1 Participants

Eight boys (age (mean ± SD) 9.3 ± 0.9 y, ht 129.8 ± 4.7 cm, mass 31.8 ± 6.0 kg) and eight men (age 21 ± 2.1 y, ht 180.5 ± 13.4 cm, mass 78.8 ± 8.3 kg) volunteered to participate in this study, which was approved by the Ethics Committee of the School of Sport, Health and Exercise Sciences. All participants gave written informed consent. In the case of the children, parents/guardians gave written consent and children gave verbal assent to participate in this study. All participants received a familiarization training session one day prior to testing. During this session, they were given the opportunity to become familiar with the demands of the test and to ask any additional questions. Data were considered reliable when the participants' torque values become consistent (within 5% across trials). This period also served to obtain target values that the participant was encouraged to exceed on the following day during testing.

4.3.2 Torque-joint angle relationship

The torque-joint angle relationships were assessed on an isokinetic dynamometer (Kin Com, 500H Chattecx, Chattanooga, TN, USA). Participants were tested in the seated position with their arms folded across their chest. Wooden boards were placed behind the participant and the back of the seat in order to ensure that the angle between the thigh and the torso were the same for all participants. The axis of rotation was aligned with the lateral condyle of the femur and restraining straps were used at the hip, thigh and chest to prevent any extraneous movement. The pad of the lever arm was positioned proximal to the malleoli. The dynamometer lever arm length and horizontal and vertical positions were recorded for each participant in order to ensure that the testing position was the same as the familiarization position. Participants were asked to perform two maximal 3 second, maximal voluntary isometric contractions of the quadriceps, at six different joint angles (20°, 40°, 60°, 80°, 90°, 100°, (0° = full extension)). Contractions were performed consecutively at each of the six joint angles. Each participant was encouraged to exceed the target values obtained in the familiarization period the day prior. Visual feedback, via a visual display unit, which displayed force in real time, was provided throughout all testing (Baltzopoulos, et al., 1991). Participants received a 5-min break between the first and second set of six contractions and a 3-min recovery period between each of the six contractions at each joint angle in each set. The mean force for each 3-second contraction was recorded and the mean of the two contractions at each joint angle was used as the performance measure (Gleeson and Mercer, 1996).

Figure 4.1: Placement of participants on the isokinetic dynamometer.

4.3.3 ANALYSIS

Data were expressed as percentage of peak torque and analyzed using a two-factor mixed model (2 x 6; group x joint angle) analysis of variance with alpha set at 0.05. The assumption of sphericity was confirmed by the Mauchly test. A modified Tukey test for mixed model designs (Stevens, 1996) was applied to determine where significant differences lay.

4.4 RESULTS

There was a significant main effect for joint angle ($F_{5,70} = 165.1$, $P<0.05$) and a significant group x joint angle interaction on relative torque ($F_{5,70} = 7.67$, $P<0.05$). The men produced higher relative torque (expressed as a percentage of peak torque) measurements at 20^o, 40^o and 60^o knee flexion, compared to the boys. No significant differences were observed between groups at angles of 80^o and 90^o knee flexion. Both groups demonstrated an expected increase in relative torque as the joint angle increased (i.e. on the ascending portion of the torque joint angle curve). These increases were significant between angles 20°, 40° and 60° for men, and 20°, 40°, 60° and 80° for boys. Men attained peak torque at 80° of knee flexion, whereas boys attained peak torque at 80° and 90° of knee flexion with torque remaining high at 100°. Relative torque at joint angles of 90° and 100° was significantly lower in men. Changes in torque at these angles (90°, 100°) were not significant in boys. Relative torque at 100° was significantly higher in boys compared to men (Figure 4.2).

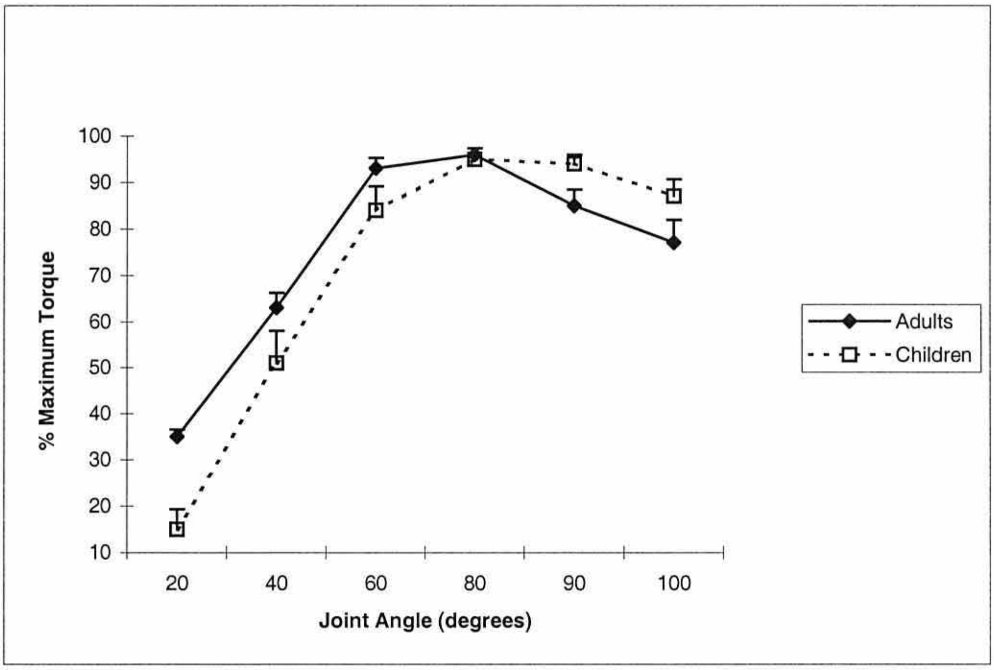


Figure 4.2: Comparison of the torque-joint angle relationship in boys and men. Values are means and SEM.

4.5 DISCUSSION

Both boys and men demonstrated a characteristic torque-joint angle curve where relative torque increased until an optimal joint angle was achieved, and thereafter began to decrease, which concurs with previous findings (Williams and Stutzman, 1959; Kulig *et al.*, 1984; Charteris and Goslin, 1986). However, these data suggest that the torque-joint angle curve of the quadriceps muscle in children is situated to the right of the adults' curve. Relative torque in boys was significantly lower at angles 20° 40° and 60° on the ascending portion of the torque-joint angle curve. However, the boys did not demonstrate the same reductions in relative force at the higher joint angles, with torque at 100° being higher in boys.

Research on the torque-angle relationship in children is limited. Williams and Stutzman (1959) included both children and adults in their study, and found the relationship to be similar. However, joint angle was manipulated using 30° increments, which may have reduced the sensitivity of the study for identifying any differences between these two groups.

The differences in the torque-joint angle relationship between men and boys in the present study may be explained by muscle stiffness. It is generally accepted that flexibility, which is highly correlated with passive stiffness (Gleim and McHugh, 1997), decreases as age increases (Alter, 1996). It has been suggested that increases in stiffness results from increases in the stability and content of collagen (Alnaqeeb *et al.*, 1984; Bailey, 1989; Kovanen, 1989; Menard, 1994; Alter, 1996). Observations on rat striated muscle have demonstrated increases in collagen with age, although this is affected by activity (Kovanen and Suominen, 1989; Zimmerman *et al.*, 1993;

Walfarth et al., 1997). Similarly, elastin becomes more brittle with age (Menard, 1994). It is likely that collagen and elastin respond similarly in human striated muscle. However, not all research findings have demonstrated an increase in muscle stiffness with age (Brown et al., 1999).

These observations can be explained by differences in muscle compliance. Lower levels in the rate of force development (Paasuke et al., 2001) and greater electromechanical delay in children (Asai & Aoki, 1996) provide some support for greater muscle compliance in children. It is acknowledged that in-vivo assessments are influenced by mechanical factors such as lever characteristics of the articular arm system. Changes in pennation angle of the muscle fascicles as the muscle contracts (Ito et al., 1998), and the size of the tibial tuberosity (Kulig et al., 1984), also influence the torque-joint angle relationship.

Theoretically, at any give point on the torque-joint angle curve, sarcomeres in a more compliant muscle will be shorter, necessitating a greater joint angle and hence longer muscle length, in order to attain an optimal joint angle which elicits peak torque. Wilson et al. (1994) and Walshe et al. (1996) have argued that the length of sarcomeres in a stiffer muscle will be longer at any given point during a muscle contraction. This would be favorable for the rate force development, as there should also be less stretch in the series elastic component of the muscle in a stiffer muscle.

At shorter muscle lengths (lower joint angles), resistance from the Z-lines is thought to reduce torque by deforming actin and myosin crossbridges (Gordon *et al.*, 1966a; Rassier *et al.*, 1999). This would manifest itself to a greater extent in a more compliant musculotendinous unit by necessitating greater shortening of the muscle fibres in order to accommodate a greater stretch in the series-elastic component of the muscle, resulting in lower torque values. Theoretically, greater compliance might require a longer muscle length (greater joint angle) to attain sarcomere lengths that would elicit peak torque. This should shift the optimal angle for attaining peak torque towards a greater joint angle or muscle length, shifting the curve to the right. At increased lengths (greater joint angles) a stiffer muscle should show greater reductions in torque due to a limited availability of crossbridges, as force is believed to be directly proportional to the number of available crossbridges (Gordon *et al.*, 1966b; Morgan *et al.*, 1991). This appeared to be the case in this study, as torque in adults demonstrated a greater decline at greater joint angles.

Differences in the torque-joint angle relationship might have ramifications for the evaluation of strength in studies on exercise-induced muscle soreness and damage. Muscle length is an important factor, which plays a prominent role in the amount of damage incurred during exercise (Newham *et al.*, 1988; Saxton and Donnelly, 1996; Jones *et al.*, 1997; Morgan and Allen, 1999) and the amount of muscle weakness following damage. It has been observed that greater damage following eccentric exercise occurs at longer muscle lengths and that disproportional decreases in strength occur at shorter muscle lengths (Wood et al., 1993; Saxton and Donnelly, 1996; Jones, *et al.*, 1997; Byrne *et al.*, 2001). Differences in the torque-joint angle relationship between adults and children may play a prominent role in, firstly explaining any differences in the severity of the symptoms of muscle damage between these two groups. Secondly, following muscle damage, strength losses are often explained by a shift in the length tension relationship towards longer muscle length. It is possible that previous observations of a similar pattern of strength loss in children and adults following eccentric exercise-induced muscle damage, in study 1 (chapter 3), were affected by differences in the torque-joint angle relationship found in the present study. Research that evaluates isometric strength following muscle damage in children and adults, might consider the use of individual optimal angles that elicit peak torque in order to try and standardize this point on the torque-joint angle curve. This should minimize the effect of a shift in the torque-joint angle curve effecting one group to a greater extent.

4.6 Summary

In summary, the torque-joint angle curve of the quadriceps muscle in boys appears to be situated to the right of the men's curve. That is, on the ascending portion of the curve, relative torque is lower in boys. In addition, relative torque in boys remains high at greater joint angles in comparison to men, with boys producing higher torque at 100^o. This can be explained by lower levels of muscle stiffness in boys, which would necessitate a greater joint angle and hence a longer muscle length in order to attain optimal sarcomere lengths. The influence of biomechanical differences is acknowledged. This observation might have implications for studies that include measures of strength at the same joint angles in children and adults. It may also have implications for studies on strength loss following exercise-induced muscle damage in children and adults. It is recommended that future studies that include measures of strength loss following exercise-induced muscle damage and soreness in children and adults, should examine strength over a range of joint angles, or identify individual optimal joint angles for both groups.

CHAPTER 5

Delayed onset muscle soreness and muscle function in boys and men following eighty plyometric jumps.

Data from this study were presented at the European Pediatric Work Physiology group meeting, Belgium September, 2001 and The Physiological Society, York, December 2001, with the following publications:

Eston, R.G. and Marginson, V.F. (2001). The relationship between isometric torque and knee joint angle in boys and men. *Journal of Physiology, 539*, 17-19P.

Marginson, V.F., Eston, R.G. (2001) Delayed onset muscle soreness in boys and men following eighty plyometric jumps. *Pediatric Exercise Science*, 13, 329-330 P.

5.1 ABSTRACT

Research on symptoms of exercise-induced muscle damage (EIMD) in children is limited and results are equivocal. This study investigated the severity of the symptoms of EIMD in boys and men after unaccustomed exercise. Ten boys aged 9-10 years and ten men aged 20-29 years performed eight sets of ten plyometric jumps to induce muscle damage in the knee extensors. Power output was adjusted for lean thigh volume for each set of 10 jumps. Isometric strength, soreness, squat jump and counter movement jump height, were recorded before, and at 30 min, 24, 48 and 72 h after the plyometric exercise. Hip extension, with the knee flexed at 120° was also recorded at baseline. Hip extension was higher in children (38^{O} cf. 23.8^{O}) ($P< 0.05$). Corrected power output was higher in adults during the plyometric protocol. Following the plyometric protocol, children maintained power output across the eight sets whereas it decreased by approximately 10% in adults by set 8 ($P< 0.05$). Children experienced less soreness (0.8 cf. 3.6) ($P< 0.05$), less overall strength loss (2.0 cf. 15.9%) ($P<0.05$) and lower decrements in jump height (3.8 cf. 10.3%) ($P<0.05$). These findings may be explained by the lower power output per lean leg volume in boys during the plyometric jumps, suggesting a possible lower strain per unit muscle area. Also, the ability of the children to maintain power output could perhaps be attributed to a greater dependence on slow twitch muscle fibres, which are less susceptible to damage and fatigue. A further factor which may account for less severe symptoms of EIMD in boys may be the higher muscle compliance in this group.

5.2 INTRODUCTION

Few studies have investigated symptoms of exercise-induced muscle damage (EIMD) in children (Webber et al., 1989; Soares et al., 1996; Duarte et al., 1999, chapter 3). Common indices of EIMD include strength loss, changes in range of motion, increased creatine kinase activity and muscle soreness (Armstrong, 1984). Recently, research on the effect of EIMD on explosive strength measures, such as jump height, has been conducted in adults (Mair et al., 1995; Chambers et al., 1998; Horita et al., 1999; Byrne and Eston, 2002). However, there has been no research in this area in children following eccentric exercise.

The evaluation of jump height provides a convenient model in which to study jump parameters with and without the use of the stretch shortening cycle. Muscle actions that utilize the stretch shortening cycle are frequent within the sporting context where an eccentric muscle action precedes a concentric muscle action (see chapter 2) (Horita et al., 1999). There are commonly three types of jump: squat jump; counter movement jump and drop jump. Squat jump involves a concentric muscle action only, whereas the concentric phase in counter movement and drop jumps is preceded by an eccentric muscle action. Drop jumps are performed by jumping off a box at a given height. The enhanced muscle performance, which follows an eccentric muscle action, has been consistently demonstrated (Komi, 1984; Finni et al., 2000) and is thought to result from a mixture of elastic strain energy (Cavagna et al., 1965; 1968; Cavagna, 1970; Anderson and Pandy, 1993; Finni et al., 2000) and neural reflexes (Bobbert et al., 1986; Walshe et al., 1998; Bobbert and Zandwijk, 1999; Bosco, 1999; Komi et al., 2000).

The amount of EIMD incurred and the magnitude of the strength loss following EIMD, is dependant on muscle length (Newham et al., 1988; Wood et al., 1993; Saxton and Donnelly 1996; Child et al., 1998; Byrne et al., 2000; Rowlands et al., 2001). Greater damage is incurred when the muscle performs eccentric actions at longer lengths. This phase of muscle action corresponds to the descending portion of the torque-joint angle curve (Morgan 1990; Morgan and Allan 1999; see Figure 4.2, chapter 4, p 56). Chapter 4 revealed differences in the torque-joint angle characteristics of the knee extensors in boys and men. Therefore, the use of an individual optimal joint angle that elicits peak torque is an important consideration when measuring EIMD-related strength decrements in these two populations.

A rightward shift in the torque-joint angle relationship towards longer muscle lengths is often observed following EIMD (Morgan and Allan, 1999). Morgan (1990) suggested that this is due to the overextension of weaker sarcomeres, which fail to re-interdigitate and become temporarily non-functional. Adjacent sarcomeres are therefore believed to shorten.

As highlighted earlier in chapter 3 (p 34), passive muscle stiffness (muscle compliance), defined as the amount of passive torque exerted by a muscle or muscle group at a given range of motion, plays an important role in the severity of symptoms associated with EIMD (McHugh et al., 1999). Stiffer muscles seem to experience greater symptoms of EIMD. Flexibility, which is correlated with muscle stiffness (Gleim and McHugh, 1997), decreases with age. In the absence of passive torque measures, flexibility is a convenient, easy method of evaluating muscle stiffness. No previous study has related the symptoms of EIMD to range of motion.

Elongation of the tendon as muscle fibres shorten during isometric contractions has been observed in-vivo in the medial gastrocnemius of the cat (Griffiths, 1990), in-vitro in the semitendinosus of the frog (Kawakami and Lieber, 2000) and in-vivo in the human tibialis anterior muscle (Ito et al., 1998). McHugh et al. (1999) postulated that there might be a greater elongation in the aponeurosis of a more compliant musculotendinous unit during eccentric exercise, which provides a mechanism by which less sarcomere overextension occurs. In other words there would be a greater amount of stretch in the non-contractile component of the muscle. Thus, theoretically, a greater number of sarcomeres would function at lengths corresponding to the ascending portion of the torque-joint angle curve, which is associated with less sarcomere overextension (Morgan, 1990; Morgan and Allan, 1999).

The aim of this study was to evaluate the severity of the symptoms associated with EIMD in boys and men and to examine the relationship between the symptoms of EIMD and range of motion. Specifically, the purpose of this study was to focus on soreness, squat jump height, counter movement jump height, the torque-joint angle relationship before and after damage and to compare the torque-joint angle relationship data to previous studies (chapter 3) in these two populations.

5.3 METHODS

5.3.1 Participants

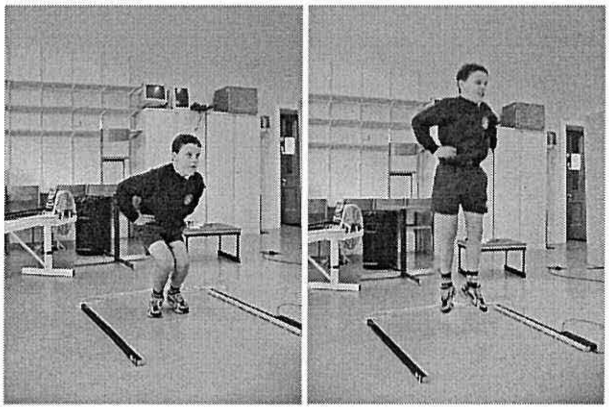
Ten boys (age (mean ± SD) 9.9 ± 0.32 y, ht 138.2 ± 5.4 cm, mass 32.2 ± 6.3 kg) and ten men (age 22.2 ± 2.7 y, ht 183.5 ± 5 cm, mass 71.8 ± 6.3 kg) volunteered to participate in this study. All participants gave written informed consent. In the case of the children, parents/guardians gave written consent and children gave verbal assent to participate in this study. Prior to any participation in this study, all participants completed health questionnaires in order to screen for any potential health risk. Participants who reported any history of knee pain or injury were not recruited in this study. At the onset of the study, participants attended the laboratory for a familiarization training session one day prior to testing. During this session, participants were given the opportunity to become familiar with the demands of the tests, which had been previously approved by the North West Wales NHS Trust Ethics Committee and to ask any additional questions. This period also served to obtain target values that the participant was encouraged to exceed the following day during testing. Measures of hip extension and leg volume, using surface anthropometry (Jones and Pearson, 1969) were also collected during this time period. It should be noted that the Jones and Pearson (1969) equation was developed on an adult population and may not be suitable for use with children.

5.3.2 Plyometric exercise protocol for inducing muscle damage

Power output was assessed using an infra-red jump system (Optojump, Microgate S.R.L, Bolzano, Italy) interfaced with a Hi Grade AMD K2 366mHz lap top computer. Participants were asked to stand between the two infra-red sensor bars in an upright position with their legs apart and their hands on their hips facing the VDU of the laptop. Following a warm-up of 5 sub-maximal and 5 maximal continuous jumps and a standardized stretch of the quadriceps muscle, whereby the foot was raised to the buttocks, participants performed eight sets of ten continuous maximal plyometric jumps (Figure 5.1 a & b). Each set of ten jumps was separated by a one-minute rest period, where the participant was allowed to leave the space between the infra-red bars and walk around. Participants were asked to jump as high as possible on each jump following a preparatory downward eccentric movement, to a knee bend of approximately 90°, which was performed as fast as possible. Participants were asked to try and beat or maintain target values that were based on their maximal counter movement jump height, throughout the eight sets of ten plyometric jumps. Total power output in watts was recorded for each set of ten jumps. Data were then corrected for lean thigh volume (L) using a simple ratio standard (W/L) and analysis of covariance (ANCOVA). Watts were calculated using the following equation

$$W = \frac{g^2 . \sum t_{flight} . (\sum t_{flight} + \sum t_{contact})}{4 . N_{jump} . \sum t_{contact}}$$

Where $g = 9.8065\ ms^{-2}$, t_{flight} = flight time (ms), $t_{contact}$ = contact time (ms), N= number of jumps.



Figures 5.1a & b – Plyometric jumping protocol for inducing muscle damage

5.3.3 MEASURES

5.3.3.1 Passive hip extension

Participants were placed in the prone position on a portable treatment couch (Darley, Cornwall, U.K.). A restraining strap was placed across the pelvis to prevent any extraneous movement. A partner also stabilized the hips. A Leighton flexometer was attached 2 cm proximal to the lateral malleolus. The knee was flexed to 120° and splinted in order to lengthen the quadriceps muscle. The Leighton flexometer was then transferred to the lateral epicondyle of the femur. The experimenter placed one hand under the iliocristale bone, to ensure that the hip was not lifting off the couch and the other hand under the thigh, just proximal to the knee. The participant was asked to relax while the experimenter lifted his thigh to extend the hip to its maximum range of motion. Maximum hip extension was indicated by the participant saying 'stop' (Figures 5.2a & b). The mean of three trials were taken as the performance measure, as mean scores are considered more reliable (Hubly-Kozey, 1991).

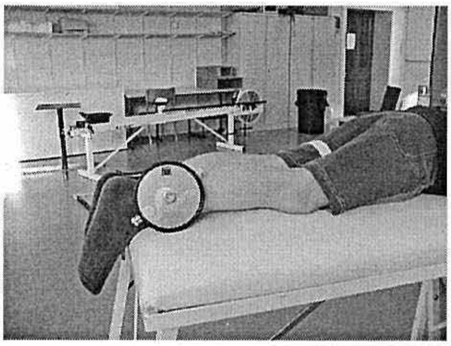


Figure 5.2a - placement of the Leighton flexometer at the lateral malleolus

Figure 5.2b – Measurement of hip extension

5.3.3.2 Torque-joint angle relationship

The torque-angle relationship was assessed on an isokinetic dynamometer (Kin Com, 500H Chattecx, Chattanooga, TN, USA). Participants were tested in the seated position with their arms folded across their chest. Wooden boards were placed behind the participant and the back of the seat in order to ensure that the angle between the thigh and the torso was the same for all participants. The axis of rotation was aligned with the lateral condyle of the femur and restraining straps were used at the hip, thigh and chest to prevent any extraneous movement. The pad of the lever arm was positioned proximal to the malleoli. The dynamometer lever arm length and horizontal and vertical positions were recorded for each participant in order to ensure that the testing position was the same across all testing days. Participants were asked to perform two maximal 3 second, maximal voluntary isometric contractions of the quadriceps, at six different joint angles (20°, 40°, 60°, 80°, 90°, 100°, (0° = full extension)). Contractions were performed consecutively at each of the six joint angles. Each participant was encouraged to exceed the target values obtained in the familiarization period on the day before. Visual feedback, via a visual display unit, which displayed force in real time, was provided throughout all testing (Baltzopoulos et al., 1991). Participants received a 5-min break between the first and second set of six contractions and a 3-min recovery period between each of the six contractions at each joint angle, in each set. The mean force for each 3-second contraction was recorded and the mean of the two contractions at each joint angle was used as the performance measure (Gleeson & Mercer, 1996). The torque-joint angle relationship was assessed prior to and 30-minutes after damage.

5.3.3.3 Jump height

Jump height was assessed with and without a rapid downward eccentric movement, which utilized the stretch shortening cycle (squat jump and countermovement jump) using an infra-red jump system. Prior to the assessment of jump height, all participants received a warm-up of 5 sub-maximal continuous jumps and 5 maximal continuous jumps. Participants performed 3 maximal jumps, separated by a 1-minute rest. Visual feedback via the VDU was provided throughout all testing. Participants were encouraged to perform to their maximal capacity and to try and jump higher than their previous jump. The highest jump height was taken as the performance measure. Jump height was calculated using microgate optojump software (DOS version 3), which utilizes the Komi and Bosco (1978) method to calculate the height of rise in the centre of gravity. The vertical take-off velocity (V) of the centre of gravity is calculated by:

$$V = 0.5(t_{air} \times g)$$

Where g = acceleration of gravity (9.81 m/s^2) and t_{air} = flight time in seconds

The height of the rise of the centre of gravity can be then calculated as follows:

$$\text{Height (m)} = \frac{V^2}{2g}$$

Only squat jump and counter movement jump height were evaluated in this study to avoid any potential risk of injury in the children's growth plates, as loads are high in this type of jump. Further, more changes in proprioception following EIMD may lead to poor muscle control and exacerbate the risk of injury (Saxton et al., 1995; Brocket et al., 1997; Pearce et al., 1998; Leger and Milner, 2001). Jump height was assessed before, 30 minutes, 24 hr, 48 hr and 72 hr after the plyometric protocol.

5.3.3.4 Squat jump (SJ)

Participants were asked to stand between the two infra-red sensor bars with their knees flexed to 90° and their hands on their hips. Participants were asked to look in an upward direction, as a number of participants had reported that looking up helped to eliminate any preparatory downward eccentric movement. This was also evident from a visual assessment of their performance during the familiarization period and during pilot work prior to the study. Upon the command "3,2,1 go", the participant jumped as high as possible. If the participant deviated from this position, or performed a preparatory downward movement they were asked to repeat the jump.

5.3.3.5 Counter movement jump (CMJ)

Participants were asked to stand between the two infra-red sensor bars in an upright position with their legs apart and their hands on their hips. On the command "3,2,1 go", the participant jumped as high as possible following a preparatory downward eccentric movement, where the knees bent to approximately 90° as fast as possible. Any deviation from the above criteria, the participant was asked to repeat the jump.

5.3.3.6 Pre-stretch augmentation

Pre-stretch augmentation was calculated using squat jump and counter movement jump heights in the following equation:

$$\text{Pre-stretch augmentation} = \frac{(\text{CMJ} - \text{SJ})}{\text{SJ}} \times 100 \quad \text{(Walshe et al., 1996)}$$

5.3.3.7 Isometric strength

Isometric strength was assessed in the seated position on an isokinetic dynamometer (Kin Com, 500H Chattecx, Chattanooga, TN, USA) at the individual optimal angle that elicited peak torque using the same method described in the torque-joint angle section.

5.3.3.8 Perceived Muscle Soreness

Perceived muscle soreness was evaluated using an illustrated visual analogue scale developed in chapter 3. Participants were asked to stand in an upright position with their legs apart and their hand on their hips facing the investigator. Following a slow knee bend, to a 90° angle, participants moved the sliding pointer along the continuum to indicate the sensation of soreness in their thighs.

5.3.3.9 Analysis

Isometric strength at the optimal angle, squat jump and counter movement jump data were expressed as a percentage of baseline measures in order to remove baseline differences. Torque-joint angle data were expressed as a percentage of peak torque. Isometric strength, squat jump and counter movement jump heights and perceived soreness data were analyzed using a 2-way mixed model analysis of variance (ANOVA) (Group, 2 x Time, 5) with repeated measures on time. Torque-joint angle data were expressed as a percentage of peak torque, pre and post damage data were then analyzed with a (Group, 2 x Joint angle, 6 x Time, 2) 3-way mixed model ANOVA. Power output data were corrected for lean thigh volume using a simple ratio standard (W/L), and a ANCOVA with lean leg volume as the covariate. Data were then analyzed using a 2-way (Group, 2 x Set, 8) mixed model ANOVA, and a 2-way ANCOVA with lean thigh volume as the covariate. ANCOVA was selected in favour of a power function ratio as the exponents for boys and men were significantly different (1.469 and 0.54 for boys and men respectively). Therefore, it was not possible to use a common exponent (Nevill, 1994; Vanderburgh et al ., 1995). Alpha was set at 0.05. The sphericity assumption was tested using Mauchly's Test of Sphericity. In the event of any violation of this assumption, Greenhouse-Geisser ($_{GG}$) corrections were applied. This method reduces the degrees of freedom and increases the critical value of the F statistic. Significant results were followed up using an adapted Tukeys' post hoc analysis for repeated measures (Stevens 1996). Hip extension, lean thigh volume, and pre-stretch augmentation data were analyzed using an independent groups t-test. A series of Pearson's product moment analyses correlations were performed to investigate the relationship between hip extension, soreness, peak isometric strength, squat jump height, counter movement jump height, % isometric strength loss after damage, % loss in squat jump height post damage and % loss in countermovement jump height after damage.

5.4 RESULTS

5.4.1 Passive hip extension and pre-stretch augmentation

An independent t-test indicated that boys had a significantly higher hip extension score than men 38 ± 4.9° cf. 23.8 ± 8.5° ($t_{2,18} = 4.5$, $P < 0.01$). There was no difference in pre-stretch augmentation between boys and men 21.8 ± 8.6 1 % cf. 19.9 ± 10.2 % ($t_{2,18} = 0.4$, $P > 0.05$).

5.4.2 Lean thigh volume

As expected boys had a significantly lower lean thigh volume 1.94 ± .33 l cf. 4.49 ± .51 l ($t_{2,18} = 13.3$, $P < 0.01$) concurring with the observations of Chia et al. (1997), who measured thigh volume using magnetic resonance imaging.

5.4.3 Power output during the plyometric jumping protocol

There was a significant interaction of group by set on absolute power output ($F_{3.9, 71.4} = 6.1$ $P<0.01)_{GG}$ and corrected power output expressed in watts per litre ($F_{3.9, 70.59} = 3.47$ $P<0.05)_{GG.}$ Follow-up tests indicated that power output was significantly higher for men than boys across all sets. There were no significant changes in boys' power output across sets. Absolute power output in men declined significantly by set 6 compared to sets 1, 2, 3, 4, and 5. Corrected power output (W) in men declined significantly by set 5 compared to set 1, with set 6 being significantly lower than sets 2, 3 and 4. (Figures 5.3a & b). When leg volume was used as a covariate, there were no significant main effects of set or group by set interaction (P>0.05).

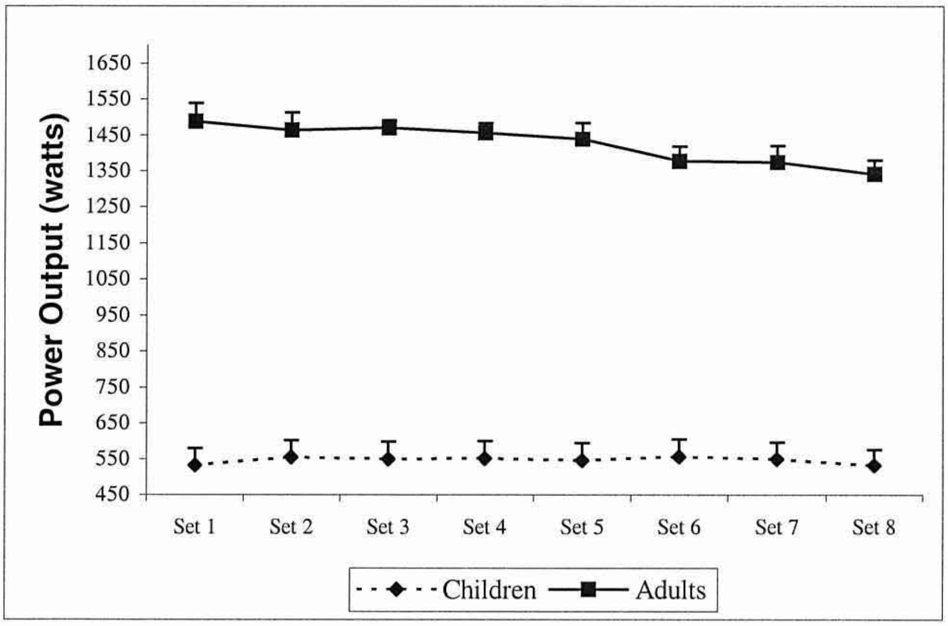


Figure 4a: Comparison of power output between boys and men during the plyometric protocol. Values are means and SEM.

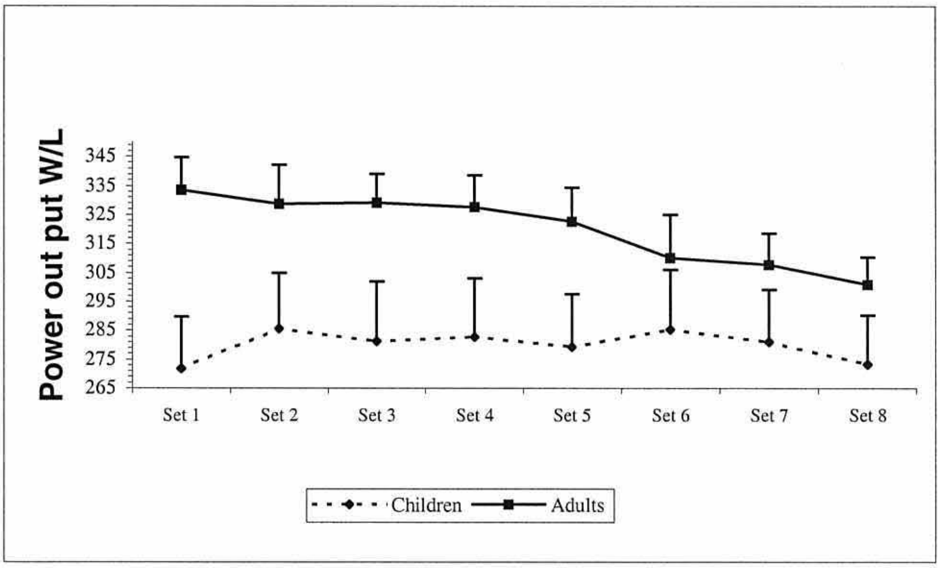


Figure 4b: Comparison of power output between boys and men during the plyometric protocol. Leg volume was used to correct power output (W/L). Values are means and SEM.

5.4.4 Torque-joint angle relationship

The 3-way ANOVA revealed a significant interaction of group by joint angle on the percentage of maximal torque ($F_{2.5,45} = 38.99$ $P<0.01$)$_{GG}$. Follow-up tests indicated that torque increased significantly at 20 °, 40 °, 60 ° and 80° of knee flexion in both groups. Torque at 90 ° and 100 ° decreased significantly in men, whereas there was no significant differences in torque at these angles in boys. Torque at 20 °, 40 ° and 60 ° was significantly higher in men compared to boys. There was no significant difference in torque between boys and men at 80° of knee flexion. Torque at 90 ° and 100 ° was significantly higher in boys compared to men (Figure 5.4). There was no significant main effect for time ($F_{1,18} = 0.11$ $P>0.05$), and no interactions involving time ($P>0.05$), indicating that there was no rightward shift in the torque-joint angle relationship after damage in either group.

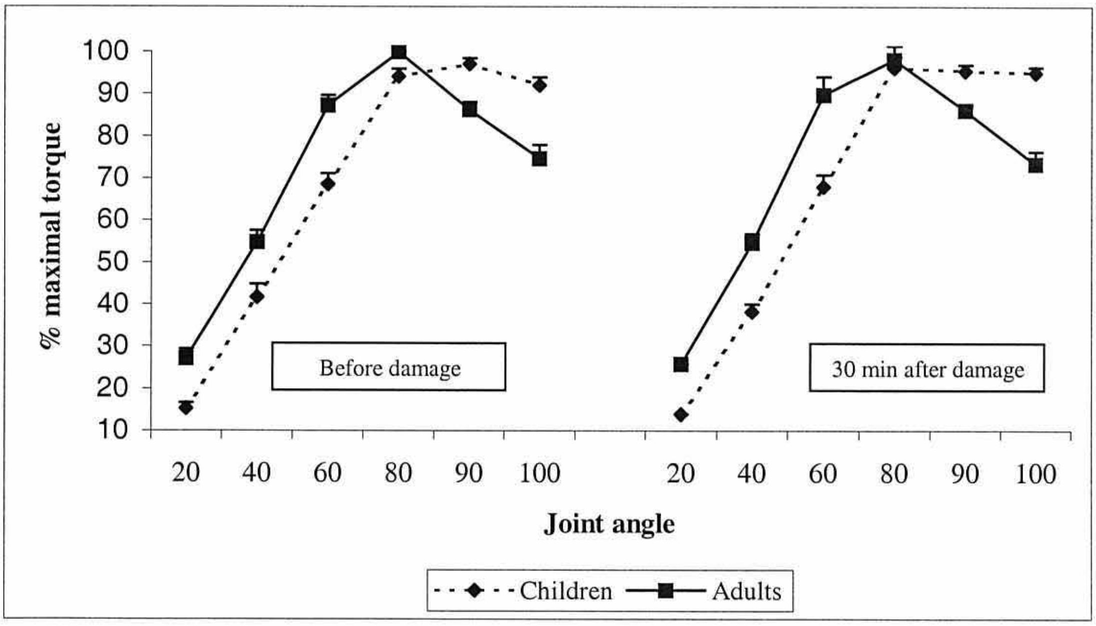


Figure 5.4: Comparison of the torque-joint angle relationship in boys and men. Values are means and SEM.

5.4.5 *Jump height*

There was no significant difference between percentage squat jump height and percentage counter movement jump height after plyometric exercise (when the data were expressed as a percentage of baseline values) ($F_{1,18} = 0.058$ $P>0.05$). A significant time by group interaction ($F_{2.4, 44.8} = 3.5$ $P<0.01$), indicated that percentage jump height in boys was significantly lower than baseline 30-minutes after plyometric exercise. The percentage jump height in men was significantly lower than baseline at all time points following the plyometric exercise. The percentage jump height in boys was significantly less affected at all time points after plyometric exercise, in comparison to men (Figure 5.5).

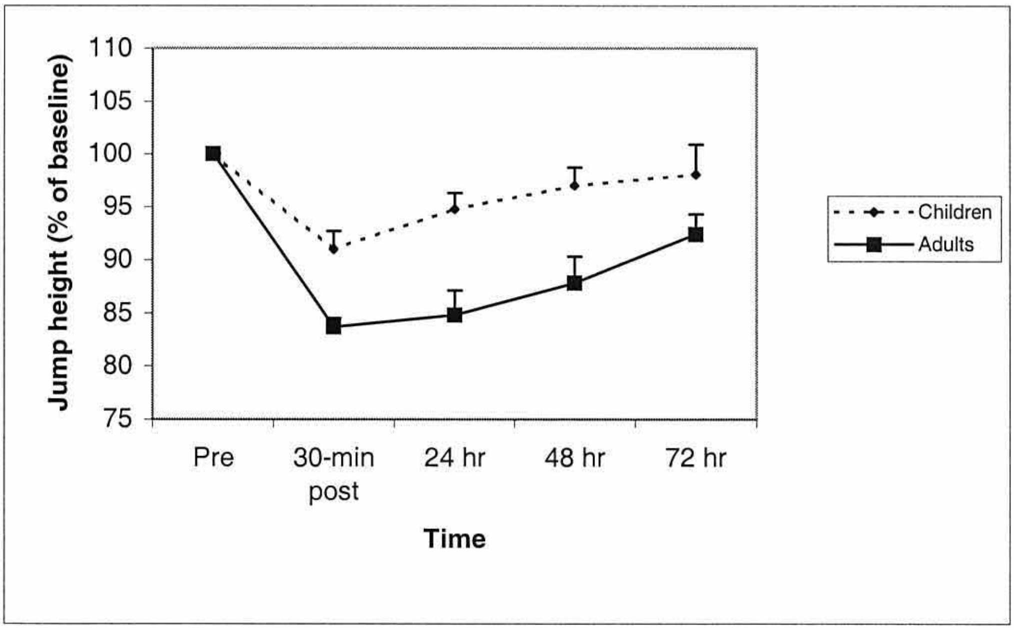


Figure 5.5: Comparison of jump height in boys and men. (Values are expressed as a percentage of baseline). Values are means and SEM.

5.4.6 *Isometric strength*

A significant interaction of time by group on isometric strength ($F_{2.6, 46.8} = 4.85$ $P<0.01)_{GG}$ indicated that % isometric strength in boys was significantly lower than baseline 30-minutes after plyometric exercise only. Isometric strength in men was significantly lower than baseline at all time points after plyometric exercise. Boys experienced significantly lower strength decrements at all time points after plyometric exercise in comparison to men (Figure 5.6).

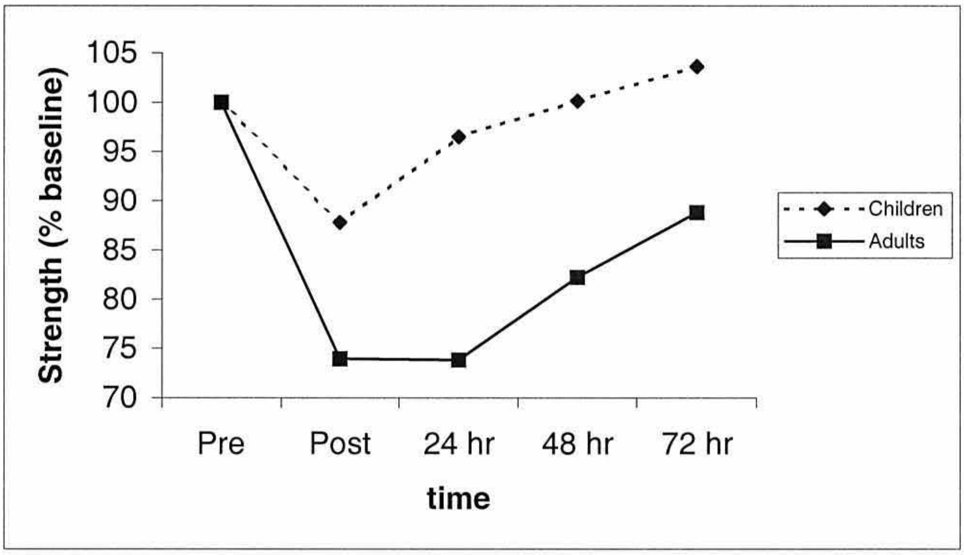


Figure 5.6 – Comparison of isometric strength at the angle that elicited peak torque in boys and men (values are expressed as a percentage of baseline). Values are means and SEM.

5.4.7 *Perceived muscle soreness*

A significant interaction of time by group on perceived soreness ($F_{2.3, 42} = 16.96$ $P<0.01)_{GG}$ indicated that perceived soreness in boys was significantly higher than baseline at 30-minutes and 24 hr after plyometric exercise. Perceived soreness in men was significantly higher than baseline at all time points after plyometric exercise. Boys experienced significantly lower levels of soreness at all time points after plyometric exercise in comparison to men (Figure 5.7).

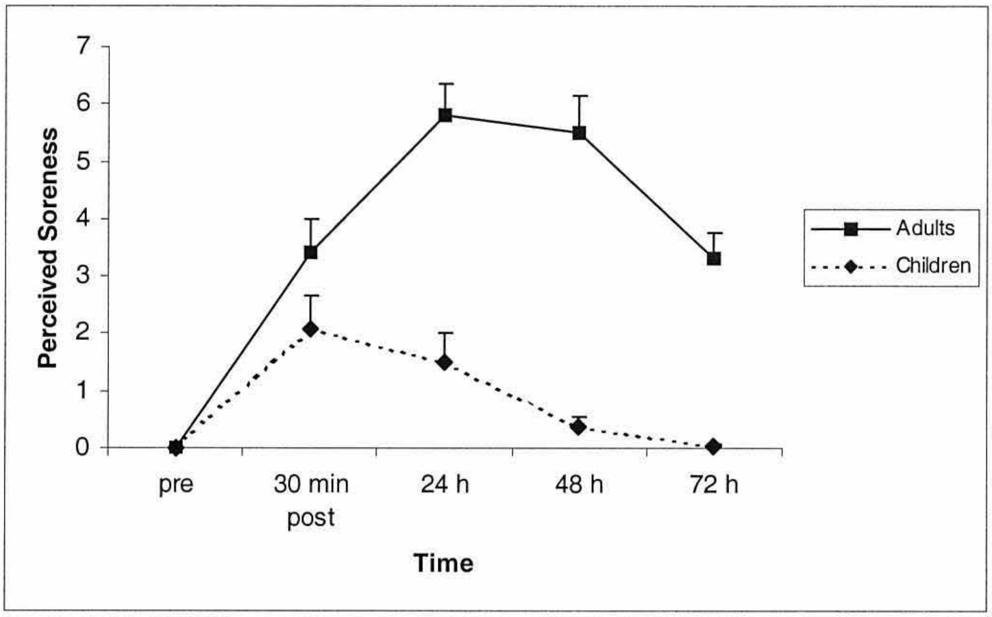


Figure 5.7: Comparison of perceived muscle soreness in boys and men. Values are means and SEM.

5.4.8 Relationship between indices of muscle damage and hip extension, peak isometric strength, and peak jump height in boys and men

5.4.8.1 Men

There was a significant negative relationship between hip extension and perceived muscle soreness (r = -0.62, P < 0.05) in men. Perceived soreness was also significantly related to the percentage loss in strength (r = - 0.63, P = 0.03). Peak isometric strength was significantly related to percentage loss in squat jump height (r = - 0.70, P = 0.01) and percentage loss in counter movement jump height (r = - 0.57, P = 0.04). The percentage loss in squat jump height was significantly related to the percentage loss in counter movement jump height ($r = -0.63$, $P = 0.03$). No other relationships were significant.

5.4.8.2 Boys

Peak isometric strength was significantly related to percentage loss in isometric strength ($r = -0.7$, $P < 0.05$), (i.e. the stronger children experienced a greater strength loss). The relationship between peak isometric strength and percentage loss in counter movement jump height ($P < 0.05$) and peak counter movement jump height were ($r = 0.57$ and $r = 0.58$, $P = 0.04$ and $P < 0.05$) respectively.

5.5 DISCUSSION

5.5.1 Passive hip extension and pre-stretch augmentation

Hip extension in boys was higher which suggests a higher level of muscle compliance or lower muscle stiffness. McHugh et al. (1999) observed that individuals with stiffer muscles experienced greater symptoms of EIMD. They suggested that more compliant muscles offer greater absorption in the aponeurosis-tendon complex during eccentric muscle action. This could reduce the amount of myofibrillar strain resulting in a lower number of sarcomeres being over extended beyond their normal functional range.

There was no difference in pre-stretch augmentation between boys and men. This index is thought to be indicative of the muscle's ability to use the stretch shortening cycle (SSC) (Walshe et al., 1996). It has been consistently observed that greater compliance is facilitative during activities requiring SSC (Wilson et al., 1991; 1994;

Walshe et al. 1996). This does not seem to be the case in the present study. Although the boys had a higher hip range of motion, there was no difference in pre-stretch augmentation. Paasuke et al. (2001) reported that pre- and post pubertal boys were unable to utilise the positive effects of the SSC, which contrasts with our findings. The possible lack of difference in the amount of augmentation in boys and men may possibly be explained by neural responses. The SSC is not purely a function of elastic strain energy. Neural reflexes such as the myotatic reflex also play a role (Komi, 2000). As the men were stiffer, an earlier myotatic response may have accounted for the lower availability of elastic strain energy.

5.5.2 Power output during the plyometric jumping protocol

The corrected power output values for men were higher in comparison to the boys. It may be inferred that the higher power output in the men would have likely resulted in a higher strain per muscle fibre, which induced greater muscle damage (Lieber and Friden, 1993). Additionally, power output in boys did not change across the eight sets, whereas power output in men decreased significantly by the fifth set. This observation may provide support for greater reliance on slow twitch fibre recruitment in boys. It has been suggested that the proportion of fast twitch fibres in children is lower in comparison to adults (Bell et al., 1989; Armstrong and Welsman, 1996). Preferential damage has been reported to occur in fast twitch fibres (Friden and Lieber, 1985, 1992; Jones et al., 1986; Byrne and Eston, 2002b), which might also offer a partial explanation for lower symptoms of EIMD in boys. However, when data were analysed with ANCOVA using lean thigh volume as the covariate, there was no significant difference in the power output between boys and men or any group by set interaction.

5.5.3 *Torque-joint angle relationship*

The torque-joint angle relationship demonstrated very similar characteristics to those observed in study 2 (chapter 4). No measure of muscle compliance was evaluated in the latter study, although it may be inferred that the differences could have been a result of a greater compliance in the boys. Measures of range of motion were included in the present study, which lend support for the differences being due to a greater level of muscle compliance in the boys. The possibility of biomechanical differences is acknowledged, as indicated earlier in chapter 3.

Muscle length is an important moderating factor in the amount of muscle damage that is sustained and the magnitude of the strength loss following muscle damage (Newham et al., 1988; Wood et al., 1993; Saxton and Donnelly 1996; Child et al., 1998; Byrne et al., 2000; Rowlands et al., 2001). Morgan's (1990) popping sarcomere theory predicts a greater disruption to sarcomeres when the muscle functions at longer lengths corresponding to the plateau or descending portions of the torque-joint angle curve. It is likely that the quadriceps muscle in men was exercising at longer muscle lengths in comparison to the boys due to differences in muscle compliance (see figure 4.2 in chapter 4).

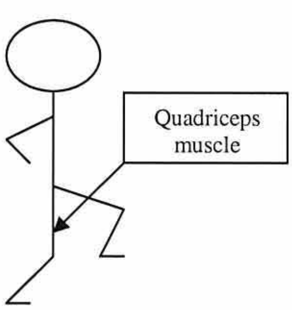


Figure 5.8a: muscle length during hopping

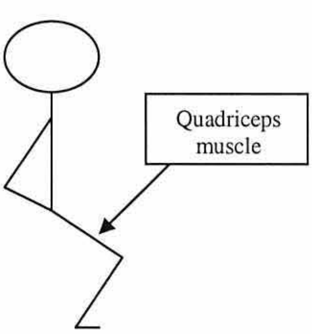


Figure 5.8b: muscle length during jumping

It can be noted from the above figure that hopping required a greater muscle length. It is apparent that the angles at the knee during these two activities correspond to different positions of the torque-joint angle curve (Figure 5.4), which may have resulted in greater levels of muscle damage.

It was postulated in chapter 3 that the similarities in the strength loss in the boys and men may have been due to the fact that individual optimal angles to elicit peak torque were not determined. Theoretically, a shift in the torque-joint angle curve towards longer muscle lengths may have exaggerated the decrements in strength in the boys (this is explained by Figure 3.6). A disproportional decrease in strength has been observed at short muscle lengths following damage (Wood et al., 1993; Saxton et al., 1996; Jones et al., 1997; Byrne et al., 2000). While the present study did not observe a rightward shift of the torque-joint angle relationship towards longer muscle length following damage, the possibility that a shift did occur following the hopping protocol used in chapter 3 cannot be totally excluded, as this relationship was not evaluated in chapter 3. The two different protocols, hopping for distance and plyometric jumps may have imposed different levels of strain on the muscle, and this may have resulted in differing amounts of muscle damage. The load was accommodated with both legs during jumping, whereas only one leg was loaded during hopping. Additionally the muscles would have been forced to function at longer lengths while hopping for distance in comparison to jumping (Figure 5.8a &b).

5.5.4 Jump height

Previous research has reported that squat jump is affected to a greater extent in comparison to counter movement jump following muscle damage (Chambers et al., 1998; Byrne and Eston, 2002a). In the present study, both jumps were affected to a similar extent. This may be due to protocol differences. Byrne and Eston (2002a) employed an eccentric squat protocol and Chambers et al. (1998) evaluated jump height following a 90-km foot race. The plyometric jumping protocol employed in this study will have been more dependant on the stretch shortening cycle in comparison to a much slower eccentric squat protocol used by Byrne and Eston (2002a). It may have therefore caused damage to both the contractile and non-contractile component of the muscle. Although, running involves the stretch shortening cycle, a 90-km race (such as in the study by Chambers et al., 1998) may have imposed a large metabolic demand on the muscle resulting in free radical damage, which may explain the contrasting results in the present study. Additionally the muscle would have functioned at longer lengths during the plyometric protocol in the present study

This is the first study to consider explosive strength in the form of jump height in children following exercise associated with high incidence of muscle damage. Jump height was consistently less in boys, suggesting less muscle damage. The decline in jump height in boys at 30 minutes may be attributable to fatigue.

5.5.5 Isometric strength at the optimal torque angle

Isometric strength in boys was significantly less affected after the exercise protocol. The strength loss in boys observed after 30 minutes was most likely due to fatigue. These observations concur with Soares et al. (1996), who observed greater strength decrements in adults following a bench press protocol. However, observations in chapter 3 indicated a similar reductions in strength in boys and men. These differences may be due to differences in the muscle damage protocols, as alluded to earlier. There is a greater eccentric force in hopping for distance, and the muscle was forced to function at a longer length in comparison to jumping. The muscle length of both boys and men in chapter 3 may have been functioning on the descending portion of the torque-joint angle curve.

5.5.6 Perceived muscle soreness

Boys reported less soreness then men, which concurs with previous observations (Soares et al. 1996; chapter 3). However, these findings differ to the observations of Webber et al. (1989) who reported that children experienced similar discomfort to adults following a downhill run. Boys reported peak soreness at 30 minutes after the exercise protocol. This returned to baseline by 48 hours. Men's soreness peaked at 24 to 48 hours after exercise and did not returned to baseline after 72 h. The differences in the temporal pattern of soreness in these two groups concur with the findings of chapter 3 and Soares et al. (1996).

5.5.7 Relationship between indices of muscle damage and hip extension, peak isometric strength, and peak jump height in boys and men

A significant negative relationship between hip extension and soreness indicated that men who had a greater hip range of motion reported less soreness. This finding supports the observation by McHugh et al. (1999), who reported that less stiff muscles experience less damage. A significant positive relationship between soreness and strength loss suggests that pain may have inhibited isometric torque in men. A significant positive relationship between strength loss and SJ and CMJ indicated that men who demonstrated the larger reductions in isometric strength also demonstrated larger reductions in SJ and CMJ. However, the relationship between SJ and CMJ with soreness was not significant, suggesting that pain did not inhibit explosive strength.

A significant positive relationship between peak isometric torque and isometric and CMJ strength loss in boys, suggests that stronger boys experienced greater reductions in isometric strength and CMJ after plyometric exercise. It is possible that a stronger muscle was able to exert greater force during the plyometric exercise resulting greater muscle damage and functional decrements.

5.5.8 Summary

In summary, boys experienced lower symptoms of EIMD following eighty plyometric jumps. Men demonstrated a higher power output during the damaging plyometric protocol, which remained when power output was corrected for lean thigh volume, suggesting a greater strain per unit of lean volume. The boy's ability to maintain power output during the plyometric exercise may be attributed to a greater reliance on slow twitch fibres in boys. Preferential muscle damage tends to occur in fast twitch muscle fibres, which are also more resistant to fatigue. Greater hip extension scores in boys suggests a greater level of muscle compliance, which was associated with lower symptoms of EIMD. In conclusion the lower symptoms of EIMD in boys, may be explained by a greater power output per unit of lean thigh volume during plyometric exercise in men, a possible greater reliance on slow twitch fibres in boys and a greater range of hip motion in boys. This is the first study to include measures of explosive strength after exercise that is associated with a high incidence of EIMD in boys and men. This study is also the first to relate the severity of the symptoms of EIMD with range of motion.

CHAPTER 6

Symptoms of exercise-induced muscle damage in boys and men following two bouts of eighty plyometric jumps.

The data from this chapter were presented at a meeting of the Physiological Society, York, 2001: Marginson, V.F. and Eston, R.G. (2001). Symptoms of exercise-induced muscle damage in boys and men following two bouts of eighty plyometric jumps. *Journal of Physiology, 539*, 17-19P.

6.1 ABSTRACT

Research on symptoms of exercise-induced muscle damage (EIMD) in children is limited. It is unknown if previous EIMD provides a protective effect in children. Ten boys aged 9-10 y and ten men aged 20-29 y, performed 8 sets of 10 plyometric jumps, on two different occasions. Power output was recorded and adjusted for lean thigh volume for each set of 10 jumps. Soreness, isometric strength, squat jump (SJ) and counter movement jump (CMJ) height, were recorded immediately before, 30 minutes, 24, 48 and 72 h after exercise. Both groups experienced less soreness following bout two, although boys experienced less soreness than men after both bouts of exercise (0.8 ± 0.9, 0.2 ± 0.9, for boys cf. 3.7 ± 1.0, 1.8 ± 1.0 for men, for bouts 1 and 2, respectively). Soreness in boys recovered faster following both bouts ($P<0.05$). There was a repeated bout effect for men only for the percentage of maximal squat jump height (%SJ) (97.4 ± 3.8 % and 98.4 ± 3.4 % for boys, cf 88.6 ± 3.5 %, 94.9 ± 3.6 % for men, for bout 1 and 2, respectively, $P<0.05$). However, a repeated bout effect was observed for both groups (95.3 ± 7 % and 101.3 ± 4.9 % cf 90.8 ± 5.1 % and 95.1 ± 4.6 % for men, for bout 1 and 2, respectively, $P<0.05$) for the percentage of maximal counter movement jump (%CMJ). Boys experienced less of a decline in %CMJ$_{max}$ and %SJ$_{max}$ following both bouts of exercise ($P<0.05$). There was a repeated bout effect for maximum strength retention for men only, (83.8 ± 8.2 % cf 90.3 ± 5 % $P<0.05$ for bout 1 and 2 respectively). Strength retention was higher in boys after both bouts (97.8 ± 11.6%, 102 ± 6.6 % for boys, cf 82.6 ± 11.7 %, 90.7 ± 6.8% for men, $P<0.05$). In conclusion the severity of the symptoms of EIMD was lower in boys. A prior bout of plyometric exercise attenuates all symptoms of EIMD in men. In boys, the only factors in which a repeated bout effect was observed was soreness and %CMJ height.

6.2 INTRODUCTION

The prophylactic effect of a prior bout of exercise-induced muscle damge (EIMD) and delayed onset muscle soreness is well documented in adults (Armstrong 1983; Ebbling and Clarkson, 1989; Morgan, 1990; Clarkson and Nosaka, 1992; McHugh et al., 1999; Proske and Morgan 2001). However, it is unknown if the same phenomenon is true for children. In adults, symptoms associated with EIMD are dramatically attenuated following a second bout of unaccustomed eccentric exercise. This effect is commonly referred to as 'the repeated bout effect' and is attained even if the symptoms associated with EIMD after the first bout are mild (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethy, 2001).

The protective effect of EIMD have been reported to last between 6-10 weeks (Byrnes et al, 1985; Nosaka et al., 1991) and up to 6 months for creatine kinase following damage to the elbow flexor muscles (Nosaka et al., 2001), but not in the quadriceps muscles (Lund et al., 1998).

Explanations for the repeated bout effect include neural, cellular and mechanical changes within the muscle (McHugh et al., 1999). The neural theory suggests a change in the recruitment and or an increase the synchronization of firing neurons (Perrynowski et al., 1987; Hortobagyi et al., 1998; Warren et al., 2000; Nosaka et al., 2001). Cellular adaptations include removal of weaker sarcomeres from the pool (Armstrong et al., 1983; Newham et al., 1987; Foley et al., 1999) and/or an increase in strength of the sarcolemma (Ebbeling and Clarkson, 1989) and the longitudinal addition of sarcomeres

(Friden et al., 1983; Lynn and Morgan, 1994; Lynn et al., 1998; Proske and Morgan, 2001; Brockett et al., 2001). Mechanical adaptations result from changes in the collagen content. The neural and mechanical theories suggest that the changes lead to a reduction in the mechanical stress placed on muscle fibres. The cellular theory suggests a strengthening of the muscle structures.

Recently, research on the effect of EIMD on explosive strength measures, such as jump height, has been conducted in adults (Mair et al., 1995; Chambers et al., 1998; Horita et al., 1999; Byrne and Eston, 2002). With the exception of the study by Mair et al., (1995), which evaluated explosive strength following two bouts of EIMD. There has been no research on the repeated bout effect in children following eccentric exercise. It is therefore unknown if a previous bout of EIMD attenuates symptoms following a second bout of eccentric exercise in children.

The aim of this study was to evaluate the severity of the symptoms associated with EIMD in boys and men following two bouts of eighty plyometric jumps. Specifically, the purpose of the study was to focus on the effects of two bouts of EIMD on soreness, squat jump height, counter movement jump height and isometric strength at the joint angle that elicited peak torque, in boys and men.

6.3 METHODS

6.3.1 Participants

Ten boys (age (mean ± SD) 9.9 ± 9.32 y, ht 138.2 ± 5.4 cm, mass 32.2 ± 6.3 kg) and ten men (age 22.2 ± 2.7 y, ht 183.5 ± 5 cm, mass 71.8 ± 6.3 kg) volunteered to participate in this study. All participants gave written informed consent. In the case of the children, parents/guardians gave written consent and children gave verbal assent to participate in this study. Prior to any participation in this study, all participants completed health questionnaires in order to screen for any potential health risk. Participants who reported any history of knee pain or injury were excluded from the study. At the onset of the study, participants attended the laboratory for a familiarization training session one day prior to testing. During this session, participants were given the opportunity to become familiar with the demands of the tests, which had been previously approved by the North West Wales NHS Trust Ethics Committee and to ask any additional questions. This period also served to obtain target values that the participant was encouraged to exceed during all subsequent testing. Measures of leg volume, using surface anthropometry (Jones and Pearson, 1969) were also collected during this time period.

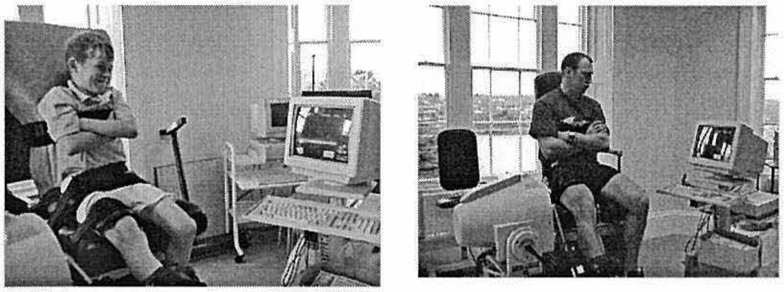
6.3.2 Plyometric exercise protocol for inducing muscle damage

Power output was assessed using an infra-red jump system (Optojump, Microgate S.R.L, Bolzano, Italy) interfaced with a Hi Grade AMD K2 366mHz lap top computer. Participants were asked to perform two bouts of eighty plyometric jumps separated by a two-week break. Data were then corrected for lean thigh volume (L) using a simple ratio standard, watts per litre (W/L) and analyzed using a multiple 2-way ANOVA (set (8) x Group (2)) and (set (8) x bout (2)) for both groups. Additionally data were analyzed using a 2-way ANCOVA (set (8) x Group (2)) with lean thigh volume as the covariate. For full details please refer to chapter 5.

6.4 MEASURES

6.4.1 Torque-joint angle relationship and isometric strength at the individual optimal angle for eliciting peak torque.

The torque-angle relationship was assessed at the onset of the study on an isokinetic dynamometer (Kin Com, 500H Chattecx, Chattanooga, TN, USA) in-order to identify the individual optimal joint angle that elicited peak torque for each participant. Participants were tested in the seated position and asked to perform two 3-second, maximal voluntary isometric contractions of the quadriceps muscle, at six different joint angles (20°, 40°, 60°, 80°, 90°, 100°, (0° = full extension)) (Figures 6.1a, b). The joint angle that elicited peak torque, based on the torque-joint curve, was then used to assess isometric strength at all other time points following both bouts of plyometric exercise. Please see chapter 5 for full details.



Figures 6.1a & b: Placement of participant for the measurement of isometric strength.

6.4.2 Jump height

As in chapter 5, jump height was assessed using an infra-red jump system (Optojump, Microgate S.R.L, Bolzano, Italy) interfaced with a Hi Grade AMD K2 366mHz lap top computer. Jump height was assessed with and without a rapid preparatory downward eccentric movement, which utilized the stretch shorten cycle (squat jump and countermovement jump). Prior to the assessment of jump height, all participants received a standardised warm-up of 5 sub-maximal continuous jumps and 5 maximal continuous jumps, in order to minimise the risk of injury. Participants performed 3 maximal jumps, separated by a 1-minute rest. Visual feedback via the VDU of the laptop computer was provided throughout all testing. Please see chapter 5 for full details.

Figure 6.2: Start position for the squat jump.

6.4.3 Perceived Muscle Soreness

Perceived muscle soreness was evaluated using an illustrated visual analogue scale developed in chapter 3. Following a slow knee bend, to a 90° angle, participants moved the sliding pointer along the continuum to indicate the sensation of soreness in the thighs (Figure 6.3).

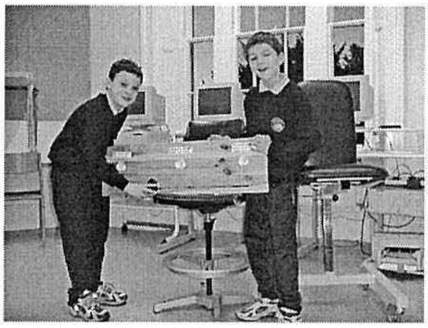


Figure 6.3: Participants with the soreness scale.

6.4.4 Analysis

Isometric strength at the optimal angle, and jump height during the squat jump and counter movement jump data were expressed as a percentage of baseline measures in order to minimise baseline differences. Isometric strength, squat jump and counter movement jump data were initially analyzed using a 3-way ANOVA (Bout (2), x Group (2) x Time (5)), which showed no main effect for bout. However, it was felt that the boys data was removing any effect for bout therefore, data were analyzed with separate 2-factor, ANOVAs (Bout, 2 x Time, 5) and (Group, 2 x Time, 5). Perceived soreness data were analyzed using a 3-factor ANOVA (Group, 2 x Bout, 2 x Time, 5). Power output data were corrected for lean leg volume using both a simple ratio standard (W^{-1}) and analysed using a 2-factor ANOVA (Group, 2 x Set, 8), and a 2-factor ANCOVA with (Group, 2 x Set, 8) with lean thigh volume as the covariate. Alpha was set at 0.05. The sphericity assumption was tested using Mauchly's Test of Sphericity. In the event of any violation of this assumption, Greenhouse-Geisser ($_{GG}$) corrections were applied. Significant results were followed up using an adapted Tukeys post hoc analysis for repeated measure (Stevens, 1996). Lean leg volume was analyzed using an independent groups t-test.

6.5 Results

5.5.1 Lean thigh volume

As expected, boys had a significantly lower lean thigh volume (1.94 ± 0.33 L cf. 4.49 ± 0.51L for boys and men, respectively) ($t_{2,18} = 13.3$, $P < 0.01$).

6.5.2 Power output during the plyometric jumping protocol

6.5.2 a Power output during bout 1

There was a significant interaction of group by set on absolute power output ($F_{3.9, 71.4} = 6.1$ $P<0.01)_{GG}$ and corrected power output expressed in watts per litre ($F_{3.9, 70.59} = 3.47$ $P<0.05)_{GG.}$ Follow-up tests indicated that absolute (W) and corrected (W/L) power output was significantly higher for men than boys across all sets. There were no significant changes in boys' power output across sets. Absolute power output in men declined significantly by set 6 compared to sets 1, 2, 3, 4, and 5. Corrected power output (W/L) in men declined significantly by set 5 compared to set 1, with set 6 being significantly lower than sets 2, 3 and 4. When leg volume was used as a covariate, there were no significant main effects or interaction ($P>0.05$).

6.5.2 b Power output during bout 2

A significant main effect for group ($F_{1,18} = 140$, $P<0.01$), indicated that men demonstrated a higher absolute power output during the second bout of plyometric exercise. There was no main effect for set ($P > 0.05$) or interaction of set by group ($P>0.05$). There was no significant difference in power output between boys and men ($F_{1,18} = 0.2$ $P>0.05$) during bout 2, with both groups maintaining power output across sets ($F_{7,126} = 0.4$ $P>0.05$) when the data was corrected using a simple ratio standard

(W/L). When the data were corrected using ANCOVA with lean thigh volume as the covariate, there was no significant main effect for set, or group ($P< 0.05$), and no group by set interaction ($p< 0.05$) (Figures 6.4a &b).

6.5.2 c Power output during bout 1 compared to bout 2 in boys and men

There was no significant difference in the power output of bout 1 and 2 for the boys ($P>0.05$). However, the men produced a significantly lower power output during the second bout of plyometric exercise ($F_{1,9} = 5.0$ $P=0.05$).

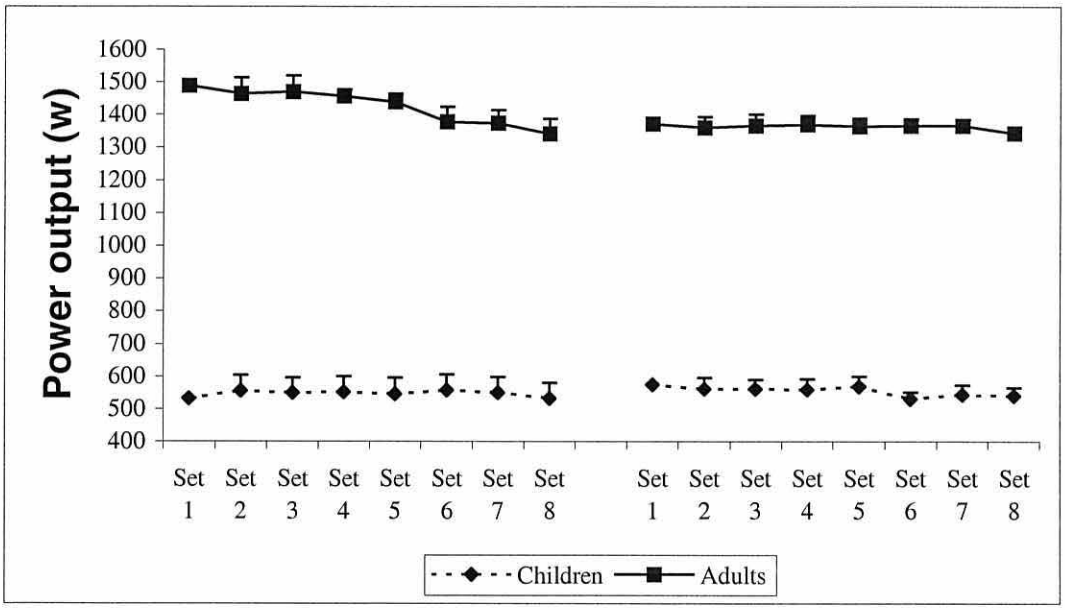


Figure 6.4a: Comparison of absolute power output in watts during the damaging plyometric protocol between boys and men. Values are means and SEM.

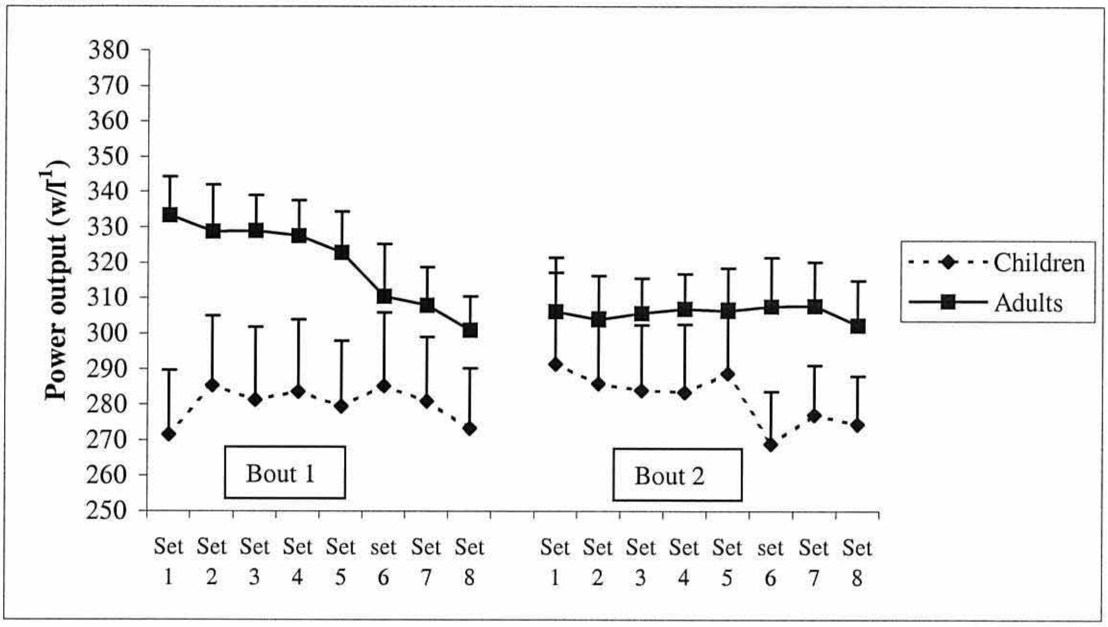


Figure 6.4b: Comparison of corrected power output in watts per litre during the damaging plyometric protocol between boys and men. Values are means and SEM.

6.5.3 *Individual optimal angle for peak torque*

Nine of the adults attained peak torque at 80° of knee flexion, one adult attained peak torque at 60°. However, the angle for attaining peak torque in children was more variable. Six children attained peak torque at 90°, two children attained peak torque at 100° and two children attained peak torque at 80° of knee flexion.

6.5.4 *Squat jump height*

Percentage of maximal squat jump height was significantly less affected following the second bout of plyometric exercise in the men only ($F_{1,9} = 14.9$ $P<0.05$). Following the first bout of exercise, a significant time by group interaction ($F_{4,72} = 5.2$ $P<0.01$) indicated that the boys % squat jump height was significantly less affected and had returned to baseline values 48 h after exercise. Men's % squat jump height had not returned to baseline values 72 h after exercise. Following the second bout of exercise, a significant main effect for group ($F_{1,18} = 4.9$ $P<0.01$) and time ($F_{4,72} = 9.2$ $P<0.01$) indicated that boys % squat jump was less effected and that % squat jump height had returned to baseline values 72 h after exercise. Men's percentage squat jump height had not returned to baseline values 72 h after exercise (Figure 6.6).

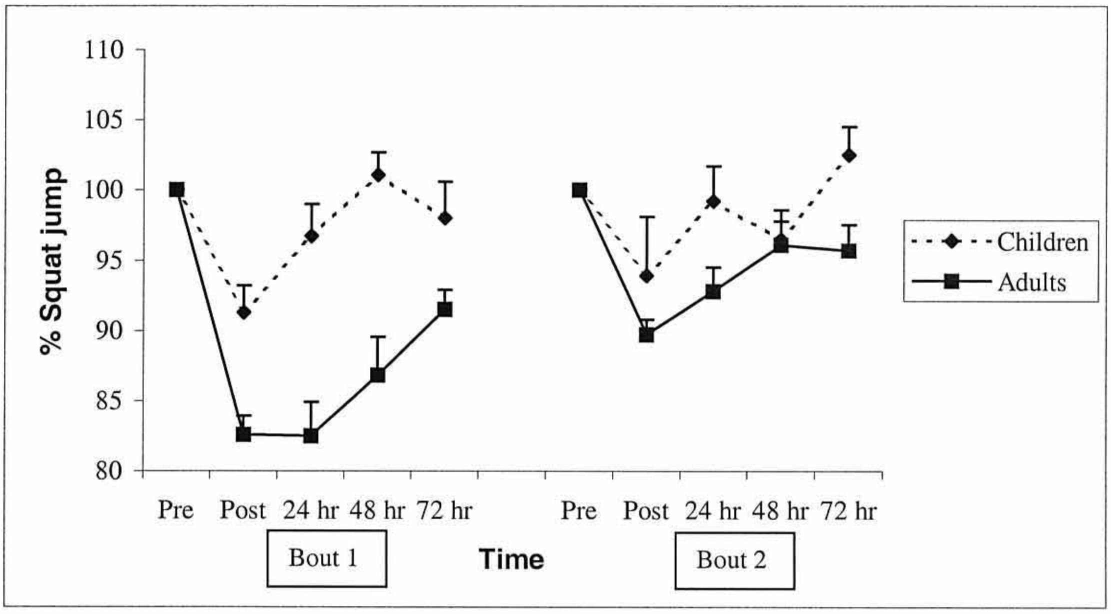


Figure 6.6: Comparison of percentage squat jump height in boys and men (values are expressed as a percentage of baseline). Values are means and SEM.

6.5.5 *Counter movement jump height*

Percentage of maximal counter movement jump height was significantly less affected following the second bout of plyometric exercise in both boys ($F_{1,9} = 8.5$ $P<0.05$) and men ($F_{1,9} = 7.6$ $P<0.05$). The percentage CMJ height was significantly higher in boys following bout 1 ($F_{1,18} = 5.4$, $P<0.05$) and bout 2 ($F_{1,18} = 15.2$ $P<0.01$)

compared to men (Figure 6.7). A significant main effect for time ($F_{4,72} = 14.4$ $P<0.01$) indicated that percentage counter movement jump height in boys was significantly lower than baseline values at 30 minutes, 24 and 48 hours after the first bout of exercise. Following the second bout of exercise, a significant time by group interaction ($F_{4,72} = 2.7$ $P<0.05$) indicated that the percentage counter movement jump height in boys was not significantly lower than baseline 30 minutes, 24 and 48 h after exercise and was significantly higher than baseline values 72 h after exercise. Percentage counter movement jump height in men was significantly lower than baseline values 30 minutes, 24 and 48 h following the plyometric exercise, recovering by 72 h.

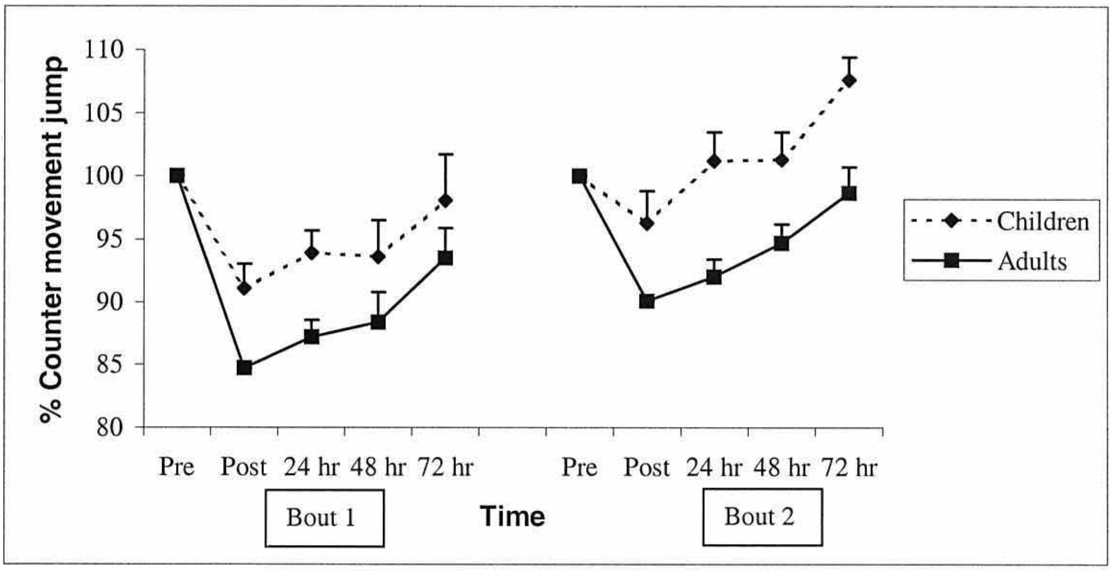


Figure 6.7: Comparison of percentage counter movement jump height in boys and men (values are expressed as a percentage of baseline). Values are means and SEM.

6.5.6 *Isometric strength.*

Percentage isometric strength was significantly less affected following the second bout of plyometric exercise in the men only ($F_{1,9} = 6.6$ $P<0.05$). Following the first bout of exercise, a significant time by group interaction ($F_{2.4, 42.9} = 4.0$ $P<0.01)_{GG}$ indicated that the boys' relative isometric strength was significantly higher than men's at all time points and was not significantly different from baseline values at any time point. Men's isometric strength had not returned to baseline values 72 h after exercise. Following the second bout of exercise, a significant group by time interaction ($F_{4, 72} = 4.0$ $P<0.05$) indicated that the boys isometric strength retention was significantly higher than men's at 24, 48 and 72 h after exercise and was lower than baseline values 30 minutes after exercise only. Men's isometric strength was lower than baseline values 30 minutes, 24, and 48 h after exercise. (Figure 6.8).

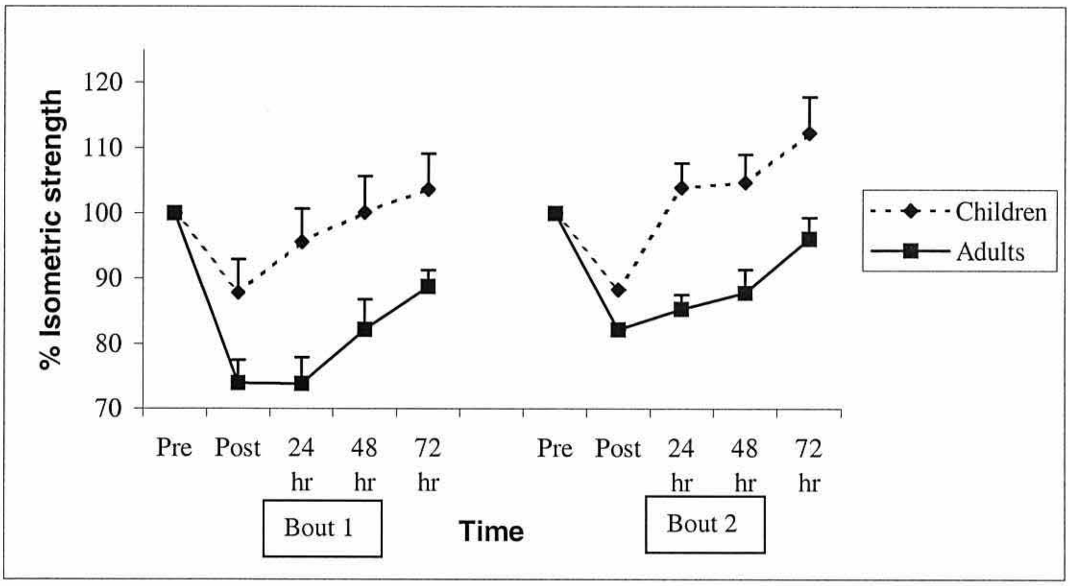


Figure 6.8: Comparison of percentage isometric strength retention at the individual joint angle that elicited peak torque in boys and men (values are expressed as a percentage of baseline) for boys and men. Values are means and SEM.

6.5.7 Perceived muscle soreness.

There was a significant interaction of bout by time by group on perceived soreness ($F_{2.1, 33.8} = 3.2$ $P= 0.05)_{GG}$. Post hoc tests revealed that perceived soreness in boys was significantly higher than baseline at 30-minutes and 24 hours after the first bout of plyometric exercise. Perceived soreness in men was significantly higher than baseline at all time points after the first bout of plyometric exercise. Boys experienced significantly lower levels of soreness at all time points after plyometric exercise in comparison to men following the first bout of plyometric exercise. Following the second bout of plyometric exercise, boys' soreness values were not significantly different from baseline. Perceived soreness in men increased significantly above baseline 30-minutes, 24 and 48 hours after exercise. After the second bout of exercise, perceived soreness in boys was significantly lower following at 24 and 48 h compared to bout 1. Men's soreness was significantly lower at 30 min, 24 and 48 hours after exercise compared to bout 1. Soreness in boys was significantly lower than men's at 24 and 48 hours after exercise in comparison to men following the second bout of exercise (Figure 6.9).

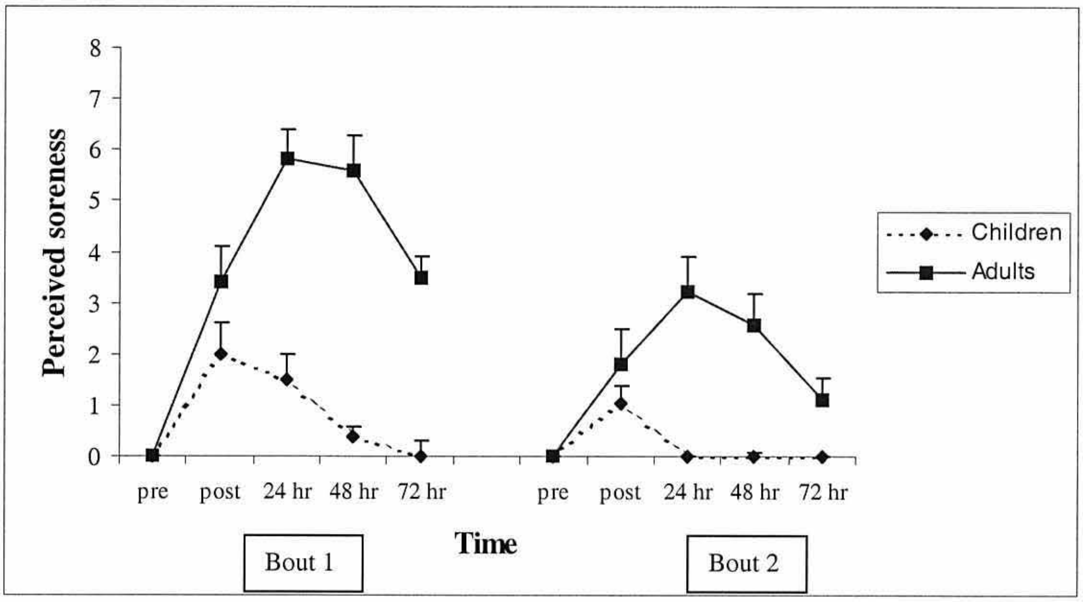


Figure 6.9: Comparison of perceived muscle soreness in boys and men. Values are means and SEM.

6.6 DISCUSSION

6.6.1 Power output

Boys' absolute power output (W) was significantly lower than men's during both bouts of plyometric exercise. Corrected power output (W/L) was lower in boys during the first bout, but similar during second bout. This may suggest that greater symptoms of EIMD experienced by men might be due to a higher force per lean thigh volume and thus a greater force per fibre. However, group differences for the second bout were removed when the data were corrected for lean thigh volume using the simple ratio standard (W/L) method and for both bouts using ANCOVA with lean thigh volume as the covariate. If the differences in the symptoms of EIMD were a result of differences in power output, then it might be anticipated that the symptoms following the second bout of exercise would have been similar in boys and men. This was not the case. It may be concluded that the differences in power output alone cannot account for the differences in the symptoms of EIMD.

The boys maintained power output during both bouts of plyometric exercise. However, power output in men declined by set 5 (W/L) or 6 (W) during the first bout, but did not decline significantly during the second bout. Boys' power output was similar during both bouts of plyometric exercise, with men producing a significantly lower power output during their second bout of exercise. As suggested in chapter 5, a greater reliance on slow twitch, fatigue-resistant muscle fibres, in the boys during exercise may account for the differences in EIMD between groups. This suggestion is supported by the fact the boys maintained their power output during both bouts of exercise. It was interesting to note that the men produced a lower power output that they were able to maintain during the second bout. Warren et al. (2000) reported a lower median frequency during a second bout of eccentric exercise and suggested a greater reliance on slow twitch muscle fibre activity, which are more resilient to damage (Friden and Lieber, 1988, 1992; Jones et al., 1986; Linnamo et al., 2000; Byrne and Eston, 2002b). Bell et al., (1989) and Armstrong and Welsman, (1996) have suggested that children have a lower proportion of fast twitch muscle fibres, which also supports the notion of a greater reliance on the slow twitch muscle fibre.

6.6.2 Differences in the individual joint angle that elicited peak torque

The joint angle that elicited peak torque in adults occurred at 80° of knee flexion in 9 out of 10 of the men. However, this angle was not consistent in the boys. Six boys attained peak torque at 90°, 2 attained peak torque at 100° and 2 attained peak torque at 80°. This finding is consistent with the observations in chapter 4 and could possibly be explained by growth. During growth, the bone grows faster than the muscle, forcing the muscle to elongate and adapt with the addition of sarcomeres (Alter, 1996). If this were the case, the angle that elicited peak torque would be anticipated to occur at shorter muscle lengths during this period. It would also be expected to manifest itself as a decrease in flexibility. This did not seem to be the case. Mean hip extension scores for boys who attained peak torque at 100°, 90° and 80° were 42.5°, 36° and 39°, respectively. Measurement of alkaline phosphotase levels, which increase following bone growth, may have provided a clearer picture of growth in this sample of boys (Eyre, 1997). Further research may consider the effects of growth on this variable on a larger sample in a longitudinal study, which includes measures of alkaline phosphotase. Additionally, reducing the increments between angles of knee flexion to 5° might afford a greater sensitivity highlighting any change.

6.6.3 Squat jump height

The percentage squat jump height in boys was less effected following both the first and second bouts of plyometric exercise, suggesting less muscle damage in the boys. Boys % squat jump height was similar following both bouts of exercise indicating that there was no prophylactic effect of a prior bout of eccentric exercise in boys. As expected, men demonstrated a repeated bout effect. The pattern of decline in percentage squat jump height in men concurs with previous observations following a single bout of eccentric exercise (Chambers., et al 1998., Byrne and

Eston, 2002 a). This is the first study to include measures of percentage squat jump to investigate the repeated bout effect in both adults and children making comparisons difficult.

6.6.4 Counter movement jump height

The percentage counter movement jump height was higher in boys following both bouts of plyometric exercise, suggesting less EIMD in boys. Both groups demonstrated a repeated bout prophylactic effect. However, the term repeated bout effect should be used with caution in the case of the boys. While the overall mean percentage counter movement jump was higher following the second bout of exercise, boys demonstrated a supra-maximal response 72 h after the second bout of exercise which will have exaggerated the difference. The supra-maximal response in the boys might have been as a result of a motor learning effect due to a faster recovery following the second bout of exercise (72h v 24h following the first and second bout respectively). Alternatively, changes in the neural firing pattern (Perrynowski et al., 1987; Hortobagyi et al., 1996; 1998; Warren et al., 2000; Nosaka et al., 2001; McHugh et al., 2001) or addition of sarcomeres (Friden, 1984; Morgan 1990; Lynn and Morgan, 1994; Lynn et al, 1998; Brockett et al., 2001) may also be responsible. Lynn et al. (1998) observed an increase in the number of sarcomeres after eight days in rat muscle following down hill running. However, it is difficult to say which of these mechanisms could be responsible. An EMG recording would have elucidated neural changes and should be considered in future studies in this population. It could be anticipated that if an addition of sarcomeres had occurred, a change in the optimal angle that elicited peak torque would have occurred. Again it is difficult to come to any definitive conclusion, as these changes would have been very small, making it unlikely to be observed in the 10^{O} increments between joint angles employed in this study. It would be logical for children to have a more dynamic system, both neurologically and morphologically, in order to accommodate growth. This is the first study to include measures of counter movement jump in children. The pattern of decline and recovery in countermovement jump in men concurs with previous findings following a single bout of eccentric exercise (Chambers., et al 1998., Byrne and Eston, 2002 a) and the repeated bout effect focusing on one leg (Mair et al., 1994).

6.6.5 *Isometric strength*

Isometric strength retention in boys was higher than men's at all time points following the first bout and at 24, 48 and 72 h after the second bout of exercise, suggesting less EIMD. These results concur with those of Soars et al., (1996) following a single bout of bench press exercise. There was no repeated bout effect for isometric strength in boys, although values were approaching significance. As expected, men demonstrated a repeated bout effect, where isometric strength was higher following the second bout of exercise and recovered faster, concurring with past observations (Newham et al., 1987; Eston et al., 1996; Hortobagyi et al., 1998; Rowlands et al., 2001)

It was interesting to note a similarity in the pattern of percentage countermovement jump and the percentage isometric strength following both bouts of exercise in both boys and men. The differences in the values in these two variables might be due to the exploitation of elastic strain energy from the series elastic component of the muscle and the myotatic reflex during the stretch shortening cycle (Walsh et al., 1996; Komi et al., 2000) during the counter movement jump. Isometric strength is more reliant on contractile components (sarcomeres redistributing and shortening (Gordon et al., 1966a; Edman and Reggiana, 1994)). It was surprising to see a greater similarity in the shape of the counter movement jump and isometric strength graphs. It would be more logical for the squat jump and isometric graphs to be similar, as these two variables are reliant on the contractile components of the muscle. Squat jump was the most difficult to perform out of these three variables and probably had the least experimental control and ecological validity for the sporting context. Future studies should consider either not using squat jump or assessing the day to day variability via a coefficient of variation in undamaged muscle.

6.6.6 Perceived soreness

Boys perceived lower levels of soreness following both bouts of exercise and recovered faster, concurring with Soars et al. (1996) observation following a single bout of bench press exercise. Both groups perceived lower levels of soreness and recovered faster following the second bout of exercise. This is a consistent observation in adults (Newham et al., 1987; Eston et al., 1996; Hortobagyi et al., 1998; Rowlands et al., 2001), but this is the first study to demonstrate this finding in children. Research has demonstrated that mild symptoms of EIMD in adults have resulted in a repeated bout protective effect (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethly, 2001), which might explain the reduction in soreness in the boys following the second bout of exercise.

Soreness in boys had returned to baseline values 24 h following the second bout of plyometrics, suggesting that fatigue was the most likely course of discomfort 30 minutes after exercise.

6.6.7 Summary

In summary, boys demonstrated a repeated bout effect for counter movement jump and soreness only, while men demonstrated this effect for all variables. This is probably due to minimal EIMD in the boys. Mild symptoms of EIMD result in a repeated bout effect for adults (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethly, 2001), which can account for the repeated bout effect in soreness and counter movement jump in boys. However, the difference between bouts for the boys counter movement jump was emphasised by a supra-maximal response 72 h after the second bout of exercise. As expected the men in this study demonstrated a repeated bout protective effect for all variables concurring with past observations (Mair et al., 1994). The boys in this study experienced few symptoms of EIMD on all variables in comparison to men, suggesting less muscle damage.

CHAPTER 7

Conclusions

7.1 Soreness and strength loss in boys and men

7.2 New contributions to the literature

7.2.1 Differences in the torque-joint angle relationship in boys and men

7.2.2 Differences in the symptoms of EIMD in boys and men

7.2.3 Explosive strength following muscle damage in boys and men

7.2.4 Evidence of differences in muscle compliance in boys and men

7.2.5 Other theories to explain differences in the symptoms of EIMD in boys and men

7.2.6 Repeated bout protective effect in boys and men

7.3 Study limitations

7.3.1 Sample size

7.3.2 Limitations of Chapters 3 and 4

7.4 Further directions

7.4.1 The effects of growth on the torque-joint angle relationship

7.4.2 The effects of growth and maturation on EIMD

7.4.3 The effects of a PNF stretching programme on EIMD

7.1 Soreness and strength loss in boys and men (chapter 3)

Differences in levels of soreness as a result of the high and low eccentric overload were detected in both groups. This suggests that the illustrated visual analogue scale was sensitive to differences induced by a higher overload. The temporal pattern of soreness concurred with past observations for both groups (Newham et al., 1987; Webber et al., 1989; Eston et al., 1996; Soares et al., 1996; McHugh et al., 1999), providing additional support for the sensitivity of the scale.

The boys in this study experienced lower levels of soreness following the high and hopping protocol only. Lower levels of soreness in boys following eccentric exercise concurs with the observations of Soares et al. (1996) following a weight training protocol. Additionally Duarte et al. (1999) observed that a higher eccentric stepping protocol induced greater levels of soreness in 13-year-old boys. The lack of differences in soreness following the low protocol is probably due to minimal damage occurring in both groups.

An alarming finding in this study was that while overall levels of soreness were lower in boys, strength loss was similar to that observed in the adult group. If discomfort is limited in children following eccentric exercise, then the possibility of an increased risk of injury might occur. If the muscle is weak, other structures such as the bone-tendon complex may well have to accommodate additional force. Incidents of chronic injuries such Osgood-Schlatters disease, which results from high forces on the bone–tendon complex (Kujala et al., 1985; Tansey, 1998) and osteochondritis dessicans, which results from high compressive forces (Singer, 1986; Ellenbecker and Mattalino, 1997) may be increased in sports that contain high frequencies of eccentric muscle actions (gymnastics). Reductions in proprioception have been reported following EIMD in adults (Miles et al., 1993; Saxton et al., 1995; Leger and Milner, 2001). It is likely that similar findings will exist in children and might increase the risk of injury.

While Warren et al. (1999) have argued for the use of functional measures to be used as indirect markers of EIMD, soreness acts as limiting moderator in levels of muscle action in adults. Thus the absence of soreness in children in this study is an important observation. As indicated in chapter 3, differences in the torque-joint angle relationship between boys and men may have resulted in the assessment of strength in boys being evaluated at relatively shorter muscle length. A disproportional reduction in muscle strength has been reported at shorter muscle lengths following EIMD (Wood et al., 1993; Saxton & Donnelly, 1996; Jones et al., 1997; Byrne et al., 2000). This point was addressed in study 2 (chapter 4) by evaluating the torque-joint angle relationship in boys and men and in studies 3 and 4 (chapters 5 and 6) by using the individual joint angle that elicited peak torque.

7.2 New contributions to the literature

7.2.1 Differences in the torque-joint angle relationship in boys and men (Chapters 4 and 5)

Research on the torque-joint angle relationship in children is limited. Williams and Stutzman (1959) observed a similar torque-tension relationship in a study that included both children and adults. However, joint angle was manipulated using 30° increments, which may have reduced the sensitivity of the study for identifying any differences between these two groups. Study 2 (chapter 4) was the first study to identify differences in the torque-joint angle relationship of the quadriceps muscle in boys and men. This finding was replicated in study 3 (chapter 5) using a slightly larger sample size.

Observations from studies 2 and 3 (chapters 4 and 5) indicated that the joint angle that elicited peak torque in men was fairly consistent at 80° of knee flexion. However, this angle was variable in boys and ranged between 80° and 100° of knee flexion with a mean of 90°. It was postulated that differences in muscle compliance could account for this finding. If children have a greater level of muscle compliance, then a longer muscle length might be required to elicit peak torque. As the contractile component (sarcomere) of the muscle shortens, it is thought that the non-contractile component (series elastic component and connective tissue) of the muscle lengthens (Griffiths, 1990; Ito et al., 1998; Griffiths, 1990). Therefore, theoretically greater levels of muscle compliance might result in a greater lengthening of the non-contractile component of the muscle, requiring a greater muscle length to attain the optimal muscle length that elicits peak torque.

The clinical correlate of muscle compliance is range of motion (Gleim & McHugh, 1997). One of the limitations of chapter 4 was that no measure of flexibility was assessed. However, this limitation was addressed in chapter 5 and discussed in chapter 6. It was anticipated that children with a greater range of motion would demonstrate a longer muscle length and hence attain peak torque at a greater joint angle (90 – 100°). However, this did not seem to be the case. Reduction in the increments between joint-angles to 5° may have afforded a greater sensitivity and highlighted smaller differences. Range of motion, as assessed by an adapted hip extension measure described in chapter 5, indicated that the boys in studies 5 and 6 had a significantly higher range of motion, suggesting a higher level of muscle compliance.

7.2.2 Differences in the symptoms of EIMD in boys and men (chapters 3, 5, & 6)

All symptoms of EIMD were lower in the boys in chapters 5 and 6 with lower levels of soreness reported in study 1 (chapter 3) only. Conclusions regarding the findings of chapter 3 are presented above. The differences in the observations between chapter 3 in comparison to chapters 5 and 6 may be accounted for by the use of the optimal angle that elicited peak torque for the measurement of isometric strength in chapters 5 and 6 and differences in muscle length while hopping and jumping. As indicated in chapter 5 figures 5.8a &b (p 83), the muscle length during hopping is assumed to be greater. Greater levels of EIMD are associated with exercising the muscle eccentrically at longer muscle lengths in adults, especially lengths that correspond with the descending portion of the length-tension curve (Newham et al., 1988; Wood et al., 1993; Saxton and Donnelly 1996; Child et al., 1998; Byrne et al., 2000; Rowlands et al., 2001).

The findings of study 3 (chapter 5) support the observations of Soars et al. (1996) who reported lower symptoms of EIMD in children following a weight training protocol. However, they contrast with the findings of Webber et al. (1989) following a downhill running protocol. Exercise that includes the use of the stretch shortening cycle (e.g. jumping, hopping) is probably a more ecologically valid activity for children, being a fundamental characteristic of chidren's play activities. However, the length at which the muscle functions is probably similar in hopping and downhill running, which may explain the similarities in strength loss between boys and men in study 1 (chapter 3). Unfortunately, Webber et al. (1989) did not include strength measures in their study, making comparisons difficult. Additionally, the use of both genders (men, women, boys and girls) may have reduced the effect size and hence the sensitivity of this study, as women have been reported to experience lower symptoms of EIMD due to the protective effect of oestrogen (Kendall and Eston, 2002).

7.2.3 *Explosive strength following muscle damage in boys and men (chapters 5 & 6)*

Few studies have evaluated explosive strength, such as jump height, following EIMD. Recently, measures of explosive strength (jump height), have been conducted in adults (Mair et al., 1995; Chambers et al., 1998; Horita et al., 1999; Byrne and Eston, 2002a). Studies 3 and 4 (chapters 5 and 6) are the first studies to include such measures in children following eccentric exercise. As indicated in study 3 (chapter 5), jump height provides a convenient model in which to study jump parameters with and without the use of the stretch shortening cycle and is a more ecologically valid muscle action within the sporting context (Horita et al., 1999). Muscle function has been considered a more reliable marker of EIMD and there has been a call for a greater use of functional measures following EIMD (Warren et al., 1999). The pattern of decline and recovery was similar to that of isometric strength loss in both groups, especially counter movement jump. This was a surprising finding as counter movement jump utilizes the stretch-shortening cycle, while isometric strength is more reliant on the contractile component (sarcomere shortening and redistribution). It was suggested in study 4 (chapter 6) that this may have been due to squat jump being more difficult to perform correctly.

7.2.4 Evidence of differences in muscle compliance in boys and men (chapters 5 & 6)

As indicated above, the clinical correlate of muscle compliance is range of motion (Gleim & McHugh, 1997). Hip extension was significantly higher in boys compared to men ($38 \pm 4.9^{\circ}$ cf. 23.8 ± 8.5). There was no significant difference in pre-stretch augmentation (chapter 5 section 5.5.5.6.) between boys and men (21.8 ± 8.61 % cf. 19.9 ± 10.2 %), although boys did tend to demonstrate higher values than men. On the basis of these measures it was concluded that there was evidence of higher levels of muscle compliance in boys. Lower levels in the rate of force development (Paasuke et al., 2001) and greater electromechanical delay in children (Asai & Aoki, 1996) have been observed in previous studies and support the notion of higher levels of muscle compliance in children. It is logical that greater muscle compliance would lead to an increase in electromechanical delay and a lower rate of force development as the muscle would have to reel in the stretch of the series elastic component (take up the slack) before the force would be translated to the bone-tendon complex. Further study is needed to evaluate the relationship between electromechanical delay, rate of force development and range of motion.

7.2.5 Other theories to explain differences in the symptoms of EIMD in boys and men

The work presented in the thesis is the first to evaluate and present evidence that children, like adults (Newham et al., 1988; Wood et al., 1993; Saxton and Donnelly 1996; Child et al., 1998; Byrne et al., 2000, Rowlands et al., 2001), will demonstrate differences in the symptoms of EIMD as a result of exercising at longer muscle lengths. Additionally, this work is the first to postulate and present evidence that muscle compliance may be a moderating factor in EIMD in children. This extends the work of McHugh et al. (1999) who presented evidence of differences in symptoms of EIMD which were attributed to passive muscle stiffness in adults.

It was felt that additional factors, such as a lower percentage of fast twitch fibres in children (Bell et al., 1989; Armstrong and Welsman, 1996), which are more susceptible to EIMD, (Friden and Leiber, 1988; 1992; Jones et al., 1996; Byrne and Eston, 2002b) could also explain differences in symptoms of EIMD in these two populations. A difference in the percentage of fast twitch fibres between the two groups would have manifested itself as a difference in the pattern of power output during the damaging protocol. Studies 3 and 4 (chapters 5 and 6) supported the notion of a lower percentage of fast twitch fibres in boys, as power output was consistent across all 8 sets of exercise during both the first and second bouts of plyometric exercise, suggesting that children were more reliant on slow, fatigue-resistant muscle fibres. However, men, were unable to maintain power output in bout 1 (chapter 5) suggesting a greater reliance on the fatigue susceptible fast twitch fibres, where damage is more prevalent (Friden and Leiber, 1988; 1992; Jones et al., 1996; Byrne and Eston, 2002b). In chapter 6, both boys and men maintained their power output, with men demonstrating a lower power output during this bout compared to the first. This was consistent with the suggestion of Warren and co-workers (2000), who presented EMG evidence of a greater reliance on slow twitch, fatigue-resistant muscle fibres during a second bout of eccentric exercise. This could account for lower indirect markers of EIMD (repeated bout protective effect) observed in this study.

A greater force per muscle fibre in men could account for greater symptoms of EIMD in men. Power output during the first bout (W/L of lean thigh volume) was higher in men, but similar to that of the boys in the second bout. When data were corrected with ANCOVA, power output during both bouts was similar in boys and men. If the differences in symptoms of EIMD were solely due to a higher power output in men, then symptoms of EIMD could be expected to be similar in both groups following the second bout of exercise as power output was similar. This was not the case. Boys demonstrated lower symptoms on every variable following the second bout of exercise.

7.2.6 Repeated bout protective effect in boys and men (chapter 6)

Study 4 (chapter 6) is the first study to investigate the prophylactic effect of a prior bout of eccentric exercise in children. As expected, men demonstrated a repeated bout effect for all variables. However, boys demonstrated a repeated bout effect for soreness and counter movement jump only. This is probably due to minimal decrements in isometric strength and squat jump suggesting that minimal EIMD occurred in boys. There were also small reductions in counter movement jump, with a supra-maximal response 72 h after the second bout of exercise. This will have emphasized the differences between bouts. This suggests that minimal EIMD occurred and allowed a learning effect to take place. Alternatively, the hypothesised addition of sarcomeres (Friden, 1984; Morgan, 1990; Lynn and Morgan, 1994; Lynn et al., 1998; Brocket et al., 2001), which would provide scope for greater cross bridge formations, could account for this change. It was notable however, that there was no change in squat jump and isometric strength, which if this was the case, would provide further evidence of the proposed theory of sarcomere addition. Neural changes (Perrynowski et al., 1987; Hortobagyi et al., 1996; Warren et al., 2001; Nosaka et al., 2001; McHugh et al., 2001) may also provide an explanation. This would be more likely to manifest itself in the counter movement jump, as the stretch shortening cycle utilizes the myotatic reflex as well as elastic strain energy. The use of EMG in future studies would provide further clarification on this question. As indicated above, this is the first study to investigate the repeated bout effect in children. The reduced soreness in boys following a prior bout of eccentric exercise, concurs with the observations in adults, where mild symptoms of EIMD can result in a prophylactic effect (Clarkson and Tremblay, 1988; Brown et al., 1997; Nosaka et al., 2001; Paddon-Jones and Abernethy, 2001).

7.3 Study limitations

7.3.1 Sample size

All studies in the thesis contain between 8 –10 subjects. While these sample sizes provided sufficient statistical power for the large effect sizes within the studies, further study is needed to confirm the findings in order to generalise to the general population (Huck and Cormier, 1996).

7.3.2 Limitations of chapters 3 and 4

Studies 3 and 4 make reference to differences in muscle compliance to explain their findings. However, no measures of flexibility were included in the studies. This limitation was addressed in chapter 5 and evidence of greater muscle compliance was presented.

Measures of isometric strength were conducted at 80° of knee flexion in chapter 3. It was suggested that this was inappropriate due to a disproportional reduction in strength occurring at shorter muscle lengths (Newham et al., 1988; Wood et al., 1993; Saxton and Donnelly 1996; Child et al., 1998; Byrne et al., 2000, Rowlands et al., 2001) and that if children had greater levels of muscle compliance, then differences in the torque-joint angle relationship may be observed. Chapter 4 addressed this point and demonstrated torque-joint angle differences. This finding was also replicated in chapter 5. However, it was difficult to conclude that the differences in the torque-joint angle relationship could be solely due to differences in muscle compliance (chapter 6). It could be anticipated that children with greater hip extension scores would have attained peak torque at longer muscle lengths (90-100° of knee flexion), but this did not seem to be the case. It is acknowledged that the visual analogue scale used throughout this thesis is a subjective measure and has been suggested to be a less reliable indicator of EIMD (Warren et al., 1999). It is difficult to validate such a measurement tool as there is no criterion measure in which to make comparison with.

7.4 Further directions

7.4.1 The effects of growth on the torque-joint angle relationship

During growth, the bone grows faster than the muscle stretching it (Alter, 1996). The muscle adapts with the addition of sarcomeres. Changes in the torque-joint angle relationship, where the angle that elicits peak torque occurs at shorter muscle lengths during this period would be logical. There has been no research effort on the effects of growth on this relationship or at what point children or adolescent display a similar torque-joint angle relationship to that of adults. Measures of chemical markers such as alkaline phosphates to indicate growth and hormones for maturational status could also be considered in future studies.

7.4.2 The effects of growth and maturation on EIMD

Similar to research on the torque-joint angle relationship, there has been no research on the effects of growth and maturation on EIMD and at what point symptoms of EIMD in children and youths are similar to those of adults. It could be anticipated that during the adolescent growth spurt, symptoms of EIMD would increase. This would be due to a decrease in range of motion during this period. Eccentric actions at longer lengths incur greater EIMD. Differences in the findings of study 1 (chapters 3) in comparison to studies 3 and 4 (chapters 5 and 6) may be explained by the assumption that hopping exercise requires the muscle to function at longer lengths, concurring with adult findings. It would therefore, be logical to observe changes in symptoms of EIMD due to growth.

7.4.3 The effects of a PNF stretching programme on EIMD

It is well documented that PNF stretching induces a significant increase in range of motion in a short period of time (Holt, et al., 1970; Tanigawa, 1972; Sady et al., 1982; Etnyre and Lee, 1988). Stretching immediately before or after eccentric exercise has no effect on the symptoms of EIMD (High et al., 1989; Lund et al., 1998; Johansson et al., 1999; Black and Stevens, 2001). Suprisingly, there has been no research on the effect of increasing range of motion on the symptoms of EIMD. It would be more appropriate to conduct this study on adults, as the National Coach Foundation (personal communication), does not recommend PNF for children. Concentric training is associated with a decrease in the number of sarcomeres, forcing the muscle to function at shorter muscle lengths where the muscle functions on the descending portion of the length-tension curve. Subsequent eccentric exercise results in greater EIMD (Lynn and Morgan, 1994, Lynn et al., 1998) in rats and in humans (Whitehead et al., 1998; Ploutz-Snyder et al., 1998; Gleeson et al, 2003). Therefore, increasing range of motion should theoretically, shift the torque-joint angle relationship towards longer muscle lengths.

CHAPTER 8

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Appendix A

Examples of letters to parents

Dear parent/guardian

I am a PhD student at the University of Wales Bangor. I am studying the effects of exercise on children, in the School of Sport, Health and Exercise Sciences to establishing whether or not children suffer from muscle soreness following certain types of exercise.

I am about to commence the first study and request permission for your son to participate if he is willing. Please find enclosed details of the investigation and an informed consent form. I would appreciate it if you could sign this form and return it to your son's school. I will contact you soon to arrange times and transport to and from our laboratory.

Yours sincerely

Vicky Marginson

Appendix B

Example of children's informed consent

Informed Consent Form

Dear Parent/Guardian

Re: Study of muscle compliance in children and adults: implications for delayed onset muscle soreness

Description of the study

The sensation of muscle soreness following exercise is very common. The aim of this study is to establish if children experience the same amount of muscle soreness as adults after exercise. This study will measurement: hip flexibility, which involves the investigator moving your child's' leg through its normal range of motion and thigh strength, which is measured in a sitting position on a Kin Com isokinetic dynamometer. This is a machine for measuring strength. Strength measurements will involve maximal contractions of the thigh muscle at six different joint angles. This will be repeated following a five-minute rest. After a further period of rest each child will perform a series of jumps.

Children will be asked to attend the laboratory one week prior to all testing for a familiarisation period, where they will be given the opportunity to try the strength and jumping tests. In the following week they will be asked to return to the laboratory to perform the above tests again. This will be followed by three sets of 25 continuous jumps separated by a three-minute rest between each bout (total of 75 jumps). Participants will be free to stop or withdraw at any time during these jumps. These measures will take approximately one hour of your child's time. It is possible that your child may experience a short, mild bout of muscle soreness, which will be most evident approximately two days after jumping. This will disappear after a few days.

Your child will then be asked to return to the laboratory one hour later and on a daily basis for assessments of any muscle soreness, jump height and leg strength. Assessment of muscle soreness involves lowering into a crouch position by bending the knees and moving a pointer along a sliding scale to indicate discomfort. Strength will be measured as described above. Children will then perform six jumps for height. These tests will take approximately half an hour per day for five consecutive days. There will be a minimum of two adults present at all times, and you are welcome to come along and observe. Transport to and from the laboratory will be arranged. All testing will be carried out outside school hours in order to prevent interruption to your child's education. If you have any questions about the study please feel free to phone us on the above numbers.

Thank you for your help.

Vicky Marginson, PhD Student
Dr Roger Eston (Head of School)

Freedom of consent

I understand that my child will be asked to participate in the above investigation and that he may experience a short bout of muscle soreness for a few days following a bout of jumping exercise. I am happy that I have received enough information regarding the requirements and purpose of this study, and that we have had an adequate chance to ask questions. I understand that we may ask additional questions at any time. I agree that my child is participating in this study of his own free will and that either my child or I may withdraw from this study at any time without prejudice.

Name of child ____________________________

Signature of Parent/Guardian ___________________ Print _________________________

Date ________________ Home phone number _________________________

Appendix C

Example health questionnaire

UNIVERSITY OF WALES, BANGOR
SCHOOL OF SPORT, HEALTH AND EXERCISE SCIENCE
CHILDRENS' PRE-TEST HEALTH QUESTIONNAIRE

STRICTLY CONFIDENTIAL

Name:

Age:

Please answer these questions truthfully and completely. The sole purpose of this questionnaire is to ensure that you are in a fit and healthy state to complete the exercise tests.

1. How would you describe your child's present level of activity?

Vigorous activity:

- Less than once a month
- Once a month
- Once a week
- Two or three times per week
- Four or five times a week
- More than five times a week

What form of activity/sport if any, does your child take part in?

---

2. Does your child suffer or have they ever suffered from any heart complaints?
YES/NO

3. Does your child suffer from or have they ever suffered from:

Asthma	YES/NO	Diabetes	YES/NO
Bronchitis	YES/NO	Epilepsy	YES/NO
High blood pressure	YES/NO		

4. Has your child had to consult your doctor in the last three months?
YES/NO
If YES, please give brief details:

____

____

____

5. Is your child currently taking any form of medication? YES/NO
If YES, please give brief details:

____

____

____

---

6. Does your child have any form of muscle or joint injury?
YES/NO
If YES, please give brief details:

____

____

____

7. Has your child suffered from a bacterial or viral infection in the last two weeks? YES/NO

8. Has your child had to suspend his training in the last two weeks for any physical reason? YES/NO

9. Is there any reason why your child should not be able to successfully complete tests which require maximum effort? YES/NO
If YES, please give brief details:

____

____

____

Signature of Subject: .... Date: ....

Signature of Parent/Guardian: .... Date: ....

Appendix D

Example of ethics approval

Prifysgol Cymru · University of Wales
BANGOR

School of Sport, Health and Exercise Sciences
University of Wales, Bangor
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Ysgol Gwyddorau Chwaraeon, Iechyd ac Ymarfer
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Mrs Vicky Marginson
SSHES
UWB

22nd November 1999

Dear Vicky

Re: A comparison of the relationship between soreness and muscle function in children and adults after eccentric exercise

Thank you for submitting the above proposed study to the School Ethics Committee. I am pleased to inform you that the study has this Committee's full ethics approval.

If, during the course of the study, there are substantial protocol changes, serious adverse events, or major participant recruitment problems, you are required to notify the Committee as soon as possible.

The Committee wishes you every success with your research.

Yours sincerely

Roger Eston.

Dr Roger G Eston
Ethics Committee Chairman

NORTH WALES HEALTH AUTHORITY
RESEARCH ETHICS COMMITTEE (WEST)

PWYLLGOR MOESEG YMCHWIL (GORLLEWINOL)
AWDURDOD IECHYD GOGLEDD CYMRU

Ffôn/Tel : (01248) 384877 (direct line)

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Room 1/178
Ysbyty Gwynedd
Bangor
Gwynedd LL57 2PW

Certificate of Confirmation of Ethics Approval

Name of Lead Researcher : Dr R Eston

Title of Study : Muscle compliance in children an adults: implications for exercise-induced muscle damage and delayed onset muscle soreness.

I confirm that all requirements have now been received for the study mentioned above. The research therefore has this Committee's full ethics approval. (Approval from host institutions must be sought separately).

If, during the course of the study, there are protocol changes, serious adverse events, or major subject recruitment problems, you are required to notify the Committee as soon as possible .

It is also requested that you provide an annual interim report on the conduct and progress of the study, plus a final report within three months of completion .

The Committee wishes you every success with your research.

Signed : ....

Dr.D.R.Prichard , Chairman .

Date : 11.11.99

Chairman/Cadeirydd - Dr DR Prichard FRCP, Dip HC Law