# THE ACUTE EFFECTS OF ECCENTRIC EXERCISE ON INDICATORS OF HAMSTRING MUSCLE DAMAGE


**Ben Reynolds**

BHSc (Physiotherapy)


**A thesis submitted to the Auckland University of Technology in partial fulfilment of the degree of Master of Sport and Exercise**


School of Sport and Recreation


2015

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

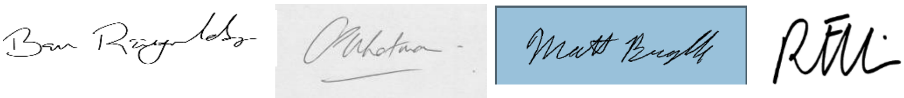
Chapters 2 to 4 of this thesis represent three separate papers that will be submitted to peer-reviewed journals for consideration for publication. My contribution and the contribution by the various co-authors to each of these papers are outlined at the beginning of the thesis. All co-authors have approved the inclusion of the joint work in this Master's thesis.

Ben Reynolds

November 2015

# CANDIDATE CONTRIBUTIONS TO CO-AUTHORED PAPERS

| | |
|---|---|
| **Chapter 2**<br>Reynolds, B.J., Whatman, C., Brughelli, M. The acute effects of eccentric thigh exercise on indicators of muscle damage; a review of the literature. To be submitted to *Sports Medicine* | Reynolds 80%,<br>Whatman 10%,<br>Brughelli 10%. |
| **Chapter 3**<br>Reynolds, B.J., Ellis, R., Whatman, C., Brughelli, M. Reliability of ultrasound echo intensity and cross sectional area measurements of the hamstring muscles. To be submitted to *Ultrasound in Medicine & Biology.* | Reynolds 80%,<br>Ellis 10%,<br>Whatman 5%,<br>Brughelli 5% |
| **Chapter 4**<br>Reynolds, B.J., Whatman, C., Brughelli, M., Ellis R. The Acute effects of two eccentric hamstrings exercises on indicators of hamstring muscle damage. To be submitted to *The Journal of Strength & Conditioning Research* | Reynolds 80%,<br>Whatman 10%,<br>Brughelli 5%,<br>Ellis 5% |



Ben Reynolds Chris Whatman Matt Brughelli Richard Ellis

# ACKNOWLEDGEMENTS

Firstly I would like to thank Chris, my primary supervisor. Your calm and professional approach and sense of humour has helped me keep a modicum of sanity through the setbacks and delays. Your prompt and thorough feedback and motivation have kept me on track and your mentorship has been invaluable. I can't thank you enough.

To Richard, your ultrasound knowledge and eye for detail has been a great help and thank you for coming on board when I needed you.

To Matt, thanks for your expert opinion on all matters eccentric and hamstring. Your advice and input is greatly appreciated.

To Scott my ultrasound guru, you went far and above what I initially asked from you. Your generosity with your time and expertise blew me away. Without you I wouldn't have been able to continue. Thank you. Thank you. Thank you.

Thank you to my colleagues and friends within the MIT School of Sport, for their parts in providing an encouraging and supportive environment throughout this process. A special thanks goes to my research assistants- Joey and Graeme. The School of Sport is my second home and you are all my second family.

To my students who have struggled along with me: you have been part of my inspiration. Even if you didn't know it, seeing you striving hard to better yourselves motivated me to keep going. Thank you for putting up with me always being tired from writing until 2 o'clock in the morning, and always using the hamstrings or eccentric training as an example in lectures.

To my wonderful participants: thank you for agreeing to be part of my study into the effects of eccentric exercise on muscle DAMAGE. Even when it was explained we were going to cause you pain. You are all lovely.

To my family, both Reynolds and Winchester: Thank you for the support you've provided in various shapes and forms throughout this educational journey. Thank you for believing in me. I would never have got this far without you all.

And finally to my beautiful bride Rachel: You are my rock and I love you to the moon and back. I'm sooooooooo sorry it took this long. It wasn't my fault, I promise. Thanks for your love, patience and encouragement. I understand the extra stress and considerable sacrifice you have made so that I could lock myself away and write. I look forward to spending more time with you and the boys now that this is completed but first I'll get straight out and mow the lawns darling. Make me a list of jobs that have been put on hold - I'll get right onto it.

# ETHICAL APPROVAL

Ethical approval for this research was granted by the Auckland University of Technology Ethics Committee (AUTEC). The AUTEC reference was 13/124, with approval granted originally on the 25 June 2013.

# ABSTRACT

The prevention and treatment of hamstring strains are important as they represent a large proportion of non-contact sporting injuries. With insufficient rehabilitation, hamstring strains can become recurrent and lead to extended periods away from training and match play. Eccentric hamstring training using the Nordic hamstrings exercise has been shown to decrease the incidence of hamstring strains in several studies, however the overall rate of reported hamstring injuries has not reduced. This may be because the areas of the hamstrings that are stressed during Nordic hamstrings training and the subsequent areas that undergo hypertrophy are different from the areas of the hamstrings that are commonly injured. Therefore, a different form of eccentric hamstring training that more closely replicates the biomechanics of hamstring strain injury and stresses the areas that are commonly injured may offer superior injury protection and rehabilitation. A literature review on the acute effects of eccentric exercise showed that eccentric exercise causes a decrease in peak torque (PT), a shift in the optimal angle of peak torque (APT) to longer muscle lengths, increased ultrasound echo intensity (EI) and muscle thickness (MT) and cross sectional area (CSA), and limb circumference (LC) and increase visual analogue scale (VAS) scores. The literature review exposed the lack of studies specifically on the hamstring muscles and a lack of reliability studies on ultrasound echo intensity and cross sectional area measurements involving the hamstrings. Furthermore, most studies assessed ultrasound measures at one or a few sites only, thereby potentially missing areas of damage. The aims of this thesis were to establish the reliability of measuring ultrasound EI and CSA of the hamstrings and to compare the acute effects of the NH and DL exercises on markers of eccentric muscle damage.

An ultrasound echo intensity and cross sectional area scanning protocol was developed and the within session and between session reliability of an experienced sonographer was assessed at seven locations on the hamstrings. Following a familiarisation period, the protocol was found to have high or greater within-session reliability (ICC range = 0.84 to 1.00) for hamstring cross sectional area (CSA) and echo intensity (EI) at 7 different locations. However, there were a number of sites where the between-session reliability of EI and CSA did not reach the level of high reliability (ICC<0.75). A second study was then conducted and the drop lunge was chosen as an alternative to the Nordic hamstrings exercise because it is a unilateral exercise that incorporates eccentric control of hip flexion. To compare the acute effects of these exercises two groups of eight healthy recreationally active females were randomly assigned to perform either the Nordic hamstrings exercise or the drop lunge. Markers of eccentric muscle damage were assessed (PT, APT, EI, CSA, LC and VAS) before exercise, immediately after exercise and for three days post exercise. The key findings were that following both exercises changes in some markers of muscle damage were evident (ES ranges; PT = -0.29 to -0.83, APT = -0.28 to -0.53, EI = 0.38 to 0.92, CSA = 0.20 to 0.85, VAS = 0.8 to 3.0) but there were few clear differences in the magnitude of these changes between the exercises. Therefore the drop lunge appears to provide a similar eccentric stimulus to the Nordic hamstrings exercise and should be

considered as an additional eccentric hamstring exercise for hamstring strain injury prevention and rehabilitation. The drop lunge may be especially beneficial for addressing limb asymmetries. However, longer term studies are needed to investigate if the drop lunge can reduce the risk of HS injury and further investigation is needed to ensure adequate between session reliability when determining EI and CSA for some areas of the hamstrings.

# CHAPTER 1

## INTRODUCTION AND RATIONALE (PREFACE)

**Background**

Hamstring strain injuries (HSI) are the most common non-contact injury in sports involving stretch shorten cycle activities, such as: Rugby Union (Brooks, Fuller, Kemp, & Reddin, 2006), American Football (Feeley et al., 2008), Football (Ekstrand, Hägglund, & Waldén, 2011), Australian Rules Football (Orchard & Seward, 2010), Gaelic Football (Murphy, O'Malley, Gissane, & Blake, 2012), Sprinting (Alonso et al., 2009), and Cricket (Orchard, James, Alcott, Carter, & Farhart, 2002). HSI result in considerable loss of training time and match play (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010) and have a high rate of recurrence (Petersen, Thorborg, Nielsen, & Hölmich, 2010). These factors may have a negative impact on team performance, success, finances and player well-being (Henderson, Barnes, & Portas, 2010). Eccentric hamstring exercises are recommended for reducing the incidence of hamstring injuries and there have been encouraging findings from studies investigating eccentric hamstring training (Thorborg, 2012). Although some of these studies had small sample sizes, combined they represent over 1200 participants and reported significant decreases in HSI rates. The most common form of eccentric training is the Nordic hamstrings exercise (NH). It has been shown to decrease hamstring injuries by 65-70% in both elite and amateur soccer players (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Petersen, Thorborg, Nielsen, Budtz-Jørgensen, & Hölmich, 2011; van der Horst, Smits, Petersen, Goedhart, & Backx, 2015). It has also been shown to be more effective than the hamstring curl in well trained soccer players to improve eccentric torque production and hamstrings: quadriceps ratio (Mjolsnes, Arnason, Raastad, & Bahr, 2004). Conversely, other studies haven't shown a difference in rates of HSI (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2008; Gabbe, Branson, & Bennell, 2006). This may be due to methodological limitations of these studies which led to poor compliance rates or excessive levels of delayed onset muscle soreness. Despite the positive results from eccentric training studies, it is concerning to note that overall HSI rates haven't decreased over the last 30 years (Mendiguchia, Alentorn-Geli, & Brughelli, 2011). This may be due to the increasing size and speed of athletes in professional sport (Leach, 2000), or the lack of adoption of eccentric training protocols (Bahr, Thorborg, & Ekstrand, 2015). Thus greater work needs to be done to prevent these injuries and the lack of improvement in HSI rates suggests that the current HSI prevention and rehabilitation strategies may not be the most effective.

While most eccentric training studies have used the NH, it does have several potential limitations as an exercise to prevent HSI. The NH consists of bilateral eccentric knee extension with the hips held in a neutral position. This is markedly different from the proposed mechanism of HSI during the terminal swing phase of gait which is unilateral and involves significantly more hip flexion combined with knee extension (Schache, Dorn, Blanch, Brown, & Pandy, 2012; Thelen, Chumanov, Sherry, & Heiderscheit, 2006). The hamstrings are close to maximal elongation during sprinting whereas they are in mid-range at the completion of the NH. Also the NH does not address the biomechanics of sprinting relating to the mechanism of HSI and the demands on the gluteals and core musculature to control the lumbo-pelvic region. Furthermore, the neuromuscular control constraints are markedly different from sprinting and there have been issues regarding DOMS and therefore participant compliance problems. In addition, the NH is an open chain bilateral exercise and this allows the potential for a stronger limb to compensate for a weaker limb. Additionally differences in optimal length have been reported between legs and these differences have increased after NH training (Clark, Bryant, Culgan, & Hartley, 2005). Some authors have gone as far as suggesting the NH is contraindicated because of the non-functional position of the body and because it only works the biarticular hamstrings over one joint and therefore is not specific enough to reproduce sprinting biomechanics (Gambetta & Benton, 2008).

A further potential limitation of the NH is that although it trains the hamstrings to work eccentrically, the gluteals work predominantly isometrically to maintain the hip in neutral. During gait, the gluteals assist the hamstrings eccentrically to decelerate the thigh; therefore an exercise that incorporates hip flexion may be more beneficial in reducing HSI. The eccentric Drop Lunge (DL) has been proposed as an additional eccentric exercise to the NH because it emphasises the hamstring's role to eccentrically control hip flexion (placing greater demand on the gluteals) compared to the NHs emphasis on eccentric control of knee extension (Brughelli & Cronin, 2008). The DL is also a unilateral exercise which overcomes the fact that the NH has been criticised for being a bilateral exercise and thus not being able to address limb strength asymmetry.

Acute MRI findings have shown the NH exercise stresses the proximal Biceps Femoris short head (BFSH) of the hamstrings (Mendiguchia, Arcos, et al., 2013); however the most commonly strained muscle of the hamstrings group is the Biceps Femoris long head (BFLH) (Silder, Heiderscheit, Thelen, Enright, & Tuite, 2008). Long term MRI follow up of participants post hamstring injury have shown hypertrophy of BFSH and atrophy of BFLH (Silder, et al., 2008). Additionally, the BFLH has been shown to have greater loading during exercises resisting hip flexion rather than knee extension (Mendiguchia, Garrues, et al., 2013). Therefore, an eccentric exercise that preferentially resists hip flexion (stressing the BFLH) such as the DL may have superior injury prevention potential.

Although the DL is a potential addition to the NS, it is unknown if it provides sufficient eccentric stimulus given the shortening of the hamstring at the knee occurring in conjunction with lengthening at the hip. The potential for eccentric exercise to reduce the risk of hamstring injuries is based on the magnitude of this eccentric stimulus and the effect on muscle function.

In the literature, acute markers of this include significant reductions in isometric and isokinetic strength peaking from 1-3 days post exercise and lasting up to 16 days (Proske & Morgan, 2001). Additionally eccentric exercise has been shown to shift the optimal angle of torque generation to longer muscle lengths (Brockett, Morgan, & Proske, 2001), increase ultrasound echo intensity (T. C. Chen, Lin, Chen, Lin, & Nosaka, 2011), muscle cross sectional area (Howell, Chleboun, & Conatser, 1993), and muscle thickness (Chapman, Newton, McGuigan, & Nosaka, 2011). These ultrasound changes are similar to the changes seen in MRI which suggests that the T2 signal from MRI and the increased echo intensity on US may have a common source which is most probably oedema (Whittaker & Stokes, 2011). Lastly limb circumference and soreness have been reported to change post eccentric exercise (Dannecker et al., 2012) and are two further indicators of the magnitude of the stimulus.

**Conclusion**

Hamstring strains are a common sports injury with prolonged recovery times and high recurrence. Eccentric exercise has the potential to decrease the incidence of HSI and knowledge regarding the eccentric effect of different eccentric hamstring exercises could help inform clinicians' exercise prescription for rehabilitation and injury prevention. The vast majority of studies on the acute effects of eccentric exercise are on the biceps brachii and there is a lack of studies which assess the acute effects of eccentric hamstring training. Changes in ultrasound measures such as cross sectional area and echo intensity may be able to identify the areas of the muscle most affected. However, there is a lack of studies utilising these measures following eccentric hamstring exercise and there is a need to establish the reliability of ultrasound echo intensity and cross sectional area testing of the hamstrings. The current literature has a bias towards the NH. Potentially, the drop lunge could offer superior injury prevention potential because it eccentrically resists hip flexion which replicates the hip position commonly seen during hamstring strain injury. This thesis will compare the acute effects of the NH with the DL. Markers of the acute effect of eccentric exercise will be assessed to compare the degree of muscle damage, the muscles involved and the relative location of the effect within the muscle. This will provide information which can help inform prescription of eccentric exercises for the prevention of HSI.

**Questions addressed by this thesis**

Given limitations in the literature, the overall question of this thesis was "How do markers of eccentric muscle damage differ between the DL and the NH?"

Specific questions were:

1. Is ultrasound echo intensity and measurement of hamstring cross sectional area reliable?
2. What are the acute effects of the NH and DL exercise?
3. What are the differences in the markers of muscle damage following equal volumes of eccentric DL and NH?

4. Do these exercises stress different areas of the hamstrings muscle group?

**Structure of the thesis**

This thesis consists of five chapters which culminate in the final discussion. References are collated at the end of the final chapter as required by AUT for thesis submission. Chapter 2 is a literature review of the acute effects of eccentric exercise on indicators of muscle damage (peak torque, angle of peak torque, limb circumference and ultrasound echo intensity). The review is divided into 2 parts. The first part reviews the acute effects of eccentric exercise on the above measures, and the second part assesses the factors that influence the degree of muscle damage following eccentric exercise. The key findings from this chapter were that eccentric exercise has been shown to cause significant reductions in isometric and isokinetic strength post exercise and to shift the optimal angle of torque generation to longer muscle lengths. Additionally increases in ultrasound echo intensity have been demonstrated in human participants after eccentric exercises, however there are a limited number of studies on the lower limb and no reliability data for hamstring echo intensity measurement. Limb circumference also increases following eccentric exercise and peaks around 3-6 days following the bout and persists to day 8-9 which is much longer than soreness thereby suggesting they may be due to different mechanisms. There are many factors that influence the degree of damage following eccentric exercise. Speed of eccentric contraction is not a strong predictor of muscle damage following moderate numbers of contractions such as 30 repetitions however with greater numbers of contractions greater speed tends to induce greater damage. Whereas, as you increase the number of eccentric contractions the extent of muscle damage increases. Greater intensity of eccentric exercise appears to be a greater determinant of muscle damage than total work done and greater damage occurs following eccentric exercise at longer muscle lengths. Also, trained participants have a greater resistance to eccentric muscle damage and the type of training appears to be a factor because power athletes have greater resistance than long distance endurance athletes.

The third chapter of this thesis is a reliability study on the ultrasound echo intensity and cross sectional area measures. These measures give an indication of the location of acute muscle damage which could then be used to evaluate which exercise stressed which part of the hamstrings group. This was necessary because there was little data on the reliability of these measures and none on the specific hamstrings protocol we developed. The key findings from this chapter were that in the hands of an experienced clinician with an appropriate length of time to become familiar with the testing protocol, this protocol has merit as a reliable within-session measure of hamstring CSA and EI at seven different locations. However, the between-day reliability of EI and CSA was also reliable for some locations but not all (ICC≥0.75). Therefore, further investigation is needed to ensure adequate reliability when determining EI and CSA for these areas. This gives some confidence for researchers to use this protocol when identifying areas of hamstring muscle damage following eccentric hamstring exercise at certain locations.

However, care must be taken interpreting this data when there is a small expected magnitude of change.

The intervention study is the fourth chapter. Sixteen healthy female tertiary students were randomly allocated into either a drop lunge or Nordic hamstrings exercise group. The acute effects of eight sets of eight repetitions of the DL or NH exercise were examined. Isokinetic concentric knee flexion, knee extension, and hip extension strength and optimum angle of torque generation at 60 degrees per second, proximal and distal thigh circumference and muscle soreness was assessed before exercise, immediately afterwards, and at 1, 2 and 3 days following exercise. Echo intensity and cross sectional area were assessed the day before exercise and at day 3 post exercise. The key findings from this chapter were that changes in markers of muscle damage were observed following both exercises. However, there were few clear differences in the magnitude of these changes between the exercises. This suggests the DL provides a similar eccentric stimulus to the NH and should be considered as an alternate unilateral eccentric hamstring exercise for hamstring strain injury prevention and rehabilitation. The DL may be especially beneficial for addressing limb asymmetries. Future studies are needed to investigate if the DL can reduce the risk of HS injury. Also, other forms of eccentric hamstring exercise should be investigated to find which exercise provides the greatest stimulus for the long head of biceps femoris.

The final chapter, chapter 5, consists of a general discussion of findings from the previous chapters, comments on limitations to the research studies, provides areas for future research, and provides some concluding statements on the key findings from the thesis.

# CHAPTER 2

## THE ACUTE EFFECTS OF ECCENTRIC THIGH EXERCISE ON INDICATORS OF MUSCLE DAMAGE; A REVIEW OF THE LITERATURE.

### Introduction

Thigh muscle strains are the most common injury sustained in sports involving high speed running such as professional football, track and field, and rugby union. (Brooks, et al., 2006; Ekstrand, et al., 2011; Malliaropoulos, Isinkaye, Tsitas, & Maffulli, 2011). Hamstring strains occur more frequently than quadriceps strains and re-injuries are common and cause significantly longer absences from training and match play (Ekstrand, et al., 2011). This is why optimal prevention and rehabilitation strategies are essential. Eccentric exercise has been shown to decrease the incidence of muscle strain injuries (Thorborg, 2012). The mechanism for this could be factors such as shifting the optimal angle for torque generation to longer muscle lengths and increasing muscular strength (Bourne, Opar, Williams, & Shield, 2015; Brockett, et al., 2001; Proske, Morgan, Brockett, & Percival, 2004). This is achieved chronically following a training program via sarcomeregenesis (Potier, Alexander, & Seynnes, 2009). The majority of eccentric training studies have used the bilateral Nordic hamstrings exercise (Thorborg, 2012). However, a risk factor for hamstring injury is a between limb imbalance in muscle strength (Bourne, et al., 2015). Therefore a unilateral exercise may better allow correction of limb strength asymmetry than a bilateral exercise. The acute responses to eccentric exercise may give an indication of the areas that could undergo chronic adaptations following a training program. This may assist in the development of more effective prevention and rehabilitation programmes.

Several mechanisms have been associated with the muscle damage observed following eccentric exercise. Eccentric muscle actions occur when there is lengthening of the musculotendinous unit against an external force. The extent of myofilament overlap and therefore sarcomere length determines the length tension curve of a muscle (Newham, Jones, Ghosh, & Aurora, 1988). As a muscle lengthens during an eccentric contraction the elongation of its sarcomeres is not uniform. Some sarcomeres maintain their length whist others are stretched to the extent that there is no longer overlap between their actin and myosin myofilaments (Flitney & Hirst, 1978; Huxley, 2000; Morgan, 1990). This extreme stretch is described as ‘sarcomere give’ (Flitney & Hirst, 1978) or ‘sarcomere popping’ (Morgan, 1990). When this occurs tension is transferred to the passive structures of the sarcomere to maintain serial tension through the muscle fibre (Morgan, 1990). The overstretched sarcomeres would normally reinterdigitate when the muscle relaxes. Instead it is the increased cyclic stress of continuing eccentric contraction that is absorbed by the passive structures following the give or pop that results in muscle damage (Morgan, 1990). Therefore, eccentric exercise is commonly used as a modality to investigate muscle damage due to the greater degree of muscle damage it elicits when compared to concentric or isometric exercise. The acute markers of muscle damage may give an indication of the chronic adaptations that may follow a chronic training program. The markers of muscle damage commonly used to monitor the effect of eccentric exercise include decreased peak torque, shifting of the optimal angle of peak torque to longer muscle lengths, increased limb circumference, changes in echo intensity of ultrasound images and increased cross sectional area or muscle thickness. This review will evaluate the evidence for how eccentric exercise acutely effects these aspects of muscle function and then assess the factors that influence this effect.

**Methods**

The databases CINAHL, MEDLINE, SPORTDiscus were selected in Ebscohost. Where possible the limiters peer reviewed, English language, and human were selected. The following combination of keywords was used (eccentric OR lengthening) AND (damage). This search strategy was repeated in Scopus, Science Direct and PubMed. The reference lists of identified articles were then manually searched to detect further relevant studies. Studies were included if they: were randomized controlled trials (RCTs) or clinical controlled trials (CCTs) published in peer-reviewed journals; had study participants who were healthy adults aged between 18-65 years; included one or more of the following measures- peak torque, angle of peak torque, ultrasound measures, or limb circumference; had measures recorded pre exercise and within 1 week post exercise and had full text available.

Studies were excluded if they: included concentric contractions; included repeated exercise bouts and did not report acute effects; did not meet the minimum requirements of an experimental study design (eg. Case reports); had participants with any pathology; did not meet the minimum training design requirements; included other interventions, supplementations or medications; or were not written in English. The titles of potentially relevant publications were screened. Potentially relevant titles were then screened at the abstract level. When abstracts were potentially relevant the full text article was reviewed for inclusion. Finally the reference lists of included articles were scanned and potentially relevant publications were reviewed for inclusion.

Thirty nine studies measured peak torque and fifteen studies measured angle of peak torque of the quadriceps or hamstrings. However, there were only 3 studies measuring limb circumference and only one study measuring echo intensity of the hamstrings or quadriceps that met the inclusion criteria. Therefore, the literature was searched again to include all muscles to review the effects of eccentric exercise on ultrasound echo intensity, cross sectional area or thickness, limb circumference and the factors that influence the effects of eccentric exercise.

# THE ACUTE EFFECTS OF ECCENTRIC EXERCISE

**Isokinetic and Isometric strength**

There is evidence from a multitude of studies that following eccentric thigh exercise there is a significant decrease in muscle strength. Thirty nine studies measured isokinetic or isometric strength following eccentric exercise of the knee flexors or knee extensors (Table 1). All of these studies except two showed a significant decrease in these measures of the affected muscles. The two studies that failed to show a significant decrease in strength measures used loads that were insufficient or the muscle wasn't exercised at a long enough length (Saka et al., 2009; Yeung & Yeung, 2008). The studies that showed acute decreases in isokinetic or isometric strength used a range of eccentric training protocols including isokinetic eccentric contractions ranging from 10-200 repetitions with velocities from 30-180 degrees/second (Alemany, Delgado-Díaz, Mathews, Davis, & Kostek, 2014; Brown, Child, Day, & Donnelly, 1997; Crameri et al., 2007), eccentric cycling (Peñailillo, Blazevich, Numazawa, & Nosaka, 2013), electrical stimulation (Black & McCully, 2008), free weights (C. Byrne & R. G. Eston, 2002), resistance machines (Black & McCully, 2008) and stepping exercises (Bowers, Morgan, & Proske, 2004). However, the vast majority of studies have investigated the knee extensors (34) with only six studies investigating the knee flexors. The observed decrease in muscle strength following eccentric exercise is significantly greater than that following concentric or isometric exercise. Six studies compared eccentric and concentric exercise and 5 of them demonstrated this. The study that showed no significant difference between concentric and eccentric training used submaximal loads that were too mild to induce significant changes in strength (Yeung & Yeung, 2008).

***Table 1: Studies evaluating the effect of eccentric exercise on muscle strength.***

| Study | Participants | Protocol | Result |
|---|---|---|---|
| (Alemany, et al., 2014) | 16 healthy Ms. 8= ecc isotonic grp 8=ecc isokinetic grp | Ex=kn ext (isotonic@110%MVT/isokinetic@120°/s), Sets=20, Reps=10, | ↓MVT (22-29%) immediately post isotonic and isokinetic, ↓MVT (22%) 48 hrs post isotonic |
| (Black & McCully, 2008) | 16 participants (9 M, 7 Fs) 8=Electrical stimulation versus 8=voluntary contraction | Ex= kn ext (machine, voluntary@120%1RM/ Stimulated@25%1RM) Sets=8, Reps=10 | ↓MVT both groups. No dif btw groups |
| (Bowers, et al., 2004) | 9 healthy participants (4 M and 5 F) | Ex= kn ext (step Ex) Sets=12, Reps=20 | ↓MVT (25.3%) immediately. |
| (Brockett, et al., 2001) | 10 healthy participants (8 M and 2 F) | Ex= kn flex (Nordic hamstrings Ex) Sets=12, Reps=6 | ↓MVT to 80.4% of control immediately after |
| (Brown, et al., 1997) | 24 healthy participants (6 M and 18 F) | Ex= kn ext (isokinetic@ 60°/s), , Reps=10 grp1, 30 grp2, 50 grp3 | ↓MVT in all grps, greater ↓ in grp with higher reps |
| (Byrne, Eston, & Edwards, 2001) | 8 participants (5Ms and 3 Fs) | Ex= kn ext (isokinetic@ 90°/s), Reps=100 | Greater ↓ in MVT at shorter muscle lengths |
| (C. Byrne & R. G. Eston, 2002) | 7 healthy participants (5 Ms and 2 Fs) | Ex= ecc barbell squats, Sets=10, Reps=10. | ↓ MVT for both grps. No dif btw change in MVT at 40° and 80° |
| (T. C. Chen, et al., 2011) | 17 sedentary Ms | Ex= kn ext/kn flex/el flex/el ext (isokinetic@ 90°/s), Sets=5, Reps=6 | ↓ MVT for all grps. |

| | | | |
|---|---|---|---|
| (Child, Saxton, & Donnelly, 1998) | 7 untrained but physically active participants (4 men and 3 women) | Ex= kn ext (isokinetic@ 90°/s), Reps=75 at short length and long length with contralateral leg | ↓ MVT for all grps. Greater ↓ in the long grp |
| (Crameri, et al., 2007) | 8 healthy sedentary Ms | Ex= kn ext (isokinetic@ 30°/s), Sets=10, Reps=10, followed by (isokinetic@ 180°/s) Sets=11, Reps=10 | ↓ MVT by 16, 25 and 8% at 4, 24 and 96 hrs |
| (Golden & Dudley, 1992) | 24 healthy Ms<br>8=con<br>8=ecc<br>8=control | Ex= kn ext (knee extension machine @85%1RM), Sets=10, Reps=10 | Greater ↓ MVT in the ecc grp |
| (Hamlin & Quigley, 2001b) | 10 healthy M participants | Ex= kn ext (bench stepping with same leading leg), 20 mins | ↓ MVT (13%) @ 3hrs |
| (Hamlin & Quigley, 2001a) | 10 healthy M participants | Ex= kn ext (bench stepping with same leading leg), 20 mins | ↓ MVT (13%) @ 3hrs |
| (Hody, Rogister, Leprince, Laglaine, & Croisier, 2013) | 18 healthy M participants | Ex= kn ext (isokinetic@ 60°/s), Sets=3, Reps=30 | ↓ MVT. No dif between dominant and non-dominant legs |
| (Hortobágyi et al., 1998) | 18 healthy participants<br>ecc =6 M, 6 F<br>control= 3 M, 3 F | Ex= kn ext (knee extension machine @80%1 ecc max), Sets=10, Reps=10 | ↓ max con force (58%) by day 2 |
| (Jamurtas et al., 2005) | 11 healthy Ms | Ex= kn ext, el flex (isokinetic@ 60°/s), Sets=6, Reps=12 | ↓ MVT in both grps. el flex had greater ↓ MVT |
| (Kubota et al., 2007) | 12 healthy Ms | Ex= kn flex, (prone leg curls@120%1RM) Sets=5, Reps=10 | ↓ MVT (25.8%) |
| (Kubota et al., 2009) | 7 healthy Ms | Ex= kn flex, (prone leg curls@120%1RM) Sets=5, Reps=10 | ↓ MVT (25.1%) |
| (Larsen, Ringgaard, & Overgaard, 2007) | 8 healthy Fs | Ex= kn ext (bench stepping with same leading leg), 30 mins | ↓ MVT (25%) |
| (McHugh, Connolly, Eston, & Gleim, 2000) | 30 healthy participants<br>20=ecc<br>10=con | Ex= kn flex (isokinetic@ 150°/s, 60%MVT), Sets=6, Reps=10 | ↓ MVT following ecc but not con Ex. |
| (McHugh, Connolly, Eston, Gartman, & Gleim, 2001) | 30 healthy participants<br>20=ecc<br>10=con | Ex= kn flex (isokinetic@ 150°/s, 60%MVT), Sets=6, Reps=10 | ↓ MVT following ecc but not con Ex. |
| (McHugh & Tetro, 2003) | 12 healthy participants (7 Ms, 5 Fs) | Ex= kn flex (isokinetic@ 150°/s, 90%MVT), Sets=6, Reps=10 | ↓ MVT |
| (Molina & Denadai, 2012) | 12 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=10, Reps=10 | ↓ MVT |
| (Newham, Jones, & Edwards, 1983) | 13 healthy participants (8 F, 5 M) | Ex= kn ext (bench stepping with same leading leg), 20 mins | ↓ MVT (20%) in ecc leg. Greater ↓ MVT than con leg |
| (Paschalis, Koutedakis, Baltzopoulos, Mougios, Jamurtas, & Giakas, 2005) | 12 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=12, Reps=10. Long length=hip 180°, short length= hip 90° | Short length contractions resulted in greater ↓ MVT |
| (Paschalis, Koutedakis, Jamurtas, Mougios, & Baltzopoulos, 2005) | 12 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=12, Reps=10. Contralateral limb= kn ext (isokinetic@ 60°/s at 50%MVT) continuous until work done = previous session | ↓ MVT in the high intensity trained limb only |
| (Paschalis, Koutedakis, Baltzopoulos, Mougios, Jamurtas, & Theocharis, 2005) | 10 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=12, Reps=10. | ↓ MVT. MVT at 60° recovered quicker than 110° |
| (Paschalis, Nikolaidis, et al., 2007) | 12 healthy Fs | Ex= kn ext (isokinetic@ 60°/s), Sets=5, Reps=15. | ↓ MVT immediately then gradually recovered by day 3 |
| (Paschalis, Giakas, et al., 2007) | 10 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=6, Reps=10. | ↓ MVT immediately after and 2 days post Ex. |
| (Paschalis et al., 2010) | 12 healthy Ms | Ex= kn flex/el flex (isokinetic@ 60°/s), Sets=5, Reps=15. | ↓ MVT in both groups. Smaller ↓ MVT in the kn flex and they recovered quicker than the el flex |
| (Peñailillo, et al., 2013) | 10 healthy Ms | Ex= 30 min concentric cycling followed 2 weeks later by 30 min eccentric cycling. | MVT was lower immediately after and 1-2 days after eccentric cycling compared to concentric cycling |
| (Philippou, Maridaki, Bogdanis, Halapas, & Koutsilieris, 2009) | 10 healthy Mn | Ex= kn ext (isokinetic@ 30°/s), Sets=2, Reps=25. | ↓ MVT that gradually returned to baseline by day 8 |
| (Prior et al., 2001) | 14 healthy Ms | Ex= kn ext (knee extension machine @90%MVT), Sets=6-8, Reps=5-10 | ↓ MVT peaked days 2 and 3. MVT had not returned to baseline by day 6 post Ex. |

| | | | |
|---|---|---|---|
| (Saka, et al., 2009) | 12 sedentary Ms | Ex= kn ext/el flex (isokinetic@ 30°/s), Sets=3, Reps=15. | No change in kn ext MVT↓ MVT el flex day 1, 2, and 3 but had recovered by day 7. |
| (Skurvydas, Brazaitis, Kamandulis, & Sipaviciene, 2010) | 11 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | ↓ MVT. Greater ↓ MVT at shorter length (90 °) compared to longer length (130 °s) |
| (Skurvydas, Brazaitis, & Kamandulis, 2010) | 11 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | ↓ MVT immediately and 24 hrs post Ex. |
| (Skurvydas et al., 2011) | 10 healthy untrained.<br>10 long distance runners<br>10 sprint runners<br>10 volleyball players | Ex= kn ext (isokinetic@ 60°/s), Sets=10, Reps=10. | ↓ MVT in all groups post Ex. Greater ↓ MVT in untrained participants compared to long distance runners, sprinters, and volleyball. |
| (Skurvydas, Brazaitis, Kamandulis, Mickevičienė, & Karanauskienė, 2011) | 10 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | ↓ MVT (27.9%) |
| (Yeung & Yeung, 2008) | 24 healthy participants (13 Ms, 11 Fs) | Ex= kn ext (stepping with same leading leg), 10 mins | No changes in MVT con or ecc |

***Abbreviations:*** Ex=exercise; kn ext=knee extension/extensors; kn flex=knee flexion/flexors; el ext=elbow extension/extensors; el flex=elbow flexion/flexors; 1RM=one repetition max; Dif=difference; Btw=between; MVT=maximal voluntary tension; Reps=repetitions; Con=concentric; Ecc=eccentric; F=female; M=male; ↓=reduced/decreased; ↑=increased/higher; Hrs=hours; Mins=minutes; Grps=groups

**Optimal angle of peak torque**

Eccentric contractions performed at muscle lengths on the descending limb of the force-length curve cause overstretching of some sarcomeres (Morgan, 1990). A consequence of overstretched popped sarcomeres is that force must be transmitted through the elastic non contractile component of these sarcomeres. This increases the series compliance of the myofibril and therefore the optimal angle of force production will be shifted to longer muscle lengths but not necessarily decreased in magnitude (Morgan & Allen, 1999). Fifteen studies assessed optimal angle of peak torque following eccentric exercise (Table 2). This shift to longer muscle lengths was observed in both the knee extensors (Child, et al., 1998) and knee flexors (Brockett, et al., 2001). However, the vast majority of studies investigated the knee extensors (14). Following eccentric exercise a greater decrease in isometric torque (McHugh & Tetro, 2003) or isokinetic torque (Skurvydas, Brazaitis, & Kamandulis, 2010) has been demonstrated at short muscle lengths compared to long or optimal muscle lengths. This shift in the optimal angle for torque generation to longer muscle lengths was demonstrated in all but 1 of the 15 studies that measured angle of peak torque changes following eccentric exercise. Following eccentric barbell squats no significant difference was seen in the change in isometric torque generated at 40 degrees (short muscle length) and 80 degrees (optimal muscle length) knee flexion (C. Byrne & R. G. Eston, 2002). However this study had several limitations including, there were only 7 participants in the study and torque wasn't measured at a muscle length beyond optimal. Also the eccentric exercise utilised was a squat to approximately 90 degrees knee flexion. This may not have exercised the quadriceps into a long enough muscle length.

*Table 2: Studies evaluating the effect of eccentric exercise on angle of peak torque*

| Study | Participants | Protocol | Result |
|---|---|---|---|
| (Bowers, et al., 2004) | 9 healthy participants (4 male and 2 F) | Ex= kn ext (step Ex) Sets=12, Reps=20 | 15.6° shift in optimum angle towards longer muscle lengths Immediately after Ex |
| (Brockett, et al., 2001) | 10 healthy participants (8 M and 2 F) | Ex= kn flex (Nordic hamstrings Ex) Sets=12, Reps=6 | 7.7° shift in optimal angle towards longer muscle lengths immediately after Ex. Peaked day 4 at 8.5° |
| (Byrne, et al., 2001) | 8 participants (5Ms and 3 Fs) | Ex= kn ext (isokinetic@ 90°/s), Reps=100 | Greater ↓ in MVT at shorter muscle lengths |
| (C. Byrne & R. G. Eston, 2002) | 7 healthy participants (5 Ms and 2 Fs) | Ex= ecc barbell squats, Sets=10, Reps=10. | No dif btw angles for relative change in MVT. |
| (T. C. Chen, et al., 2011) | 17 sedentary Ms | Ex= kn ext/kn flex/el flex/el ext (isokinetic@ 90°/s), Sets=5, Reps=6 | Optimum angle was shifted to longer lengths in all muscles except knee extensors. Greatest shift seen at 1-2 days post Ex. Changes were greater for elbow muscles |
| (Child, et al., 1998) | 7 untrained but physically active participants (4 Ms and 3 Fs) | Ex= kn ext (isokinetic@ 90°/s), Reps=75 at short length and long length with contralateral leg | Long group = greater ↓ MVT at longer muscle lengths whereas in the short group there was no interaction effects btw knee angle and MVT. |
| (Golden & Dudley, 1992) | 24 healthy Ms<br>8=concentric<br>8=eccentric<br>8=control | Ex= kn ext (knee extension machine @85%1RM), Sets=10, Reps=10 | ↓ in angle specific peak torque was greater in the eccentric group |
| (McHugh & Tetro, 2003) | 12 healthy participants (7 Ms, 5 Fs) | Ex= kn flex (isokinetic@ 150°/s, 90%MVT), Sets=6, Reps=10 | ↓ MVT at longer muscle lengths was less apparent than at shorter muscle lengths. There was a rightwards shift in the length-tension curve |
| (Molina & Denadai, 2012) | 12 healthy Ms | Ex= kn ext (isokinetic@ 60°/s), Sets=10, Reps=10 | Lengthening of APT at 24 (6.4%) and 48 (7.7%) hrs post Ex. |
| (Philippou, et al., 2009) | 10 healthy Ms | Ex= kn ext (isokinetic@ 30°/s), Sets=2, Reps=25. | An acute shift in optimal angle towards longer muscle lengths was seen which reversed towards pre-Ex levels by day 8 |
| (Skurvydas, Brazaitis, Kamandulis, et al., 2010) | 11 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | 12.1° shift to a longer muscle length immediately post Ex |
| (Skurvydas, Brazaitis, & Kamandulis, 2010) | 11 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | 2 min after Ex the optimal angle shifted to longer lengths (from 108.7° to 96.7°) |
| (Skurvydas, Brazaitis, Venckūnas, et al., 2011) | 10 healthy untrained.<br>10 long distance runners<br>10 sprint runners<br>10 volleyball players | Ex= kn ext (isokinetic@ 60°/s), Sets=10, Reps=10. | Optimal angle shifted to longer lengths in the untrained and long distance runner participants only. |
| (Skurvydas, Brazaitis, Kamandulis, et al., 2011) | 10 healthy Ms | Ex= kn ext (isokinetic@ 160°/s), Sets=10, Reps=12. | Greater ↓ MVT at short muscle lengths |
| (Yeung & Yeung, 2008) | 24 healthy participants (13 males, 11 Fs) | Ex= kn ext (stepping with same leading leg), 10 mins | Eccentric leg optimal angle moved to longer lengths. No change in optimal angle of the concentrically Exd leg |

***Abbreviations:*** Ex=exercise; kn ext=knee extension/extensors; kn flex=knee flexion/flexors; el ext=elbow extension/extensors; el flex=elbow flexion/flexors; 1RM=one repetition max; Dif=difference; Btw=between; MVT=maximal voluntary tension; Reps=repetitions; Con=concentric; Ecc=eccentric; F=female; M=male; ↓=reduced/decreased; ↑=increased/higher; Hrs=hours; Mins=minutes; Grps=groups

**Ultrasound echo intensity, cross sectional area, muscle thickness and limb circumference**

Echo-intensity (EI), as assessed by ultrasound imaging, represents sound waves being reflected back to the ultrasound probe. The brightness of the pixel will depend on the returning echo strength. Therefore a whiter image will reflect a stronger echo intensity and a darker image represents a weaker echo intensity (Whittaker & Stokes, 2011). It has been suggested that increases in EI, cross sectional area and muscle thickness indicate damage of connective tissue and inflammation leading to oedema (T. C. Chen, Chen, Lin, Wu, & Nosaka, 2009; Sbriccoli et al., 2001; Van Holsbeeck & Introcaso, 1992). Six studies have used increases in EI of B-mode ultrasound images as a measure of eccentric muscle damage (Table 3). All of these studies used the elbow flexors and found significant increases in EI following eccentric exercise. The increases in echo intensity are associated with decreases in peak torque and increases in pain (Nosaka, Newton, & Sacco, 2002b). Of the six studies, only one included muscle groups other than the elbow flexors. Chen, et al. (2011), compared the effects of eccentric exercise on the elbow flexors, elbow extensors, knee flexors and knee extensors. The only muscle group to not show an increase in EI was the knee extensors. The lack of increase in EI was associated with no change in limb circumference or optimal angle of torque generation and minimal decrease in peak torque. This may have been because each muscle was exercised at a different starting and finishing angle and the knee extensors weren't exercised at a long enough length, or that muscles have different susceptibility to eccentric damage due to their unique morphology or their conditioning from everyday activities.

***Table 3: Studies evaluating the effect of eccentric exercise on echo intensity***

| Study | Participants | Protocol | Result |
|---|---|---|---|
| (T. C. Chen, et al., 2011) | 17 sedentary Ms | Ex= kn ext/kn flex/el flex/el ext (isokinetic@ 90°/s), Sets=5, Reps=6 | ↑EI in the el flex/el ext and kn ext but not the kn ext |
| (Nosaka & Clarkson, 1996) | 14 untrained Ms | Ex= el flex (arm curl machine maximal contraction), Reps=24 | ↑EI coincided with increased signal intensity on MRI |
| (Nosaka & Sakamoto, 2001) | 10 healthy Ms | Ex= el flex (arm curl machine maximal contraction@20°/s), from 50-130° (short) or from 100-180° (long) Reps=24 | ↑EI in the brachialis in all participants. Some participants showed ↑EI in the biceps brachii in the long group. |
| (Nosaka & Newton, 2002b) | 7 healthy Ms | Ex= el flex (arm curl machine maximal contraction), from 100-180° Reps=24 | ↑EI post Ex |
| (Nosaka, et al., 2002b) | 18 healthy Ms (Con-ecc endurance grp) 50 healthy Ms (ecc grp) | Endurance= 2 hrs of con-ecc arm curl at 9% of their MVT 30 cycles per minute Ecc= 12 maximal ecc el flex contractions | ↑EI post ecc Ex only. Peaked 4-5 days post Ex. |
| (Nosaka, Newton, Sacco, Chapman, & Lavender, 2005) | 22 healthy Ms (long=11) (short=11) | Ex= el flex (arm curl machine maximal contraction@25°/s), from 50-100° (short) or other from 130-180° (long) Reps=24 | Greater ↑EI in the long group than the short group. |

***Abbreviations:*** Ex=exercise; EI=echo intensity; kn ext=knee extension/extensors; kn flex=knee flexion/flexors; el ext=elbow extension/extensors; el flex=elbow flexion/flexors; 1RM=one repetition max; Dif=difference; Btw=between; MVT=maximal voluntary tension; Reps=repetitions; Con=concentric; Ecc=eccentric; F=female; M=male; ↓=reduced/decreased; ↑=increased/higher; Hrs=hours; Mins=minutes; Grps=groups; MRI=magnetic resonance imaging

Nine studies investigated ultrasound changes in muscle size following eccentric exercise (Table 4). All of these studies were on the elbow flexors and demonstrated increased cross sectional area or muscle thickness (Chapman, et al., 2011; Howell, et al., 1993; Murayama, Nosaka, Yoneda, & Minamitani, 2000). These changes in muscle thickness on ultrasound following eccentric contractions coincide with changes in limb circumference (Nosaka & Newton, 2002a). Ultrasound measurements of the mid region of the arm show that 80% of the initial increase in girth is attributed to swelling in the muscle compartment whereas two days post exercise only 65% of the swelling was in the muscle compartment. This contrasts to the distal region where 40% of the immediate swelling was in the muscle compartment and four days following little swelling could be attributed to the muscle compartment (Howell, et al., 1993).

*Table 4: Studies evaluating the effect of eccentric exercise on muscle size*

| Study | Participants | Protocol | Result |
|---|---|---|---|
| (Chapman, et al., 2011) | 18 recreationally active M<br>Slow=10 Fast=8 | Ex= el flex (isokinetic, slow@ 30°/s, fast@210°/s), Sets=35, Reps=6 | Fast grp had greater ↑MT than slow grp. |
| (Howell, et al., 1993) | 6 men and 7 women. Healthy participants | Ex= el flex (5-9sec@90% MVT), Sets=3 Reps=5-15 | 80% of the initial muscle swelling (<1 hour post) was in the flexor muscle compartment. From 1-2 days up to 9-10 days later 65% of the swelling was from the flexor muscle compartment. |
| (Murayama, et al., 2000) | 11 healthy Ms | Ex= el flex (arm curl machine 5 sec), Reps=24 | ↑MT. Subcutaneous thickness did not change. Maximal ↑MT was 5 days post Ex |
| (Nosaka & Clarkson, 1996) | 14 healthy Ms | Ex= el flex (arm curl machine), Reps=24 | ↑MT. Peaked 3-4 days post Ex. |
| (Nosaka & Sakamoto, 2001) | 10 healthy Ms | Ex= el flex (arm curl machine maximal contraction@20°/s), from 50-130° (short) or from 100-180° (long) Reps=24 | Greater ↑MT for the long grp (11.2mm versus 5.1mm). |
| (Nosaka & Newton, 2002a) | 8 healthy M participants | Ex= el flex (dumbbell one arm maximal, contralateral arm at 50%MVT), Sets= 3, Reps=10 | ↑MT immediately in both arms. Greater ↑MT in maximal group peaking on day 4 |
| (Nosaka, et al., 2002b) | 18 healthy Ms (Con-ecc endurance group)<br>50 healthy Ms (ecc) | Endurance= 2 hrs of con-ecc arm curl at 9% of their MVT 30 cycles per minute. Ecc= 12 maximal ecc el flex contractions | ↑MT post ecc Ex only. Peaked 4-5 days post Ex |
| (Nosaka, Newton, & Sacco, 2002c) | 17 M participants (isometric=8 ecc=9) | Ex= el flex (isometric grp 5sec, eccentric grp 3 sec), Reps=24 | Immediate ↑MT in both groups but only the ecc grp continued to ↑ by day 4 |
| (Sbriccoli, et al., 2001) | 10 healthy sedentary participants<br>(5 ecc grp, 5 control grp) | Ex= el flex (arm curl machine), Sets=2 Reps=35 | ↑MT at 3hrs post Ex. The peak ↑MT was between days 2-4 |

***Abbreviations:*** Ex=exercise; EI=echo intensity; kn ext=knee extension/extensors; kn flex=knee flexion/flexors; el ext=elbow extension/extensors; el flex=elbow flexion/flexors; 1RM=one repetition max; Dif=difference; Btw=between; MVT=maximal voluntary tension; Reps=repetitions; Con=concentric; Ecc=eccentric; F=female; M=male; ↓=reduced/decreased; ↑=increased/higher; Hrs=hours; Mins=minutes; Grps=groups; MRI=magnetic resonance imaging; MT=muscle thickness

Ultrasound changes are also similar to the changes seen in magnetic resonance imaging (MRI) which suggests that the T2 signal from MRI and the increased echo intensity on US may have a common source which is most probably oedema (Lefebvre et al., 1995; Nosaka & Clarkson, 1996; Nosaka & Sakamoto, 2001; Rodenburg, De Boer, Schiereck, Van Echteld, & Bär, 1994). MRI is sensitive to changes in water distribution therefore it can be used to show late oedema which is evidence of muscle damage (Mair et al., 1992). Increase in MRI signal intensity has been shown to coincide with maximal decrease in force generation, pain and tenderness of the exercised muscle (Mair, et al., 1992; Schwane, Buckley, Dipaolo, Atkinson, & Shepherd, 2000).

Limitations surrounding the research on ultrasound measures following eccentric exercise include a lack of studies investigating any muscle group other than the elbow flexors and a lack of established reliability on EI and cross sectional area measurement. The EI and cross sectional area can be influenced by many factors such as soft tissue compression, the angle of the ultrasound probe and location (Pillen et al., 2006). These factors must be standardized and a protocol for each muscle group including multiple locations based upon anatomical landmarks should be developed and assessed for reliability.

Another measure of eccentric muscle damage and swelling is limb circumference. Thirty one studies used limb circumference as a measure following eccentric exercise (Table 5). The vast majority of these (28) assessed limb circumference changes in the upper limb. Only three studies tested the lower limb. One used a stepping exercise, one investigated the NH and another study investigated the knee extensors following eccentric isokinetic contractions. A biphasic increase in girth has been observed in some studies where a significant increase in limb circumference is noticed immediately post exercise and then it subsided by 6 hours before increasing again to peak on day 3-4 (Bowers, et al., 2004; Howell, et al., 1993; Nosaka & Newton, 2002b; Peake, Nosaka, Muthalib, & Suzuki, 2006).

A significant correlation has been found between the decrease in maximal voluntary contraction and the increase in limb circumference (Nosaka, Chapman, Newton, & Sacco, 2006). Peak increase in limb circumference occurs 3-6 days following a bout of eccentric exercise of the elbow flexors (Ahmadi, Sinclair, Foroughi, & Davis, 2008; Bottas, Miettunen, Komi, & Linnamo, 2010), thigh muscles (Bowers, et al., 2004) or knee flexors (Brockett, et al., 2001). In contrast to this, increased limb circumference has been shown to persist to day 8-9 which is much longer than soreness (Bottas, et al., 2010; T. C. Chen & Nosaka, 2006). This suggests swelling and pain have different mechanisms.

All of the reviewed studies showed a significant increase in limb circumference following eccentric exercise except following eccentric isokinetic knee extension in the 2011 study by Chen et al. (2011). A potential reason for this could be that the quadriceps was exercised at a different starting and finishing angle than the other muscles. The position of the pelvis will have an effect on the length of the knee flexors and rectus femoris (Chleboun, France, Crill, Braddock, & Howell, 2001). The knee extensors were contracted between 30-120 degrees of knee flexion compared to 90-0 degrees for the knee flexors. As the knee flexors were exercised a greater part of their descending limb they may have been subjected to greater muscle strain and therefore showed greater markers of muscle damage. Another potential reason for the difference could be that quadriceps are less susceptible to eccentric damage due to their morphology or their conditioning from everyday activities. More research needs to be conducted to investigate the changes in limb circumference in muscles other than the elbow flexors. A limitation of many studies is that circumference is only measured at one or two points (T. C. Chen & Nosaka, 2006). Different eccentric exercises could potentially cause damage in different locations. The corresponding change in girth may be missed or underrepresented therefore measures should be taken at a range of locations that are anatomically relevant.

***Table 5: Studies evaluating the effect of eccentric exercise on limb circumference***

| Study | Participants | Protocol | Result |
|---|---|---|---|
| (Ahmadi, et al., 2008) | 10 healthy Ms | Ex= el flex (isokinetic@ 30°/s), Sets=2, Reps=35 | ↑LC immediately and all times measured. Peak increase day 4-5 days post Ex. After 6 days the LC had not returned to baseline |
| (Bottas, et al., 2010) | 10 physically healthy Ms | Ex= el flex (isokinetic@ 115°/s), Reps=50 | ↑LC 2hrs after medially and at every time point after both medially and distally. Peak ↑LC between day 4-6. LC had not returned to normal by day 8 |
| (Bowers, et al., 2004) | 9 healthy participants (4 M and 2 F) | Ex= kn ext (step Ex) Sets=12, Reps=20 | ↑LC with the peak at 72 hrs (6mm). By day 8 LC had returned to control values. |
| (Brockett, et al., 2001) | 10 healthy participants (8 M and 2 F) | Ex= kn flex (Nordic hamstrings Ex) Sets=12, Reps=6 | ↑LC by day 3 post Ex which peaked at day 4. |
| (Chapman, Newton, Sacco, & Nosaka, 2006) | 12 healthy participants (6 M and 6 F) | Ex= el flex (isokinetic@ 30°/s, slow) Sets=5, Reps=6, Contralateral limb (isokinetic@ 210°/s, fast) Sets=35 Reps=6 | ↑LC all time points peaking at 72hrs in the fast group whereas ↑LC only immediately post Ex in the slow group. |
| (Chapman, Newton, Mcguigan, & Nosaka, 2008) | 16 healthy men<br>2 groups 8= 30 reps, 8= 210 reps | Ex= el flex. Grp 1 (isokinetic@ 30°/s) Sets=5, Reps=6, then 14 days later contralateral limb (isokinetic@ 210°/s, fast) Sets=5 Reps=6. Grp 2 (isokinetic@ 30°/s) Sets=35, Reps=6, then 14 days later contralateral limb (isokinetic@ 210°/s, fast) Sets=35 Reps=6 | ↑LC . No dif in LC between groups with the same number of contractions regardless of speed. |
| (T. C. Chen, 2003) | 26 healthy men | Ex= el flex. (isokinetic@ 60°/s) Sets=3, Reps=10 | ↑LC post Ex |
| (T. C. Chen & Nosaka, 2006) | 10 athletic participants per group | Ex= el flex. (dumbell@80% MVT 5 sec) Reps=30, 50, or 70 | ↑LC all groups. LC peaked 5-8 days post Ex (10-13mm) inc from baseline. Smaller ↑LC in the 30 contraction group compared to the 50 and 70 contraction group. |
| (T. C. Chen, Nosaka, & Sacco, 2007) | 52 healthy Ms<br>13=100% MVT<br>13=80% MVT<br>13=60% MVT<br>13=40% MVT | Ex= el flex. (dumbell) Reps=30 | ↑LC all groups. Peaked 4-5 days post Ex. The 40% group showed less ↑LC than the 80% and 100% groups. |
| (T. C. Chen, et al., 2011) | 17 sedentary Ms | Ex= kn ext/kn flex/el flex/el ext (isokinetic@ 90°/s), Sets=5, Reps=6 | ↑LC all muscles except knee extensors. Elbow muscles had greater ↑LC than knee muscles. |
| (Cleak & Eston, 1992) | 26 F physiotherapy students | Ex= el flex. (maximal pulleys) Sets=7, Reps=10 | ↑LC in distal musculotendinous junction and mid-belly circumference by day 3, peaking day 4 post Ex, subsiding by day 10. |
| (Dannecker, et al., 2012) | 33 healthy participants (42% women) | Ex= el flex. (isokinetic@ 90°/s) Sets=3, Reps=12 | ↑LC. No dif between men and women. |
| (Howell, et al., 1993) | 6 men and 7 women. Healthy participants | Ex= el flex (5-9sec@90% MVT), Sets=3 Reps=5-15 | ↑LC immediately post Ex then ↓ at 6hrs before ↑ to peak at day 3-4. ↑LC observed to day 9 post Ex. |
| (Hunter et al., 2012) | 19 healthy Ms | Ex= el flex (isokinetic@30°/s), Sets=5, Reps=10 | ↑LC plateauing by day 3. |
| (Lavender & Nosaka, 2008) | 12 young Ms (19 years)<br>12 middle aged Ms (48 years) | Ex= el flex (dumbbell @40%MVT), Sets=6, Reps=5 | ↑LC No dif btw groups. ↑LC following Ex and continued to increase for 4 days post Ex. |
| (Murayama, et al., 2000) | 11 healthy Ms | Ex= el flex (arm curl machine 5 sec), Reps=24 | ↑LC after Ex and remained elevated by day 5 |
| (Newton, Morgan, Sacco, Chapman, & Nosaka, 2008) | 15 trained Ms<br>15 untrained Ms | Ex= el flex (isokinetic@ 90°/s), Sets=10, Reps=6 | ↑LC in both groups immediately. Greater ↑LC in untrained group. The Peak ↑LC in trained group at day 1 post Ex (5mm) whereas the largest ↑LC was on day 5 in the untrained group (16 mm). |

| | | | |
|---|---|---|---|
| (Newton, Sacco, Chapman, & Nosaka, 2013) | 18 healthy men | Ex= el flex (isokinetic@ 90°/s), Sets=10, Reps=6 followed 4 weeks later by the contralateral arm. | No dif btw average changes btw limbs but a bout effect was noted. The contralateral limb Exd 4 weeks after the ipsilateral limb experienced less ↑LC independent of limb dominance. |
| (Nosaka & Clarkson, 1996) | 14 healthy Ms | Ex= el flex (arm curl machine maximal contraction), Reps=24 | ↑LC over 5 days post Ex |
| (Nosaka & Sakamoto, 2001) | 10 healthy Ms | Ex= el flex (arm curl machine maximal contraction@20°/s), from 50-130° (short) or from 100-180° (long) Reps=24 | ↑LC at all sites. No diff btw the 2 groups until day 3 when there was greater ↑LC in the long group. |
| (Nosaka, Sakamoto, Newton, & Sacco, 2001) | 34 healthy Ms | Ex= el flex (arm curl machine), Reps=2, 6, or 24 | ↑LC was smaller for the 2 and 6 contraction groups (3.5mm and 7.9mm) than the 24 contraction group (18.6mm). |
| (Nosaka & Newton, 2002a) | 8 healthy M participants | Ex= el flex (dumbbell one arm maximal, contralateral arm at 50%MVT), Sets= 3, Reps=10 | ↑LC both groups without a sig dif btw them immediately post Ex. There was no further ↑LC in the 50% group whereas ↑LC peaked on day 4 post Ex. |
| (Nosaka & Newton, 2002b) | 7 healthy Ms | Ex= el flex (arm curl machine maximal contraction), from 100-180° Reps=24 | ↑LC by more than 20mm at day 5 |
| (Nosaka, et al., 2002b) | 18 healthy Ms (Concentric eccentric endurance group) 50 healthy Ms (eccentric) | Endurance= 2 hrs of con-ecc arm curl at 9% of their MVT 30 cycles per minute. Ecc= 12 maximal ecc el flex contractions | ↑LC in both groups with greater ↑LC in the eccentric group (12mm versus 3mm) |
| (Nosaka, Newton, & Sacco, 2002a) | 110 participants 12 eccentric contractions=50 24 eccentric contractions= 60 | Ex= el flex (arm curl machine maximal contraction for 3sec), Reps=12 or 24 maximal | ↑LC immediately for both groups. No dif btw grps immediately. ↑LC continued to increase and peaked 3-4 days post Ex for both grp. The 24 contraction grp's ↑LC was greater than the 12 contraction grp. |
| (Nosaka, et al., 2002c) | 17 M participants (isometric=8 ecc=9) | Ex= el flex (arm curl machine), Isometric group, Reps= 24@5sec@ 90°. Ecc grp= Reps=24 in 3 seconds. | ↑LC in both groups immediately after Ex. LC returned to pre Ex level by day 1 in the isometric grp whereas the ecc grp continued to ↑LC up to day 4 |
| (Nosaka, Newton, & Sacco, 2005) | 30 healthy Ms | Ex= el flex (arm curl machine), Reps= 12 | ↑LC post Ex, peaked 4 days post Ex. |
| (Nosaka, Newton, Sacco, et al., 2005) | 22 healthy Ms (long=11) (short=11) | Ex= el flex (arm curl machine), from 50-100 (short) or 130-180 Reps= 24. | Similar ↑LC in both groups initially but by day 2 the long grp developed greater ↑LC than the short grp. |
| (Nosaka, et al., 2006) | 89 healthy Ms | Ex= el flex (arm curl machine), Reps= 24 | ↑LC. Correlation btw ↑LC and ↓MVT immediately post Ex |
| (Paddon-Jones, Keech, Lonergan, & Abernethy, 2005) | 15 healthy participants (8=M, 7=F) Slow=7 Fast=8 | Ex= el flex (isokinetic@ 180°/s or 30°/s), Sets=6, Reps=6 | ↑LC in both groups. Greater ↑LC in the slow grp at 20 min, 1 and 3 days post Ex |
| (Peake, et al., 2006) | 10 healthy Ms | Ex= el flex (isokinetic@30°/s @10%MVT), Sets=10, Reps=60 followed 2 weeks later by (isokinetic@30°/s @10%MVT), Sets=10, Reps=3 on the contralateral limb | ↑LC with no dif btw groups |

***Abbreviations:*** Ex=exercise; EI=echo intensity; kn ext=knee extension/extensors; kn flex=knee flexion/flexors; el ext=elbow extension/extensors; el flex=elbow flexion/flexors; 1RM=one repetition max; Dif=difference; Btw=between; MVT=maximal voluntary tension; Reps=repetitions; Con=concentric; Ecc=eccentric; F=female; M=male; ↓=reduced/decreased; ↑=increased/higher; Hrs=hours; Mins=minutes; Grps=groups; MRI=magnetic resonance imaging; MT=muscle thickness; LC=limb circumference

# FACTORS THAT INFLUENCE THE DEGREE OF MUSCLE DAMAGE FOLLOWING ECCENTRIC EXERCISE

**Difference in susceptibility of muscle groups to eccentric damage**

Five studies have compared the acute effects of eccentric exercise between different muscle groups. The responses to eccentric exercise have been shown to be greater in the elbow extensors and elbow flexors compared to the knee flexors and knee extensors. There appears to be no significant differences between the elbow extensors and elbow flexors however the knee flexors show greater changes post eccentric exercise than the knee extensors.

The damage profile after eccentric exercise is different between muscle groups. The knee extensors have been shown to be less susceptible to muscle damage from a bout of eccentric exercise than the knee flexors, elbow flexors or elbow extensors (T. C. Chen, et al., 2011; Jamurtas, et al., 2005; Paschalis, et al., 2010; Saka, et al., 2009). When the effects of three sets of 35 eccentric contractions at 120 degrees/second of the knee extensors and knee flexors were compared by Franklin et al. (1993) they reported the knee flexors had significantly greater muscle soreness. In 2005, Jamurtas et al. compared the effects of six sets of 12 repetitions of eccentric isokinetics (60 degrees/second) on the elbow flexors and the knee extensors. Decreases in muscle strength were significantly less for the knee extensors group. However no significant differences were found regarding range of motion (ROM) loss and delayed onset muscle soreness (DOMS). Saka et al. (2009) also compared the knee extensors and the elbow flexors. They used a protocol of three sets of 15 maximal eccentric isokinetic contractions at 30 degrees/second. Significantly smaller increases in DOMS were observed in the knee extensors group and the strength and ROM loss were also significantly less compared to the elbow flexors group. This contrast with Jamurtas et al. (2005) may be explained by different assessment and exercise protocols. Chen et al. (2011) compared the effects of five sets of six maximal isokinetic (90 degrees/second) eccentric contractions of the knee flexors, knee extensors, elbow flexors and elbow extensors. Changes in optimal angle were significantly greater for elbow flexors and elbow extensors compared to knee extensors and knee flexors. There was no significant difference between the elbow flexors and elbow extensor groups but the change in optimal angle to longer muscle length was significantly greater in the knee flexors compared to the knee extensors group. Maximum voluntary contraction (MVC) decreased significantly immediately after exercise in all groups with the elbow groups' decrease significantly greater than the knee groups' decrease with no significant difference between the elbow extensors and elbow flexors but with knee flexors having a significantly greater decrease than knee extensors. It was also shown that recovery of MVT to base line was significantly faster for the knee groups with knee extensors recovering significantly faster than knee flexors. Decreases in ROM were significantly greater in the elbow extensor and elbow flexors groups compared to the knee extensors and knee flexors groups with no significant difference between the elbow groups and a significantly greater loss of ROM in the knee flexors compared to the knee extensors group. Significant increases in limb circumference were seen in the elbow extensors, elbow flexors and knee flexors but not the knee extensors group. The elbow groups had significantly greater increases than the knee flexors group. Knee flexors showed significantly greater increases than knee extensors. Regarding post exercise muscle soreness the elbow groups suffered significantly greater levels than the knee groups with no significant difference between the elbow extensors and elbow flexors but with significantly greater DOMS in the knee flexors compared to the knee extensors. Ultrasound echo intensity increased in all groups except the knee extensors group and there was no difference between the elbow extensors and elbow flexors groups but the elbow groups had significantly greater increases than the knee groups and the knee flexors had significantly greater increases than the knee extensors. Paschalis, et al., (2010) compared the responses of the elbow flexors and knee flexors to five sets of 15 maximal eccentric contractions and found the indicators of muscle damage to be greater and were slower to recover in the elbow flexors. The findings of Chen et al. (2011) for the knee flexors are similar to those of Brockett et al. (2001) who used 12 sets of six repetitions of the Nordic hamstrings exercise to induce muscle damage.

Potential differences in the susceptibility of different muscle groups to damage from eccentric exercise may be explained by differences in their use in activities of daily living, force-length relationship, muscle architecture and muscle fibre composition (T. C. Chen, et al., 2011; Jamurtas, et al., 2005; Saka, et al., 2009). Sitting down, descending stairs and walking down hill are all lower limb eccentric activities that are common activities of daily living. It is well demonstrated in the literature that a repeated bout of eccentric exercise will cause much less damage than the previous bout (Black & McCully, 2008; McHugh, Connolly, Eston, & Gleim, 1999; McHugh & Tetro, 2003; Starbuck & Eston, 2012). These eccentric lower limb activities of daily living may help to condition the lower limb to eccentric exercise and explain the lower levels of muscle damage observed in the knee extensors and knee flexors compared to the elbow extensors and elbow flexors (Prior, et al., 2001). Resistance trained individuals showed less markers of muscle damage following eccentric exercise of the elbow flexors than untrained participants (Newton, et al., 2008). This may be another example of the preconditioning of the resistance trained participants making them more resilient to eccentric induced muscle damage. Regarding the difference between the susceptibility of the knee extensors and knee flexors to eccentric muscle damage it could be speculated that the knee extensors undertake more eccentric contractions throughout the day however this has not been investigated in the literature (T. C. Chen, et al., 2011; Franklin, et al., 1993).

Differences in muscle architecture may also influence the susceptibility of muscles to damage by eccentric muscle contraction. The knee flexors have smaller penneation angle and longer muscle length than the knee extensors which may make them more vulnerable (Slavotinek, Verrall, & Fon, 2002). The knee flexors also have less volume than the knee extensors which raises the possibility that larger muscles may be less prone to muscle damage as was evidenced when comparing the smaller elbow extensors/elbow flexors with the larger knee extensors/knee flexors (T. C. Chen, et al., 2011; Jamurtas, et al., 2005; Saka, et al., 2009; Wickiewicz, Roy, Powell, & Edgerton, 1983). Also It has been shown that larger muscles require larger stress to induce muscle fatigue compared to smaller muscles (Hoeger, Hopkins, Barette, & Hale, 1990). However, despite the muscle architecture, repeated bouts of eccentric exercise have been shown to significantly decrease markers of muscle damage (Black & McCully, 2008; McHugh & Tetro, 2003; Starbuck & Eston, 2012). Although some conclusions regarding the susceptibility of different muscle groups to damage from eccentric exercise can be drawn there is a need for more research in this area comparing a greater variety of muscle groups.

**Speed of eccentric contraction**

Six studies have investigated the influence of speed of eccentric contraction on muscle damage (Barroso et al., 2010; Chapman, Newton, Mcguigan, et al., 2008; Chapman, et al., 2011; Chapman, et al., 2006; Paddon-Jones, et al., 2005; Shepstone et al., 2005). It would appear that speed of eccentric contraction is not a strong predictor of muscle damage especially during exercise bouts with moderate numbers of contractions such as 30 repetitions but with greater numbers of contractions greater speed tends to induce greater damage. However, all of the reviewed studies tested the elbow flexors on normal healthy participants therefore more research needs to be conducted on other muscle groups and populations to determine whether trained participants or different muscle groups would respond differently.

Chapman et al. (2006) compared elbow flexor muscle damage after fast (210 degrees/second) and slow (30 degrees/second ) eccentric contractions. Significantly greater muscle damage was observed following the bout of fast eccentric contractions. This study equated time under tension between the two velocities which resulted in considerably more contractions at a higher velocity (210 versus 30). To determine the effect of velocity on eccentric muscle damage Chapman et al. (2008) used the same velocities as above but matched the numbers of contractions. They found there was no significant difference on muscle damage markers between the velocities after 30 repetitions but after 210 repetitions the markers of muscle damage were larger in the faster velocity group. Further study comparing 210 eccentric isokinetic elbow flexor contractions at 30 degrees/second and 210 degrees/second found faster eccentric contractions had significantly slower recovery of isometric strength and ROM, and greater increase in limb circumference (Chapman, et al., 2011). Greater Z-band streaming (disruption of the protein ultrastructure) which is considered to be a direct marker of muscle damage, was observed by Shepstone et al. (2005) after 30 fast (210 degrees/second) eccentric elbow flexor contractions compared to 30 slow contractions (Lieber, Shah, & Fridén, 2002). However, Z-band streaming may just indicate greater muscle protein remodelling not necessarily greater muscle damage (Yu, Carlsson, & Thornell, 2004). In contrast, greater muscle damage was not observed when Barroso et al. (2010) compared 30 maximal contractions of the elbow flexors at 60 degrees/second and 180 degrees/second. They found no significant difference in maximum isometric contraction, range of motion, and muscle soreness before or for four days following exercise. This may be because there was less of a difference in speed in this study or that there is a difference in sensitivity to change between the measures taken. Similar decreases in strength variables were observed following 36 eccentric contractions at 30 degrees/second and 180 degrees/second of the elbow flexors. However, there was a slightly greater significant increase in arm girth following the slower eccentric contractions suggesting greater muscle damage (Paddon-Jones, et al., 2005).

**Number of eccentric contractions**

Six studies have investigated the influence of the number of eccentric contractions on muscle damage by using identical exercise prescriptions and varying the number of repetitions (Brown, et al., 1997; Chapman, Newton, Mcguigan, et al., 2008; T. C. Chen & Nosaka, 2006; Howatson, Van Someren, & Hortobagyi, 2007; Nosaka, et al., 2002a; Nosaka, et al., 2001). It appears a greater number of eccentric contractions leads to greater increases in markers of muscle damage. (Howatson, et al., 2007). All of these studies tested the elbow flexors except one which tested the knee extensors.

Brown, Child, Day and Donnelly, (1997) compared the effects of 10, 30 and 50 maximal eccentric knee extensor contractions and found a greater number of contractions caused higher soreness and greater decreases in MVT for longer than fewer contractions. This has also been demonstrated using eccentric isokinetic elbow flexors contractions (Nosaka, et al., 2001). Following 2, 6, or 24 maximal eccentric elbow flexor contractions, the greater the number of contractions performed, the greater the decrease in maximal voluntary tension (MVT), increase in soreness and increase in limb circumference post exercise was observed (Nosaka, et al., 2001). Similar results were obtained by Nosaka, Newton and Sacco, (2002a) when they compared 12 and 24 maximal eccentric elbow flexors contractions. There was significantly less decrease in MVT and greater recovery of MVT four days later following 12 contractions compared to 24 maximal eccentric contractions with greater increase in limb circumference was in the 24 contraction group. When Howatson et al., (2007) compared the effects of 15 and 45 maximal eccentric elbow flexor contractions, it was found that there was greater soreness and greater decreases in MVT following 45 contractions. Significantly greater differences between the loss of muscle strength and increase in muscle circumference were observed following 210 contractions compared to 30 contractions at both fast and slow velocities (Chapman, Newton, Mcguigan, et al., 2008). Also, 50 and 70 eccentric dumbbell elbow flexor contractions have been shown to induce greater decreases in MVT and increases in limb circumference than 30 contractions however, with no significant differences in soreness (T. C. Chen & Nosaka, 2006).

**Intensity of eccentric loading**

Three studies have compared the same exercise prescription with different intensity of loading (Nosaka & Newton, 2002a; Paschalis, Koutedakis, Jamurtas, et al., 2005; Peake, et al., 2006). Two studies used the elbow flexors and the other used the knee extensors. Greater intensity of eccentric exercise appears to be a greater determinant of muscle damage than total work done. When the same number of eccentric elbow flexor repetitions were compared one with maximal eccentric contractions and the other with 50% of the maximal isometric strength, there were significantly smaller changes in the isometric strength, ROM, upper arm circumference and plasma CK levels after the 50% loading exercise bout. The differences between the groups were small immediately post exercise but the recovery was significantly faster in the 50% loading group (Nosaka & Newton, 2002a). This suggests that the initial muscle damage was similar but the secondary muscle damage was greater in the maximal loading group or the difference in load affected the recovery process more than the original changes post exercise. Similar results have been observed following 10 sets of 60 eccentric elbow flexor contractions at 10% MVT versus 10 sets of 3 maximal eccentric contractions (Peake, et al., 2006). Comparable initial losses of MVT were observed but recovery was faster following the submaximal contractions despite greater work being done in the submaximal group (6791+- 187J versus 1288+-36J) (Peake, et al., 2006). When work was equated between maximal eccentric isokinetic knee extensor contractions of one limb and isokinetic contractions at 50% MVT of the other limb, the high intensity exercised limb showed significantly greater decrease in MVT following exercise (Paschalis, Koutedakis, Jamurtas, et al., 2005).

**Total work**

There can be large variability between the degree of muscle damage that occurs after eccentric training between participants who perform the same protocol (Chapman, Newton, Zainuddin, Sacco, & Nosaka, 2008). It has been suggested that work or peak torque may play a role in influencing the degree of damage. However, this was not the case when total work, change in work, and change in peak torque were assessed for correlation with markers of muscle damage following 60 eccentric elbow flexor contractions (Chapman, Newton, Zainuddin, et al., 2008). The authors concluded that the large variability in response to a bout of eccentric exercise is not associated with torque generated or work performed during that exercise. Using identical programmes but over different elbow flexor muscle lengths it was found that the arm exercised at longer muscle lengths preformed less work but had greater loss of MVT.

When the isokinetic concentric torque, MVT, eccentric torque and eccentric work done during 10 sets of 10 maximal eccentric contractions were compared between untrained participants and national level long distance runners, sprinters and volleyball players the untrained participants and distance runners achieved lower values than the sprinters and volleyball players (Skurvydas, Brazaitis, Venckūnas, et al., 2011). Despite this the untrained participants had a greater prolonged decrease in MVT indicating greater damage. The greater isokinetic concentric torque, MVT, eccentric torque and eccentric work during exercise could be explained by the potentially greater percentage of fast twitch fibres that would be expected in well conditioned power athletes whereas greater slow twitch fibres would dominate in long distance runners and the untrained (Saltin, Henriksson, Nygaard, Andersen, & Jansson, 1977; Tesch & Karlsson, 1985).

When concentric-eccentric endurance training at 9% of MVT for 2 hours was compared with 12 maximal eccentric contractions of the elbow flexors the total work performed by the concentric eccentric group was 60,000Nm compared to maximal eccentric group at 1000Nm (Nosaka, et al., 2002b). The concentric-eccentric group had a greater initial decrease in MVT however despite the large difference in work done the eccentric group took longer to recover, had greater swelling and significantly more soreness from day 1 post exercise on. Increases in echo-intensity and muscle thickness were negligible following 2 hours concentric-eccentric exercise whereas after 12 maximal eccentric contractions echo-intensity and muscle thickness increased significantly and peaked 4-5 days post exercise. (Nosaka, et al., 2002b). Greater and longer term damage was caused by the maximal eccentric contractions despite less work performed. This suggests that high local tension in muscle fibres/mechanical factors are more important than metabolic overload in causing muscle damage (Armstrong, 1986).

**Influence of muscle length on muscle damage**

Six studies have compared markers of muscle damage following eccentric exercise at different muscle length (Child, et al., 1998; Newham, et al., 1988; Nosaka, Newton, Sacco, et al., 2005; Nosaka & Sakamoto, 2001; Paschalis, Koutedakis, Baltzopoulos, Mougios, Jamurtas, & Giakas, 2005; Pettitt, Symonds, Eisenman, Taylor, & White, 2005). It appears that greater damage occurs following eccentric exercise at longer muscle lengths. However, only three muscle groups have been investigated. Three studies tested the elbow flexors, one tested the elbow extensors and 2 studies tested the knee extensors.

As a muscle lengthens into the descending limb of its length tension curve the degree of actin and myosin overlap decreases and therefore the ability of the muscle to generate active tension decreases. At the same time the tension on the parallel elastic components is increasing consequently passive tension is increasing. Therefore the length of the muscle during eccentric contractions influences the degree of muscle damage. In human elbow flexors (Newham, et al., 1988; Nosaka, Newton, Sacco, et al., 2005; Nosaka & Sakamoto, 2001), elbow extensors (Pettitt, et al., 2005), and quadriceps (Child, et al., 1998) it has been shown that greater strength loss and greater muscle tenderness (DOMS) are evident 48 hours after in muscles eccentrically exercised at longer muscle lengths compared to shorter muscle lengths. Also greater increases in echo-intensity of biceps brachii and upper limb circumference have been observed following eccentric exercise at long lengths compared to short lengths (Nosaka, Newton, Sacco, et al., 2005). In contrast to this, greater soreness and decreases in MVT were found following 120 maximal eccentric knee extensor contractions with the participant’s hip in flexion to 90 degrees (rectus femoris at short length) versus the same exercise prescription with the participant’s contralateral hip extended in prone (rectus femoris at long length) (Paschalis, Koutedakis, Baltzopoulos, Mougios, Jamurtas, & Giakas, 2005). This finding contradicts the previous research which showed greater damage at longer muscle lengths. In this study the muscle length was modified through the hip which meant the rectus femoris was the only quadriceps muscle whose length changed and its contribution to knee extension torque is only 17% (McNair, Marshall, & Matheson, 1991). Whereas, in Child et al's (1998) study muscle length was changed at the knee therefore influencing all of the quadriceps muscles. Another difference between the two length studies on the quadriceps is the volume of contractions. Paschalis, Koutedakis, Baltzopoulos, et al., (2005) used almost double the number of knee extensor contractions than Child, et al. (1998). Paschalis, Koutedakis, Baltzopoulos, et al., (2005) also suggested greater muscle performance and motor unit recruitment found at shorter quadriceps muscle lengths (Maffiuletti & Lepers, 2003) may have brought the muscle closer to its damage limit. Further research is needed to explain this finding. At present there is greater evidence to suggest greater damage occurs following eccentric exercise at longer muscle lengths.

Other modes of exercise can cause changes in optimal angle of peak torque. Nevertheless, training at longer muscle lengths appears to be a significant factor in shifting the optimal angle to longer muscle lengths regardless of contraction type. When the effects of a single bout of concentric hamstrings contractions at shorter muscle lengths (supine with hip extension at 0 degrees) was compared to contractions at longer muscle lengths (seated with hip flexion at 80 degrees) a significant 15 degree shift of optimal angle occurred in the longer muscle length group. No significant shift occurred in the shorter muscle length group (Guex, Degache, Gremion, & Millet, 2013). Furthermore, isometric exercise of the elbow flexors at long muscle lengths caused shifts of the optimal angle to longer muscle lengths (D.A. Jones, Newham, & Torgan, 1989) but not as much as eccentric exercise (Philippou, Bogdanis, Nevill, & Maridaki, 2004; Philippou, Maridaki, & Bogdanis, 2003).

**Training status**

It would seem that trained individuals have a greater resistance to eccentric muscle damage and the type of training appears to be a factor because power athletes have greater resistance than long distance endurance athletes. The majority of studies on eccentric training have used untrained healthy participants to assess the acute effects of eccentric exercise. Resistance trained participants have shown a greater resilience to a bout of eccentric exercise. Following 10 sets of 6 maximal isokinetic eccentric elbow flexor contractions resistance trained participants had significantly less loss of MVT with faster recovery times compared to non-resistance trained participants (Newton, et al., 2008). Untrained participants also showed greater increases in upper arm circumferences which took longer to recover (Newton, et al., 2008). Additionally, when national level long distance runners, sprinters, and volleyball players were compared to untrained participants, the untrained participants had a prolonged decrease in MVT and isokinetic concentric torque however there was no significant differences in changes in muscle soreness (Skurvydas, Brazaitis, Venckūnas, et al., 2011).

**Difference in susceptibility of muscle fibre types to eccentric damage**

It has been suggested that muscle fibre type composition may affect the susceptibility of a muscle to eccentric contraction damage as type II fibres have been shown to be predominantly affected by eccentric exercise and appear to be more susceptible to eccentric damage than type I (C. Byrne & R. Eston, 2002; Chapman, Simpson, Iscoe, Robins, & Nosaka, 2013; Fridén, Sjöström, & Ekblom, 1983; D.A Jones, Newham, Round, & Tolfree, 1986). A moderate significant correlation between muscle soreness 2 days post eccentric exercise and total type II (r=0.51, P=0.04) and type IIb muscle fibres (r=0.58, P=0.02) and a corresponding negative correlation with muscle soreness and type I fibres (r=0.51, P=0.02) has been reported following isokinetic eccentric exercise of the quadriceps (Magal et al., 2010). This suggests type II fibres are more susceptible for muscle damage following eccentric exercise. There is also evidence for preferential type II muscle fibre damage following eccentric exercise of the elbow flexors. Chapman et al. (2013) found there was a significant increase in fast skeletal troponin I isoform, a marker of type II fibre damage, but not increase in slow skeletal troponin I isoform, a marker of type I fibre damage. Another study using the knee extensors, which have 60% type II fibres, found that the knee extensors were significantly less susceptible to fatigue during a 60 second maximal isometric contraction for 3 days following a bout of eccentric exercise and during a Wingate test 1 day following eccentric exercise (C. Byrne & R. Eston, 2002). Decreasing levels of phosphocreatine and glycogen utilisation has been credited for declining power output during maximal cycling (Bogdanis, Nevill, Boobis, & Lakomy, 1996) and lowered force output during isometric contractions (Soderlund, Greenhaff, & Hultman, 1992). This may explain the reduction in relative fatigue following eccentric exercise. If there is greater damage to type II fibres then their contribution to relative fatigue will be reduced and the fast rise and accompanying fall in power and force associated with this fibre type will be eliminated. Therefore, an eccentrically damaged muscle may appear more fatigue resistant because it is unable to generate the initial high force and power output (C. Byrne & R. G. Eston, 2002; Fridén, et al., 1983)

Nevertheless, autopsy studies of muscle fibre type show that the elbow extensors have a greater percentage of type II muscle fibres than the elbow flexors (67% versus 54%) but Chen et al. (2011) found no significant difference in markers of muscle damage between them after eccentric exercise (Johnson, Polgar, Weightman, & Appleton, 1973). Also the knee extensors have more type II fibres than the knee flexors (60% versus 40%) but the knee flexors have been shown to be more susceptible to eccentric damage (T. C. Chen, et al., 2011; Franklin, et al., 1993; Johnson, et al., 1973). Therefore it appears a greater percentage of type II fibres may not increase the susceptibility of a muscle to eccentric muscle damage but there are limited studies which investigate this. Other factors may have a greater influence such as muscle length during exercise, or previous conditioning. Future research should determine the relative importance of muscle fibre type on susceptibility to eccentric damage across a range of muscles.

### Influence of limb dominance on markers of eccentric muscle damage

It appears that limb dominance does not influence the degree of exercise induced muscle damage. The body of research investigating the effects of eccentric training either uses a control group to compare the extent of an eccentric exercise bout or the contralateral limb of the members of the experimental group is used. Using the contralateral limb may remove the incongruity and heterogeneity of comparing different participants but an effect on the contralateral limb has been observed following eccentric contractions thereby questioning the appropriateness of it as a control (Howatson & Van Someren, 2007; Newton, et al., 2013; Starbuck & Eston, 2012). When the effects of a single bout of eccentric elbow flexor exercise were compared between dominant and non-dominant limbs separated by 4 weeks no significant difference between average changes in muscle damage measures between limbs were observed but a bout effect was noted (Newton, et al., 2013). The contralateral limb exercised 4 weeks after the ipsilateral limb experienced less muscle damage. This was independent of limb dominance (Newton, et al., 2013). Similar results have been shown following eccentric exercise of the knee extensors (Hody, et al., 2013). One leg was exercised and the contralateral leg was exercised 6 weeks later. No significant difference was found between the dominant and non-dominant legs however, significantly less soreness and significantly less decrease in MVT was shown in the second bout of exercise. This suggests contralateral protection from eccentric damage (Hody, et al., 2013). Therefore unilateral eccentric exercise has been shown to have a crossover effect on the contralateral limb and this should be considered when using the contralateral limb as a comparison. However, if the study is counterbalanced it may be acceptable.

## CONCLUSION

Eccentric exercise has been shown to cause significant reductions in isometric and isokinetic strength peaking from 1-3 days post exercise and lasting up to 16 days. Additionally eccentric exercise causes a change in the optimal angle of peak torque to longer muscle lengths. This shift in angle of peak torque also occurs following isometric exercise at long muscle lengths but to a lesser degree. Furthermore increases in ultrasound echo intensity have been demonstrated in human participants after eccentric exercise. These ultrasound changes are similar to the changes seen in MRI which suggests that the T2 signal from MRI and the increased echo intensity on US may have a common source which is most probably oedema. Limb circumference increases following eccentric exercise and peaks around 3-6 days following the bout and persists to day 8-9 which is much longer than soreness thereby suggesting they may be due to different mechanisms. There is evidence from multiple studies showing that the muscle length, number of contractions and loading will influence the effect of eccentric exercise on muscle function more than total work done. Greater speed of eccentric contraction will induce greater damage if the numbers of contractions are greater than 30. Resistance trained athletes show greater resilience to eccentric damage than endurance athletes and untrained subjects but there seems to be no significant effect of limb dominance on the response to eccentric exercise. However, unilateral eccentric exercise has been shown to have a protective crossover effect on the contralateral limb. Lastly upper and lower limb muscles respond differently to eccentric exercise.

# CHAPTER 3

## RELIABILITY OF ULTRASOUND ECHO INTENSITY AND CROSS SECTIONAL AREA.


**Overview**

*Objectives:* To quantify within-session and between-session reliability of individual hamstring ultrasound echo intensity (EI) and cross sectional area (CSA) measurements. *Design:* Quantitative repeated measures experimental. *Methods:* Sixteen recreationally active female participants (Group 1: 22.5 years (2), 166.3 cm (7.1) and 73.2 kg (8.1), Group 2: 23 years (6), 163.6 cm (5.8) and 72.0 kg (9.8)) were recruited from a tertiary student population. Ultrasound EI and CSA were measured at seven sites by an experienced practitioner. All 16 participants were assessed twice to compare within-session reliability and then the first 8 participants returned for repeat testing between one to two hours later. Within-session and between-session reliability was assessed using an excel spreadsheet by Hopkins (2015), intraclass correlation coefficients (ICC) and the coefficient of variation (CV) were calculated. The magnitude of the ICC values were described as ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate, 0.20-0.50 = low, ≤0.20 = very low. *Results:* The within-session reliability of EI and CSA in recreationally active females was high (ICC≥0.75) or greater for all seven areas. For between-session reliability of EI three areas showed high reliability or greater, three areas showed moderate reliability (ICC = 0.50-0.75) and one area showed low reliability (ICC = 0.20-0.50). Whereas, five areas showed high reliability or greater and two areas showed moderate reliability for CSA. *Conclusions:* EI and CSA have acceptable within-session reliability but future research should investigate methods to improve the between session reliability of some hamstring EI and CSA locations.


**Introduction**

The hamstrings consist of semimembranosus (SM), semitendinosus (ST), and biceps femoris long head (BFLH) and biceps femoris short head (BFSH). Each of these muscles have different innervation patterns and unique architecture (Kubota, et al., 2007). Generally the actions of the hamstrings involve hip extension and knee flexion (concentric action) and resisting hip flexion and knee extension (eccentric action). As the hamstrings act over two joints with important concentric and eccentric actions, hamstring strain is one of the most common injuries in sports that involve high speed running activities (Petersen, et al., 2010). Hamstring injuries have a high rate of recurrence (12-43%) which results in considerable loss in training time and match play (Engebretsen, et al., 2010; Kerkhoffs et al., 2013).

A growing body of evidence suggests eccentric training may be beneficial in preventing hamstring strains. The majority of studies that have examined eccentric hamstring training have used the Nordic hamstrings exercise. Exercise produces changes in water distribution in tissues and can be shown by changes in signal intensity on magnetic resonance imaging (MRI). Acute (48 hours post exercise) increases in MRI signal intensity have shown the Nordic hamstrings exercise loads the proximal Biceps Femoris short head (BFSH) of the hamstrings (Mendiguchia, Arcos, et al., 2013). However the most commonly strained muscle of the hamstrings group is the BFLH (Silder, et al., 2008; Slavotinek, et al., 2002). At long term follow up (5-23 months post hamstring injury) , atrophy of the BFLH has been found on MRI whereas hypertrophy of the BFSH was observed (Silder, et al., 2008). The greatest risk factor for hamstring strain injury is a previous hamstring strain injury (Cabello et al., 2015). The architecture, origin, insertion and innervation of each of the hamstring muscles are different; this would suggest each should have a slightly different role in lower limb function (Mendiguchia, Garrues, et al., 2013). Rehabilitation programmes need to be better targeted to focus on individual muscles, if possible, to avoid strength imbalances continuing post injury which could predispose the athlete to further hamstring strains. Therefore, a better understanding of specifically which hamstring muscle along with which area of that muscle is stressed by different exercises will help inform clinicians, coaches and trainers when prescribing rehabilitation and training programmes.

To discover which parts of which hamstring muscles were stressed, MRI was performed on eight male participants following five sets of eight repetitions of the Nordic hamstrings exercise (Mendiguchia, Arcos, et al., 2013). These authors concluded that the Nordic hamstrings exercise predominantly stressed the proximal aspect of the BFSH. However, the most commonly strained muscle of the hamstrings group is the Biceps Femoris long head (BFLH) (Silder, et al., 2008; Slavotinek, et al., 2002). Therefore a different form of eccentric exercise from the Nordic hamstrings exercise that preferentially stresses the BFLH, may have superior injury prevention and management potential. Further MRI studies have reported the leg curl exercise predominantly stresses the ST (Kubota, et al., 2007) and the lunge exercise loads the proximal regions of the BFLH (Mendiguchia, Garrues, et al., 2013).

Changes in muscle morphology can be used to assess the acute and chronic effects of exercise. If areas of damage or hypertrophy to specific muscles or regions of muscle can be identified this has potential to guide exercise interventions. The knowledge of which specific muscles or muscle regions are stressed during an exercise will inform a clinician regarding the most appropriate exercises to prevent and treat injuries. Although MRI is the gold standard to visualise muscle morphology it is expensive and not readily available to most clinicians whereas ultrasound is a more cost effective modality for both researchers and clinicians (Whittaker & Stokes, 2011).

The validity of ultrasound imaging for measuring muscle morphology, when compared to using MRI, is reported in the literature as adequate (Whittaker & Stokes, 2011). It has been demonstrated that good agreement exists between MRI and ultrasound assessment of muscle size of biceps brachii and rectus femoris (Bemben, 2002), the rotator cuff (Juul-Kristensen, Bojsen-Møller, Holst, & Ekdahl, 2000), iliopsoas and sartorius (Mendis, Wilson, Stanton, & Hides, 2010), and trapezius (O'Sullivan, Meaney, Boyle, Gormley, & Stokes, 2009).

Echo-intensity (EI), as assessed by ultrasound imaging, represents sound waves being reflected back to the ultrasound probe. The brightness of the pixel will depend on the returning echo strength. Therefore a whiter image will reflect a stronger echo intensity and a darker image represents a weaker echo intensity (Whittaker & Stokes, 2011) It has been suggested that increases in EI indicate damage of connective tissue and inflammation leading to oedema (T. C. Chen, et al., 2009). It has been shown that muscle oedema resulting from trauma markedly increases EI (Van Holsbeeck & Introcaso, 1992). Increases in EI of B-mode ultrasound images and cross-sectional area (CSA) have been used as measures of swelling in a muscle and as measures of eccentric muscle damage in studies of the elbow flexors, elbow extensors, knee flexors and knee extensors (T. C. Chen, et al., 2011; Nosaka & Clarkson, 1996; Nosaka & Newton, 2002a)

To date, there is limited research that has utilised ultrasound imaging and measures of EI to examine the influence of specific exercises designed to stress the hamstring muscles. In order to make more informed decisions about which exercises to choose to target certain aspects of the hamstring muscles, a better understanding of the influence of these exercises on morphological parameters such as muscle oedema and swelling is critical. Therefore through this study the reliability of EI of B-mode ultrasound images and measurement of CSA will be determined for seven areas in the hamstring muscles. This data will inform future studies as to the reliability of using ultrasound to determine which area has undergone greater damage following eccentric hamstring exercises.

Sonography is a skill and in an effort to increase reliability this new protocol has been established. The reliability of one sonographer will be assessed to establish if it improves with practise. Knowledge of the difficulty an experienced sonographer has in reliably scanning using this protocol will inform less skilled clinicians or researchers on the level of experience needed to achieve an acceptable level of reliability.

## Methods

### *Participants*

A double blinded quantitative repeated measures experimental design was used to collect data at the Manukau Institute of Technology High Performance Lab and the Sound Experience ultrasound clinic. Sixteen healthy female university students were recruited to the study. Participants were excluded if they had any pre-existing musculoskeletal injuries or medical conditions limiting their ability to exercise. The participants were instructed to not perform resistance, aerobic or flexibility training or climb up or down stairs one week before the study. This was to minimise activities that could induce muscle damage. All participants provided informed consent to participate in this study and ethical approval was granted by the Auckland University of Technology Ethics Committee.

***Measurement of muscle CSA and echo-intensity***

A single investigator, a specialist musculoskeletal sonographer with 21 years of experience, performed all of the ultrasound scans. The CSA and EI of SM, ST, BFSH and BFLH were measured by B-mode ultrasound imaging. Transverse images were obtained using an iU22 Philips ultrasound with a 9-4 curvilinear probe. Manually changing the gain and system pre-set levels will influence the EI of the ultrasound image (Pillen, et al., 2006). Therefore, to ensure consistency, the gain and system pre-set levels were kept constant during all measurements and for all participants to ensure all features influencing grey scale were standardised. The EI, depth and CSA measurements, which appear on the screen, were hidden during scanning so the sonographer was blinded during the process. Unique identifiers were used for each participant and were assigned by the sonographer to enable the lead researcher to be blinded to participant and group for offline analysis.

The ultrasound measurements were taken with the participant relaxed in prone (see figure 1). To allow a standardised set of scanning locations that were relative to each participant, the distance from gluteal crease to the popliteal crease was measured. This line was then divided into thirds and a mark was placed at the superior third intersection and the distal third intersection using a permanent marker.

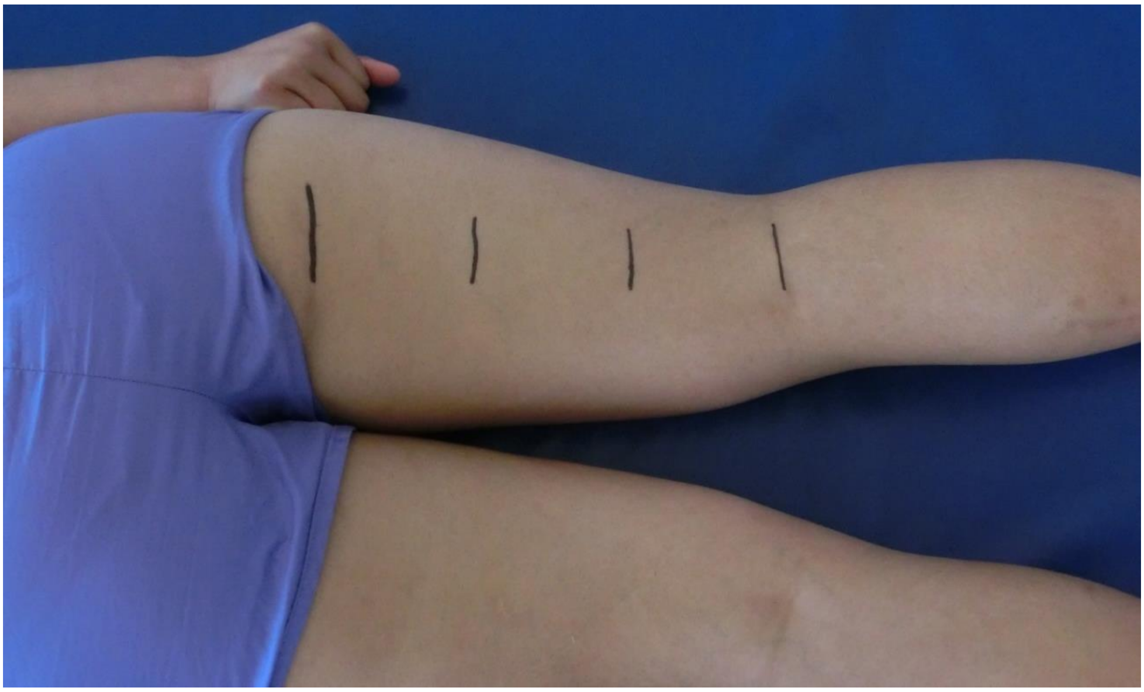


**Figure 1. Thigh markings**

Scanning began at the ischial tuberosity and followed the ST distally until the tendinous inscription of this muscle was visualised to confirm the location of ST. Ultrasound images were taken at ST 1/3 (ST1) and 2/3 (ST2) distal to the gluteal crease. SM was then visualised medial to ST. Ultrasound images were taken of SM 1/3 (SM1) and 2/3 (SM2) distal to the gluteal crease. BFLH was then visualised laterally from ST. Ultrasound images were taken of BFLH 1/3 (BFL1) and 2/3 (BFL2) distal to the gluteal crease. Finally the BFSH was visualised, with ultrasound images taken 2/3 distal to the gluteal crease (BFS). At each of the scanning locations (ST1, ST2, SM1, SM2, BFL1, BFL2, BFS) two ultrasound images were captured for each participant. The sonographer collected one ultrasound image for each location. The sonographer then started the sequence again to capture the second ultrasound image from each location.

Compression of the underlying tissue and changes in the angle the transducer interacts with the tissue will change the apparent size of the muscle (i.e. CSA) and the EI of the image. Therefore, to ensure pressure was minimised, the transducer was covered generously with transmission gel and held perpendicular to the longitudinal axis of the femur without compressing the skin surface and real time ultrasound images were observed.

To measure CSA, a digital calliper was used on-line on the two frozen transverse ultrasound images, as per methods previously reported (Fukumoto et al., 2012). Although the sonographer could visualise the digital calliper, they were blinded to the measurement made because that area of the monitor was covered. The mean of the two values for cross sectional area was used for analysis.

To enable off-line assessment of EI, a clear region-of-interest (ROI) was required to be established at each of the scanning locations. The sonographer provided the ROI at the time of capturing each ultrasound image and ensured that as much of the muscle as possible, without any bone or surrounding fascia, and was marked. Echo intensity was defined as the mean pixel intensity in the muscle (ROI) (Watanabe et al., 2013). Echo intensity was determined, off-line, by gray scale analysis using the standard histogram function in Adobe Photoshop (Adobe Systems Inc, San Jose, CA, USA, version 14.1.2 x32) (Pillen, et al., 2006; Watanabe, et al., 2013). The next day following the scanning, the lead researcher then traced the inside of the marked area to analyse it in Photoshop. The EI of the ROI was stated between 0 and 255 arbitrary units. Zero indicated a pure black image and 255 indicated a pure white image. The mean of the two values for EI was used for analysis. In a previous study EI test-retest reliability has been established for rectus femoris with an intraclass correlation coefficient of 0.96 and a mean coefficient of variance of 4.2% (Watanabe, et al., 2013). However the test-retest reliability is not known for this protocol on the hamstring muscles used in the current study.

### *Data collection*

The first group of eight participants (Group 1) underwent two testing sessions on the same day. Within-session reliability was assessed for EI and CSA following the first testing session. A second group of eight participants (Group 2) were recruited to assess if the sonographer's within-session reliability would improve. Group 2 underwent the same within-session reliability procedure as Group 1 but did not return for a second testing session.

To assess the between-session reliability the sonographer took two images as described above from the eight participants of Group 1. The participants then waited in the waiting room for one hour before being assessed in the same manner again. Between-session reliability was assessed, for Group 1, by comparing the average of the first session's EI and CSA data with the average of the second session's EI and CSA data.

### *Data analysis*

Using an excel spreadsheet by (Hopkins, 2015) for analysis of between-session reliability, intraclass correlation coefficients (ICC) and the coefficient of variation (CV) were calculated using the log transformed data. The magnitude of the ICC values were described as ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate, 0.20-0.50 = low, ≤0.20 = very low (Hinckson, Hopkins, Aminian, & Ross, 2013). This was used to evaluate both the within-session and between-session reliability.

## Results

### *Within-session reliability*

The mean (+-SD) age, height, and body mass of the participants were Group 1: 22.5 years (2), 166.3 cm (7.1) and 73.2 kg (8.1), Group 2: 23 years (6), 163.6 cm (5.8) and 72.0 kg (9.8).

Table 6 shows the within-session reliability of measuring EI and CSA. Within-session reliability of measuring ultrasound EI ranged from very high to extremely high (ICC = 0.94 to 0.99) for Group 1. The within-session reliability of measuring ultrasound EI ranged from high to very high for all measured areas for Group 2 (ICC = 0.84 to 0.98).

Measurement of muscle CSA showed moderate to extremely high reliability (ICC = 0.72 to 0.99) for Group 1. Group 2 showed high to extremely high reliability (ICC = 0.89 to 1.00) for all areas.

### *Between-session reliability*

Table 7 shows the between-session reliability of the EI and CSA for Group 1. Between-session reliability of EI was high or very high (ICC = 0.91 to 0.93) for BFL1, BFL2 and SM2. Moderate reliability (ICC = 0.67 to 0.74) was found for SM1, ST1 and ST2 and low reliability was found for BFS (ICC = 0.45).

Measurement of CSA generally had higher between-session reliability than echo-intensity for the majority of measures.

***Table 6: Within session reliability of echo intensity and cross sectional area***

| | | Group 1 | | | Group 2 | | |
|---|---|---|---|---|---|---|---|
| | **Location** | **CV (90% CL)** | **ICC (90% CL)** | **RELIABILITY*** | **CV (90% CL)** | **ICC (90% CL)** | **RELIABILITY*** |
| **ECHO INTENSITY** | **BFL1** | 4.2 (3.0 -7.7) | 0.99 (0.95-1.00) | Extremely High | 6.2 (4.3-11.4) | 0.84 (0.51-0.96) | High |
| | **BFL2** | 4.5 (3.1-8.2) | 0.99 (0.95-1.00) | Extremely High | 4.6 (3.2-8.4) | 0.98 (0.92-0.99) | Very High |
| | **BFS** | 5.2 (3.7-9.6) | 0.97 (0.90-0.99) | Very High | 2.6 (1.8-4.7) | 0.88 (0.62-0.97) | High |
| | **SM1** | 8.1 (5.7-15.0) | 0.97 (0.89-0.99) | Very High | 6.2 (4.3-11.4) | 0.94 (0.80-0.98) | Very High |
| | **SM2** | 6.3 (4.4-11.7) | 0.96 (0.87-0.99) | Very High | 4.6 (3.2-8.4) | 0.96 (0.86-0.99) | Very High |
| | **ST1** | 4.3 (3.0-7.8) | 0.97 (0.89-0.99) | Very High | 7.8 (5.4-14.4) | 0.85 (0.52-0.96) | High |
| | **ST2** | 15.2 (10.5-28.9) | 0.94 (0.79-0.98) | Very High | 6.3 (4.4-11.7) | 0.94 (0.79-0.98) | Very High |
| **CROSS SECTIONAL AREA** | **BFL1** | 4.2 (2.9-7.7) | 0.94 (0.80-0.98) | High | 3.2 (2.2-5.8) | 0.98 (0.92-0.99) | Very High |
| | **BFL2** | 5.4 (3.8-10.0) | 0.99 (0.97-1.00) | Extremely High | 7.3 (5.1-13.5) | 0.98 (0.94-1.00) | Very High |
| | **BFS** | 7.8 (5.4-14.5) | 0.92 (0.73-0.98) | High | 5.9 (4.1-10.8) | 0.89 (0.64-0.97) | High |
| | **SM1** | 5.5 (3.9-10.2) | 0.99 (0.96-1.00) | High | 4.3 (3.0-7.8) | 0.99 (0.95-1.00) | Extremely High |
| | **SM2** | 8.4 (5.9-15.6) | 0.72 (0.23-0.92) | Moderate | 5.3 (3.7-9.7) | 0.95 (0.82-0.99) | Very High |
| | **ST1** | 7.1 (4.9-13.0) | 0.94 (0.78-0.98) | Very High | 5.3 (3.7-9.7) | 0.96 (0.87-0.99) | Very High |
| | **ST2** | 6.5 (4.6-12.0) | 0.96 (0.86-0.99) | Very High | 4.4 (3.1-8.0) | 1.00 (0.99-1.00) | Extremely High |

*CV =coefficient of variation, ICC = intraclass correlation coefficient, BFL=biceps femoris long head, BFS=biceps femoris short head, SM=semimembranosus, ST= semitendinosus, 1=one third distal to gluteal crease, 2=two thirds distal to gluteal crease, *Terms for ICC magnitudes: ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate, 0.20-0.50 = low, ≤0.20 = very low.*

***Table 7: Between-session reliability of the echo intensity and cross sectional area***

| | Location | CV (90% CL) | ICC (90% CL) | RELIABILITY* |
|---|---|---|---|---|
| | **BFL1** | 10.3 (7.1-19.2) | 0.90 (0.68-0.97) | High/Very High |
| | **BFL2** | 9.6 (6.7-17.8) | 0.91 (0.70-0.98) | Very High |
| | **BFS** | 18.3 (12.6-35.4) | 0.45 (-0.18-0.82) | Low |
| **ECHO INTENSITY** | **SM1** | 18.8 (13.0-36.4) | 0.68 (0.16-0.90) | Moderate |
| | **SM2** | 8.6 (6.0-16.1) | 0.93 (0.77-0.98) | Very High |
| | **ST1** | 10.4 (7.3-19.5) | 0.74 (0.28-0.92) | Moderate |
| | **ST2** | 24.9 (17.0-49.1) | 0.67 (0.14-0.90) | Moderate |
| | **BFL1** | 13.5 (9.3-25.5) | 0.56 (-0.03-0.86) | Moderate |
| | **BFL2** | 29.8 (20.2-59.8) | 0.67 (0.14-0.90) | Moderate |
| | **BFS** | 10.1 (7.0-18.9) | 0.81 (0.43-0.95) | High |
| **CROSS SECTIONAL AREA** | **SM1** | 20.5 (14.0-39.8) | 0.77 (0.34-0.93) | High |
| | **SM2** | 6.3 (4.4-11.7) | 0.76 (0.33-0.93) | High |
| | **ST1** | 10.9 (7.6-20.4) | 0.80 (0.40-0.94) | High |
| | **ST2** | 8.3 (5.8-15.5) | 0.94 (0.78-0.98) | Very High |

*CV =coefficient of variation, ICC = intraclass correlation coefficient, BFL=biceps femoris long head, BFS=biceps femoris short head, SM=semimembranosus, ST= semitendinosus, 1=one third distal to gluteal crease, 2=two thirds distal to gluteal crease, *Terms for ICC magnitudes: ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate, 0.20-0.50 = low, ≤0.20 = very low.*

## Discussion

The purpose of this study was to establish the within session and between session reliability of CSA and EI measurement of 7 sites in the hamstring muscles. Within-session reliability of measuring ultrasound EI and CSA ranged from high to extremely high reliability for testing of the second group. Between-session reliability of EI was moderate or better for all measured areas except BFS. Measurement of CSA between-session reliability had high or very high reliability reported for all sites other than BFL1 and BFL2 which had moderate reliability.

Reports of the reliability of ultrasound measures of EI and CSA of the hamstring muscles are scarce. Furthermore there is a lack of reports comparing MRI measures of the hamstring muscles with ultrasound measures to assess validity of ultrasound EI and CSA as measures of muscle damage. However, good agreement between ultrasound and MRI measures of muscle size have been reported for biceps brachii and rectus femoris (Bemben, 2002), the rotator cuff (Juul-Kristensen, et al., 2000), iliopsoas and sartorius (Mendis, et al., 2010), and trapezius (O'Sullivan, et al., 2009) and the validity of ultrasound imaging for measuring muscle morphology is commonly reported in the literature as adequate (Whittaker & Stokes, 2011).

### *Reliability of measuring muscle CSA*

Reliability is the degree that a measurement is consistent and free from error (Hopkins, 2000). Therefore, this should be established before the measurement can be utilised for research or clinical decision making. The reliability for assessing the CSA of the elbow flexors of untrained participants was reported as high (ICC 0.94; coefficient of variation of 4.2%) (Radaelli, Bottaro, Wilhelm, Wagner, & Pinto, 2012) and extremely high (ICC 0.99) (Jenkins et al., 2015). Extremely high between-session reliability of measurement of CSA has also been shown of the intrinsic hand muscles (ICC 0.99-1.0) (Mohseny et al., 2015) and extremely high within-session reliability of multifidus has been demonstrated both on the painful (0.99) and the not painful side (0.99) of participants with unilateral low back pain (Huang et al., 2014). The within-session reliability for measuring CSA for all the hamstring sites, in the current study, ranged from high to extremely high. The between-session reliability for measuring CSA in this study were also considered high to very high for BFS, ST1, ST2, SM1 and SM2. These are generally less than the within-session reliability reported for the other muscles above but are comparable. The between-session reliability for measuring CSA of BFL1 and BFL2 were considered moderate and were considerably less than what was reported from the other muscle groups. Due to less reliability being reported for the BFL1 and BFL2 a greater effect size would have to be seen following an intervention for that effect to be clear.

### *Reliability of measuring muscle echo intensity*

The between session reliability of measuring the EI of the elbow flexors has been reported to be very high in untrained women (ICC 0.91; CV of 2.2%) (Radaelli, et al., 2012) and in untrained men (ICC 0.92; CV of 5.2%) (H.-L. Chen, Nosaka, & Chen, 2012). Another study reported intra-observer correlation coefficient of 0.92 for EI of the flexor muscles of the forearm (Li et al., 2014). Rectus femoris within-session test retest ICC of 184 elderly men was 0.96 with a CV of 4.2% (Watanabe, et al., 2013). Similar reliability for the measurement of muscle EI has been reported for vastus lateralis (ICC 0.92, CV 2.4%) (Gonzalez-Izal, Cadore, & Izquierdo, 2014). For the current study very high between-session reliability for the measurement of EI was found for BFL1, BFL2, and SM2. The other sites had moderate reliability except BFS which was low.

Many of the studies which have reported measurement of muscle EI have reported on older cohorts than this group. Musculoskeletal ultrasound images often appear brighter in an older person due to increased intramuscular fibrous and adipose tissue (Li, et al., 2014; Watanabe, et al., 2013). Therefore, there may have been increased difficulty in imaging a younger cohort. However, the within-session reliability was considerably better than the between-session reliability with all hamstring sites in the high to extremely high range for reliability and all CV's below 10% in the second group. The sonographer used the same marks, which were drawn on the participant with permanent marker, to orientate how far distal each scan should be taken. Therefore, the discrepancy between the acceptable within-session reliability and the questionable between-session reliability of some measures may come from the interpretation of the borders of the muscle. Although the sonographer would lift the head of the ultrasound off the participant after the first image before reorientating and taking the second image, he would still have some memory, and therefore recall bias, of what he had defined as the borders of each muscle.

As ultrasound waves travel through tissue, sound waves will be absorbed, reflected and scattered therefore the deeper the tissue the greater the difficulty in interpreting the image (Whittaker & Stokes, 2011). The majority of the research on the reliability of ultrasound to measure EI and CSA has used very superficial muscles such as the biceps brachii or intrinsic hand muscles (Bemben, 2002; Mohseny, et al., 2015). Many of the areas of the hamstrings that were scanned were comparatively deeper than these muscles. This may explain why the ICC and CV were not as good for the hamstrings as previously reported for other more superficial muscle groups. The region with the worst between-session ICC for EI was BFS (0.45). It was also one of the deepest areas to scan because it lies beneath the BFLH.

Another factor that may have contributed to the lower within and between session reliability of the hamstring muscles may have been the lack of highly distinguishable borders between these muscles. This leaves greater discretion for the sonographer to interpret the borders and therefore may have compromised the reliability of measurement. The regions that were chosen to scan for this study were chosen because of their potential clinical relevance and for ease of reproducibility for further research. Therefore, it is possible that different regions, within the hamstrings, may have more delineated borders that could offer greater reliability.

The orientation of the ultrasound head on the skin surface will drastically change the image seen as can the pressure exerted on the tissue by the operator (Whittaker & Stokes, 2011). On observation some images appear more compressed which would affect results therefore further discussion regarding how to better standardise the angle and pressure of the head is warranted. This is an issue that may have compromised the reliability in this study despite the sonographer making all reasonable efforts to minimise pressure from the transducer. Future research should investigate ways of standardising this. The use of a cradle and inclinometer could be assessed for feasibility.

**Limitations**

For this pilot trial, only 16 participants were available due to logistical constraints, which must be taken into consideration as a limitation of this work. This resulted in more uncertainty (as indicated by the confidence intervals) in some of the estimates of reliability than is ideal. Another limitation of this study is that all the participants in this study were female tertiary students and menstrual cycle and use of oral contraceptives were not recorded. Therefore any effects these factors may have on indicators of muscle damage may have confounded the results. Furthermore, this study utilised a single experienced sonographer, therefore these results can't be extrapolated for inter-tester reliability or to a novice sonographer, clinician or researcher. Participants were all recreationally active healthy females. Therefore reliability cannot be determined for a different population (i.e. males) or a different age group.

Between-session reliability was assessed in the first group and not the second group. Further research should assess if between session reliability would improve with greater experience using this protocol. In this study the within-session reliability for group 1 was high or better for all measures except CSA of SM2. When the second group were scanned all measures were reported to have high reliability or better. Between-day reliability was not assessed however participant activities would have to be controlled because they would affect the result.

A strength of this protocol was that it assessed seven locations in the hamstring muscle group. Previous studies utilising ultrasound measures have been limited by only assessing 1 or 2 locations. This increases the risk of missing an area of damage.

**Suggestions for future research**

Future research involving greater numbers of participants and greater numbers of trials is required to establish greater precision for estimates of reliability of this protocol. The reliability of this protocol should also be investigated for participants of different genders, ages and fitness levels. Also a different location for the scanning of BFS should be investigated because the between-session reliability of CSA was low. If this protocol is to be used for research without utilising an experienced musculoskeletal sonographer then the reliability will need to be established for these researchers.

**Implications**

Based on the ICC's the implications of this study are that if a threshold of high reliability ($ICC \geq 0.75$) is acceptable then using this testing protocol EI and CSA are reliable within-session measures for all areas. Whereas, between-session measurement reliability would be acceptable for some measures but not others.

It should be noted that ICC is a relative measure of reliability and therefore the reliability reported is specific to this cohort. We have also reported the coefficient of variation, an absolute measure of reliability, which may need to be considered when applying these measures in other settings. The CV is also useful for researchers and practitioners who are wanting to interpret absolute changes in any of the measures reported.

**Conclusion**

In the hands of an experienced clinician with an appropriate length of time to familiarise them self with the testing protocol, this protocol has merit as a reliable within-session measure of hamstring CSA and EI at 7 different locations. However, for a number of sites the between-session reliability of EI and CSA did not reach the level of high reliability ($ICC \geq 0.75$). Therefore, further investigation is needed to ensure adequate reliability when determining EI and CSA for these areas. This gives some confidence for researchers to use this protocol when identifying areas of hamstring muscle damage following eccentric hamstring exercise at certain locations.

# CHAPTER 4

## THE ACUTE EFFECTS OF TWO ECCENTRIC HAMSTRINGS EXERCISES ON INDICATORS OF HAMSTRING MUSCLE DAMAGE


**Overview**

*Background.* Hamstring strain injuries are among the most common non-contact injuries in athletics and team sport. There is some evidence to suggest eccentric training, in particular the Nordic hamstring exercise (NH), can reduce the risk of hamstring strain injuries although the incidence of these injuries remains high. The NH is a bilateral exercise which eccentrically controls knee extension. In contrast, the drop lunge (DL) is a unilateral exercise which eccentrically controls hip flexion. The DL may have advantages regarding specificity to hamstring injury mechanics and injury location. This study compared the acute effects of the NH and the DL, an alternative eccentric hamstring exercise. *Methods.* Sixteen women were randomly assigned into either a NH group ($n$=8) or a DL group ($n$=8). Each group performed 8 sets of 8 repetitions of their assigned exercise. Ultrasound echo intensity (EI) and cross sectional area (CSA) were assessed before exercise and 3 days post exercise. Other markers of eccentric muscle damage (peak torque (PT), angle of peak torque (APT), limb circumference) were taken before exercise, immediately after exercise and every day for the following 3 days. *Results.* There were clear changes in APT (to longer muscle lengths) for the hamstrings following the DL (ES = -0.28 -to -0.53), but not NH, however the difference between exercises wasn't clear. Following the DL there was a small shift in the quadriceps APT towards shorter muscle lengths (ES = -0.22 to -0.37). Knee flexion PT showed clear decreases immediately following the DL (ES = -0.36) and at all time points following the NH (ES = -0.43 to -0.83). Knee extension PT also showed clear decreases following both exercises (DL ES = -0.50 to -0.32, NH ES -0.29 to -0.48). The changes in hip extension PT and APT were mostly trivial or unclear following both exercises. There was a small change in the lower girth measurement following the DL (ES = 0.30 to 0.43) but no clear differences between exercises. Both exercises showed an increase in hamstrings soreness (DL ES = 1.7 to 3.0, NH ES = 1.8 to 2.0) and quadriceps soreness (DL ES = 1.4 to 2.5, NH ES = 0.8 to 1.4) but the DL showed a greater magnitude of change for both the hamstrings (ES = -0.7 to-1.0) and quadriceps (ES = -1.0 to-1.8). There were some small to moderate changes in echo intensity and CSA for both exercises and the locations were similar. *Conclusion.* The DL and the NH both induced changes indicative of muscle damage and there were few clear differences in the changes produced by each exercise. Therefore the DL should be investigated as an addition to the NH for hamstring strain injury prevention and rehabilitation.


**Introduction**

One of the most common injuries in team sports is the hamstring strain (HS) (Brooks, et al., 2006; Orchard & Seward, 2010). It is especially troublesome because it is associated with extended lengths of lost playing time (Engebretsen, et al., 2010) and has a high rate of recurrence (Petersen, et al., 2010). Individual studies utilising eccentric hamstring training have reported reductions in the incidence of HS (Arnason, et al., 2008; Petersen, et al., 2011; van der Horst, et al., 2015). However the overall rate of HS in sport has not decreased (Mendiguchia, et al., 2011). This may be because the exercises used to prevent the injury are not specific to the injury mechanism. Most HS injuries are thought to occur in the late swing phase of gait when the hamstrings contract eccentrically to decelerate hip flexion and knee extension (Coole & Gieck, 1987; Proske, et al., 2004). In contrast the majority of eccentric hamstring training studies have used the NH despite criticism that it is does not reproduce the biomechanics of the common mechanism of injury for a HS.

The NH involves bilateral eccentric knee extension with the hips held in neutral and places demands on muscles around the pelvis, hip and knee that differ significantly from those linked to the injury mechanism (Schache, et al., 2012; Thelen, et al., 2006). For example the NH requires the gluteals to work isometrically whereas during sprinting the gluteals are involved in eccentrically decelerating the thigh. Previous authors have suggested a unilateral closed chain exercise that involves greater combined hip flexion and/or knee extension could confer superior training stimulus by better reproducing the mechanism that endangers the hamstrings (e.g. the single leg deadlift or the drop lunge) (Brughelli & Cronin, 2008; Greenstein, Bishop, Edward, & Topp, 2011). The DL involves eccentrically controlling hip flexion placing greater demands on the gluteals which act as synergists to the hamstrings. As a unilateral exercise it also has the potential to address limb strength asymmetry. However, it is not known if the DL provides sufficient eccentric stimulus when compared to the NH.

Another factor which calls into question which exercise would be best suited for HS prevention is which location of the hamstrings is most commonly injured compared to which location of the hamstrings is stimulated during exercise. The Biceps Femoris long head (BFLH) has been reported as being the most commonly strained muscle of the hamstrings group (Silder, et al., 2008). Additionally long term MRI follow up of participants post hamstring injury have shown hypertrophy of BFSH and atrophy of BFLH (Silder, et al., 2008). The NH does not appear to address these imbalances. The NH exercise has been shown acutely on MRI to stress the proximal Biceps Femoris short head (BFSH) of the hamstrings (Mendiguchia, Arcos, et al., 2013). Whereas, the BFLH has been shown to have greater loading during exercises resisting hip flexion rather than knee extension (Mendiguchia, Garrues, et al., 2013). Therefore, an eccentric exercise that preferentially resists hip flexion (stressing the BFLH) such as the DL may have superior injury prevention potential.

Several markers of muscle damage have been reported to assess the acute effects of eccentric exercise. Increases in muscle thickness, cross sectional area (CSA) and echo-intensity of B-mode ultrasound images are thought to be indicators of damage and swelling in a muscle post eccentric exercise (T. C. Chen, et al., 2011; Nosaka & Clarkson, 1996; Nosaka & Newton, 2002a). It is also widely accepted that following eccentric exercise there is a significant decrease in peak torque and an associated shift in the optimal angle of peak torque

(APT) towards longer muscle lengths (Black & McCully, 2008; T. C. Chen, et al., 2011; Crameri, et al., 2007). Peak torque produced at shorter muscle length has been suggested to predispose athletes to HSI (Brockett, Morgan, & Proske, 2004; Brooks, et al., 2006; Proske, et al., 2004). Finally, muscle soreness and limb circumference have been used as indirect markers of muscle damage in numerous studies of eccentric muscle damage (Black & McCully, 2008; T. C. Chen, et al., 2011). This study will investigate the acute effects of the eccentric DL compared to the NH on indicators of muscle damage. The results of this research may help inform exercise prescription for eccentric training of the hamstring muscles.

**Methods:**

*Purpose*

The purpose of this study was to compare the acute effects of the DL and NH exercise on indicators of muscle damage.

*Participants*

Sixteen female tertiary students were recruited to the study. The participants were randomly allocated to a group by a coin toss. The mean (±SD) age, height, and body mass of the participants were, NH group; 23 years (±6), 163.6 cm (5.8) and 72.0 kg (9.8), DL group; 22 years (2), 166.4 cm (4.7) and 72.6 kg (8.4). Participants were excluded if they had any pre-existing musculoskeletal injuries or medical conditions limiting their ability to exercise. Participants were randomly assigned to either the DL or NH exercise group. The participants were instructed to not perform resistance, aerobic or flexibility training and to avoid climbing up or down stairs one week before and for the duration of the study and they were reminded to refrain from unaccustomed exercise or vigorous physical activity, to maintain their normal dietary habits, and not take any anti-inflammatory drugs or nutritional supplements during the study period. The participants were instructed to drink water after their eccentric exercise session, to avoid alcohol, and to not have any treatments to the affected muscles (eg. massage) during the study. The number of participants was similar to previous studies that reported significant acute effects of eccentric exercise (Brockett, et al., 2001; Nosaka & Sakamoto, 2001). All participants provided informed consent to participate in this study and ethical approval was granted from the Auckland University of Technology Ethics Committee (AUTEC) for all components of the research proposed (13/124).

*Experimental design and eccentric exercise*

This was a two group test re-test design. There was no cross over because of the repeated bout effect. The lead researcher was blinded to the exercise and exercise allocation. After a standardised warm up of 5 minutes of easy cycling at a self-selected pace, the participants performed eight sets of eight repetitions of the DL or NH exercise with a 30 second rest in between sets. The DL was performed off a 30cm high box. The participant stepped off the box and landed with their dominant leg in front. They were instructed to drop straight down and bend at the hips and knees and to land softly, maintaining alignment of knees over toes. They then stabilised in a lunge position at approximately 90 degrees knee flexion and will immediately stepped back up with their non-dominant leg and repeated the motion (Figure 2).

**Figure 2. The drop lunge.**

The NH exercise followed well established protocols (Mjolsnes, et al., 2004) and was also completed with a separate researcher to blind the lead researcher to group allocation. The participant started in a kneeling position, with the torso from the knees upward held rigid and straight. The research assistant held the participant's lower legs stable on the ground while the participant resisted a forward falling movement. The participant was instructed to slow the fall as much as they could and to use their hands to stop their fall just before their chest touched the ground.  The participant then immediately used their arms to assist in returning to the starting position (Figure 3). One week prior to testing, each participant had a familiarisation session including the warm up and testing procedures however, as it has been shown that even a few eccentric contractions can cause a protective response there was no familiarisation session for the eccentric exercises (Nosaka, et al., 2001).

**Figure 3*.* The Nordic hamstrings exercise**

*Data collection*

In both groups the following measures were taken immediately before exercise, immediately afterwards, and at 1, 2 and 3 days following exercise except the ultrasound measures which were taken the day before exercise and at day 3 post exercise.

1. Isokinetic peak torque and angle of peak torque during concentric knee flexion, knee extension, and hip extension peak torque at 60 degrees per second (Humac Norm isokinetic dynamometer, Lumex, Ronkonkoma, NY, USA)

2. Limb circumference was measured 1/3 and 2/3 of the distance between the gluteal crease and the popliteal crease (see figure 4)

3. Muscle soreness using the visual analogue scale

4. Echo intensity of B-mode ultrasound images and cross sectional area

A specialist musculoskeletal sonographer with 21 years of experience, performed all of the ultrasound scans. The CSA and EI of semimembranosus (SM), semitendinosus (ST), biceps femoris short head (BFSH) and biceps femoris long head (BFLH) were measured by B-mode ultrasound imaging. Transverse images were obtained using an iU22 Philips ultrasound with a 9-4 curvilinear probe. Manually changing the gain and system pre-set levels will influence the EI of the ultrasound image (Pillen, et al., 2006). Therefore, to ensure consistency, the gain and system pre-set levels were kept constant during all measurements and for all participants to ensure all features influencing grey scale were standardised. The EI, depth and CSA measurements, which appear on the screen, were hidden during scanning so the sonographer was blinded during the process. Unique identifiers were used for each participant and were assigned by the sonographer to enable the lead researcher to be blinded to participant and group during later analysis.

The ultrasound measurements were taken with the participant relaxed in prone. To allow a standardised set of scanning locations that was relative to each participant, the distance between gluteal crease and popliteal crease was measured. This line was then divided into thirds and a mark was placed at the superior third intersection and the distal third intersection using a permanent marker (Figure 4).

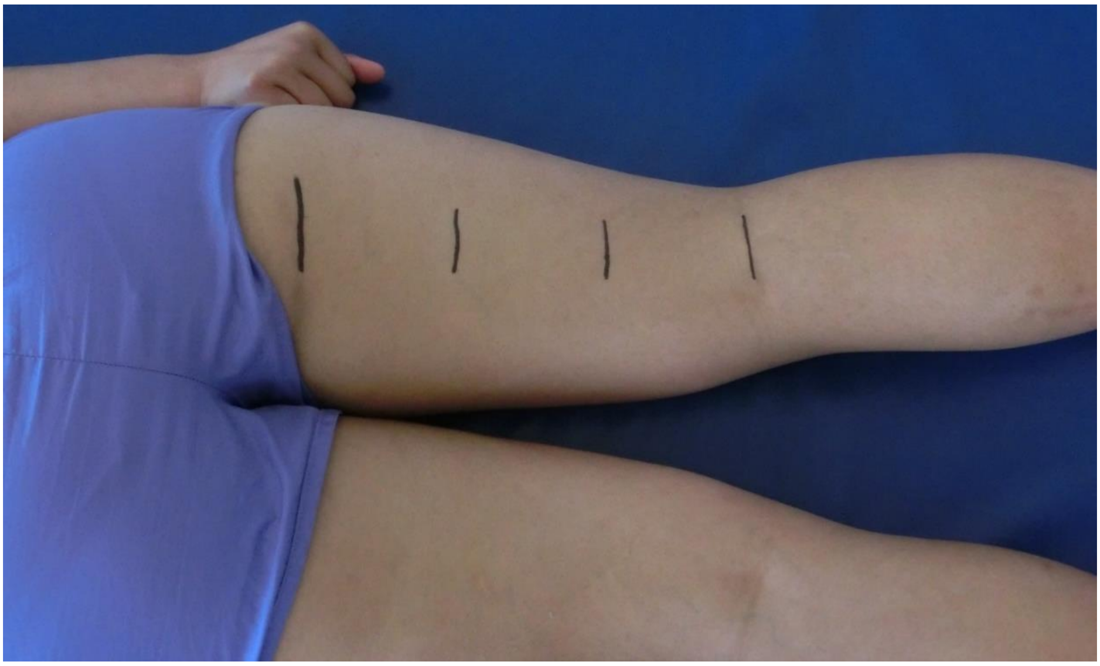


**Figure 4. Thigh markings for circumference and ultrasound measures.**

Scanning began at the ischial tuberosity and followed the ST distally until the tendinous inscription of this muscle was visualised to confirm the location of ST. Ultrasound images were taken at ST 1/3 (ST1) and 2/3 (ST2) distal to the gluteal crease. SM was then visualised medial to ST. Ultrasound images were taken of SM 1/3 (SM1) and 2/3 (SM2) distal to the gluteal crease. BFLH was then visualised laterally from ST. Ultrasound images were taken of BFLH 1/3 (BFL1) and 2/3 (BFL2) distal to the gluteal crease. Finally the BFSH was visualised, with ultrasound images taken 2/3 distal to the gluteal crease (BFS). At each of the scanning locations (ST1, ST2, SM1, SM2, BFL1, BFL2, BFS) two ultrasound images were captured for each participant. The sonographer collected one ultrasound image for each location. The sonographer then started the sequence again to capture the second ultrasound image from each location.

Compression of the underlying tissue and changes in the angle the transducer interacts with the tissue will change the apparent size of the muscle (i.e. CSA) and the EI of the image. Therefore, to ensure pressure was minimised, the transducer was covered generously with transmission gel and held perpendicular to the longitudinal axis of the femur without compressing the skin surface and real time ultrasound images were observed.

To measure CSA (Figure 5), a digital calliper was used on-line on the two frozen transverse ultrasound images, as per methods previously reported (Fukumoto, et al., 2012). Although the sonographer could visualise the digital calliper, they were blinded to the measurement made because that area of the monitor was covered. The mean of the two values for cross sectional area was used for analysis.

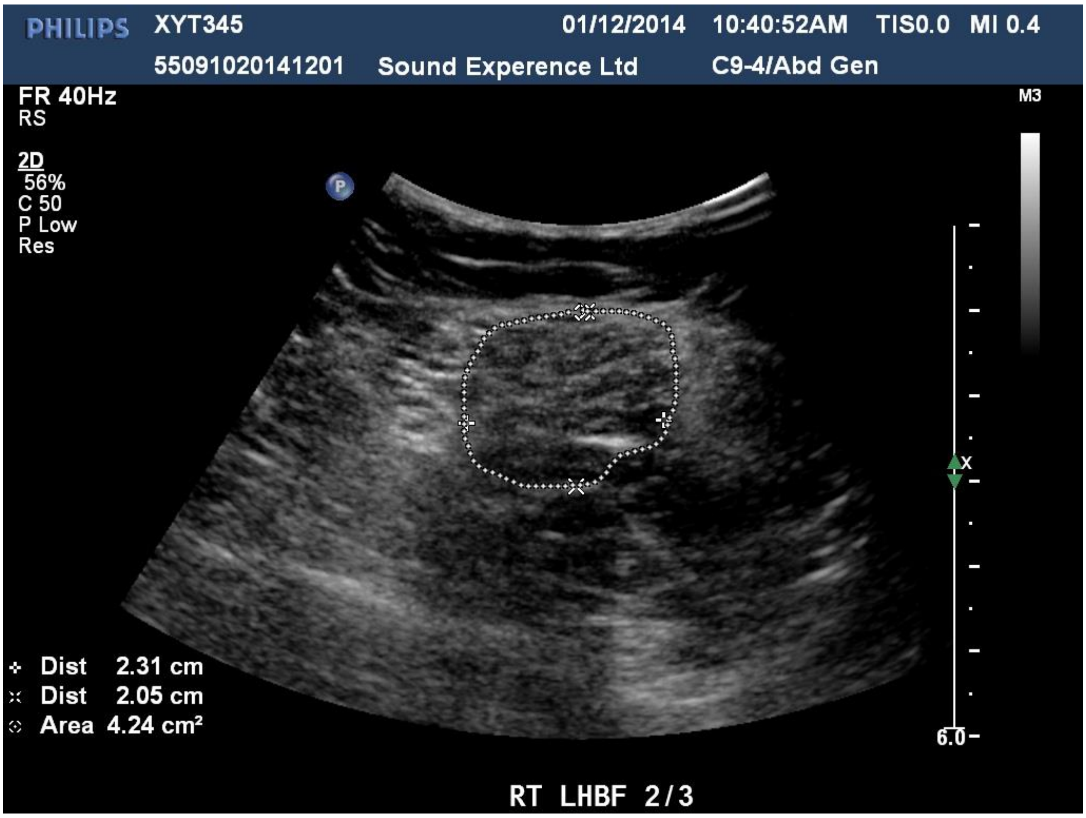



**Figure 5. Example of an ultrasound scan showing markings for cross sectional area and echo intensity measurement.**

To enable off-line assessment of EI, a clear region-of-interest (ROI) was required to be established at each of the scanning locations. The sonographer provided the ROI at the time of capturing each ultrasound image and ensured that as much of the muscle as possible, without any bone or surrounding fascia, and was marked. Echo intensity was defined as the mean pixel intensity in the muscle (ROI) (Watanabe, et al., 2013). EI was determined, off-line, by gray scale analysis using the standard histogram function in Adobe Photoshop (Adobe Systems Inc, San Jose, CA, USA, version 14.1.2 x32) (Pillen, et al., 2006; Watanabe, et al., 2013). The next day following the scanning, the lead researcher then traced the inside of the marked area to analyse it in Photoshop. The EI of the ROI was expressed as measuring between 0 and 255 units. Zero indicated a pure black image and 255 indicated a pure white image. The mean of the two values for EI was used for analysis. The between-session reliability for the protocol in the current study ranged from moderate to very high for CSA (ICC = 0.56-0.94) and moderate to very high (ICC = 0.67-0.93) for all areas for EI except BFS which was low (ICC = 0.45).

*Data analysis*

Means and standard deviations were used as measures of centrality and the spread of data. Mean changes in the dependent variables (peak torque, APT, limb circumference, muscle soreness, echo intensity of B-mode ultrasound images and cross sectional area) post eccentric exercise were calculated. Differences in these changes between the DL and NH exercises were also calculated. An Excel spreadsheet (Hopkins, 2006) was used to derive magnitude based inferences as to the true effect of each exercise on all dependent variables. A further spreadsheet for comparing the means of two groups was used to derive magnitude based inferences (Hopkins, 2007b), as to the true difference between the effect of the DL and the NH. A standardised Cohen effect size (ES) of 0.20 was used as the threshold for substantial change (Hopkins, Batterham, Marshall, & Hanin, 2009). Where the effect had a >5% probability of being substantially positive and a >5% probability of being substantially negative the inference was stated as 'unclear' (Batterham & Hopkins, 2006). Otherwise the outcome was clear and the inference was based on the likelihood the true value of the ES was greater than 0.20 using the following scale: 25-75%, possibly; >75%, likely; >95%, very likely; >99.5%, most likely (Hopkins, 2007a; Hopkins, et al., 2009). Magnitudes of observed ES's were interpreted based on the following scale: 0.2-0.59 (small), 0.6-1.19 (moderate), 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse (Hopkins, et al., 2009).

## Results

### *Changes in peak torque and angle of peak torque*

The mean and standard deviation for baseline peak torque and angle of peak torque are shown in table 8. Following the DL there was a small decrease in knee flexion PT immediately post exercise (ES=0.36) and a shift in the APT to longer muscle lengths at all time points (ES=0.28 to 0.53) (Table 9). There was also a small reduction in knee extension PT immediately post (ES=0.50) and up to day 2 (ES=0.35). All changes in hip extension PT and APT were trivial or unclear. Following the NH there was a moderate decrease in knee flexion PT immediately (ES=0.83) and at day 1 post exercise (ES=0.82) and a small decrease at day 2 (ES=0.43) and 3 (ES=0.59). Additionally a small decrease in knee extension PT was observed immediately (ES=0.48) and at day 1 post exercise (ES=0.29). Changes in hip extension PT were trivial or unclear. The only change in APT following the NH was a small decrease in hip extension APT immediately (ES=0.38) however there were no clear changes at any other time points or during knee flexion or knee extension.

***Table 8: Baseline torque measures for each group***

| Variable | Drop lunge<br>Mean; (SD) | Nordic hamstrings<br>Mean; (SD) |
|---|---|---|
| Knee flexion peak torque (Nm) | 103.70 (15.26) | 105.3 (17.71) |
| Knee extension peak torque (Nm) | 152.74 (30.37) | 140.37 (24.03) |
| Hip extension peak torque (Nm) | 230.31 (51.70) | 218.00 (49.09) |
| Knee flexion angle of peak torque (°) | 28.52 (4.82) | 28.30 (3.84) |
| Knee extension angle of peak torque (°) | 68.46 (9.60) | 67.20 (6.36) |
| Hip extension angle of peak torque (°) | 76.72 (10.19) | 78.96 (9.18) |

***Table 9: Changes (standardised Cohen effects) in peak torque and angle of peak torque and magnitude based inferences for the changes following the drop lunge and Nordic hamstrings exercise***

| | Immediate post | | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| **Drop Lunge (n=8)** | | | | | | | | |
| KF PT | -0.36 (-0.81-0.09) | Small ↓* | -0.18 (-0.75-0.39) | Unclear | -0.44 (-0.75-0.39) | Unclear | -0.28 (-0.90-0.33) | Unclear |
| KF APT | -0.28 (-0.60-0.03) | Small ↓* | -0.44 (-0.89-0.01) | Small ↓** | -0.41 (-0.77--0.05) | Small ↓** | -0.53 (-0.94--0.12) | Small ↓** |
| KE PT | -0.50 (-0.86--0.15) | Small ↓** | -0.32 (-0.61--0.02) | Small ↓** | -0.35 (-0.84-0.15) | Small ↓* | -0.08 (-0.41-0.24) | Unclear |
| KE APT | -0.22 (-0.37--0.08) | Small ↓* | -0.37 (-0.90-0.16) | Small ↓* | -0.28 (-0.64-0.08) | Unclear | -0.22 (-0.62-0.18) | Unclear |
| HE PT | -0.21 (-0.65-0.23) | Unclear | -0.19 (-0.44-0.07) | Unclear | -0.37 (-1-08-0.35) | Unclear | -0.36 (-0.91-0.19) | Unclear |
| HE APT | 0.10 (-0.17-0.38) | Trivial ↑* | -0.10 (-0.41-0.21) | Unclear | -0.28 (-0.89-0.32) | Unclear | -0.21 (-0.67-0.26) | Unclear |
| **Nordic Hamstrings (n=8)** | | | | | | | | |
| KF PT | -0.83 (-1.31--0.35) | Moderate ↓*** | -0.82 (-1.38--0.26) | Moderate ↓*** | -0.43 (-0.91-0.05) | Small ↓** | -0.59 (-1.19-0.00) | Small ↓** |
| KF APT | -0.04 (-0.54-0.45) | Unclear | 0.08 (-0.94-1.10) | Unclear | -0.43 (-1.11-0.26) | Unclear | -0.52 (-1.14-0.09) | Unclear |
| KE PT | -0.48 (-0.93--0.03) | Small ↓** | -0.29 (-0.62-0.05) | Small ↓* | 0.04 (-0.29-0.37) | Unclear | 0.04 (-0.29-0.37) | Unclear |
| KE APT | 0.26 (-0.56-1.07) | Unclear | -0.05 (-0.48-0.39) | Unclear | 0.08 (-0.46-0.63) | Unclear | 0.24 (-0.30-0.78) | Unclear |
| HE PT | -0.15 (-0.45-0.15) | Trivial ↓* | -0.11 (-0.39-0.16) | Unclear | -0.19 (-0.34--0.04) | Unclear | -0.28 (-0.65-0.08) | Unclear |
| HE APT | -0.38 (-0.81-0.05) | Small ↓** | 0.18 (-0.18-0.54) | Trivial ↑* | 0.15 (-0.13-0.43) | Unclear | 0.03 (-0.29-0.34) | Unclear |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely. KF=knee flexion; KE=knee extension; HE=hip extension; PT = peak torque; APT = angle of peak torque.

***Table 10: Mean difference (standardised Cohen units) between the change in peak torque and angle of peak torque and magnitude-based inferences for the difference in the changes following the drop lunge and the Nordic hamstrings exercise***

| | Immediate post | | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| KF PT | -0.53 (-1.15-0.09) | Small** ↓ | -0.69 (-1.44-0.06) | Moderate** ↓ | -0.01 (-0.77-0.75) | Unclear | -0.35 (-1.15-0.46) | Unclear |
| KF APT | 0.30 (-0.28-0.88) | Unclear | 0.60 (-0.49-1.69) | Unclear | 0.06 (-0.70-0.81) | Unclear | 0.10 (-0.51-0.83) | Unclear |
| KE PT | 0.11 (-0.42-0.63) | Unclear | 0.06 (-0.35-0.47) | Unclear | 0.35 (-0.22-0.92) | Unclear | 0.03 (-0.40-0.46) | Unclear |
| KE APT | 0.47 (-0.20-1.13) | Small** ↑ | 0.32 (-0.35-1.00) | Unclear | 0.36 (-0.20-0.91) | Unclear | 0.42 (-0.17-1.00) | Unclear |
| HE PT | 0.06 (-0.48-0.60) | Unclear | 0.05 (-0.32-0.42) | Unclear | 0.13 (-0.68-0.94) | Unclear | 0.05 (-0.63-0.72) | Unclear |
| HE APT | -0.47 (-1.01-0.07) | Small**↓ | 0.39 (-0.11-0.90) | Small**↑ | 0.60 (-0.17-1.37) | Moderate**↑ | 0.33 (-0.31-0.96) | Unclear |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely. KF=knee flexion; KE=knee extension; HE=hip extension; PT = peak torque; APT = angle of peak torque.

The reductions in knee flexion peak torque were greater following the NH immediately (ES=0.53) and at day 1 post exercise (ES=0.69) but there was no clear difference in knee flexion APT changes (Table 10). There were also no clear differences in changes in knee extension PT or hip extension PT. There was a small difference in the changes in knee extension APT immediately (ES=0.47) and a small difference in change in hip extension APT immediately (ES=0.47) and at day 1 (ES=0.39) with a moderate difference at day 2 (ES=0.60). However, neither of these measures showed clear changes when the within group data was analysed.

***Changes in girth and pain scores***

There were no clear changes in thigh girth 1 following either exercise and no clear changes in girth 2 following the NH (Table 11). However, there was a small increase in girth 2 at all time points after the DL (ES=0.27 to 0.43).  There were large to very large increases in hamstrings VAS scores at all time points following the DL (ES=1.7 to 3.0). The NH also produced large to very large increases in hamstrings VAS scores up to day 2 (ES=1.8 to 2.0), however by day 3 the effect was trivial. A moderate to very large increase in quadriceps VAS score that persisted at all time points was observed following the DL (ES=1.4 to 2.5). Whereas, a moderate to large increase in VAS score was shown on day 1 (ES=1.4) and day 2 (ES=0.8) post the NH but there were only trivial differences immediately post exercise and by day 3 post exercise.

There was a trivial difference in the effect of the two exercises on the girth measures at all time points (Table 12). The DL participants showed a moderately greater increase in hamstrings VAS on day 1 (ES=0.7) and day 3 post exercise (ES=1.0) however there was no clear difference observed at the other time points. There were moderate to large differences in quadriceps VAS scores between the exercises at all time points (ES=1.0 to 1.8) with the DL group reporting greater soreness.

***Changes in echo intensity and cross sectional area***

Three days following the DL, moderate increases in EI were observed at BFL1 (ES=0.76) and ST1 (ES=0.92), and small increases were seen at SM1 (ES=0.52) and SM2 (ES=0.52) (Table 13). There were no clear changes in echo intensity at BFL2, BFS and ST2. In contrast, there were small increases 3 days post exercise following the NH at BFL1 (ES=0.41), SM1 (ES=0.38), SM2 (ES=0.50), ST1 (ES=0.56), and ST2 (ES=0.58). No clear changes were seen in echo intensity at BFL2 and BFS.

A small increase in cross sectional area was observed 3 days post DL at BFL2 (ES=0.20) and ST2 (ES=0.40) and a moderate increase at BFS (ES=0.85). All changes at BFL1, SM1, SM2, and ST1 were trivial or unclear. Following the NH there was a small decrease in cross sectional area at BFS (ES=0.29), SM1 (ES=0.21), and SM2 (ES=0.42) and a small increase in cross sectional area at BFL2 (ES=0.20) and ST2 (ES=0.40). Changes at BFL1 and ST1 were all trivial or unclear.

***Table 11: Changes in girth and pain and magnitude based inferences for the changes following the drop lunge and Nordic hamstrings exercise***

| | Immediate post | | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| **Drop Lunge (n=8)** | | | | | | | | |
| Girth 1 (cm) | 0.13 (0.07-0.20) | Trivial*** | 0.16 (0.12-0.21) | Unclear | 0.18 (0.12-0.23) | Unclear | 0.18 (0.13-0.24) | Unclear |
| Girth 2 (cm) | 0.30 (0.23-0.36) | Small ↑*** | 0.27 (0.19-0.35) | Small ↑** | 0.30 (0.18-0.41) | Small ↑** | 0.43 (0.32-0.54 | Small ↑**** |
| H VAS | 1.7 (0.9-2.6) | Large ↑** | 3.0 (2.3-3.7) | Very large ↑**** | 2.8 (2.0-3.7) | Very large ↑**** | 1.9 (0.7-3.1) | Large ↑** |
| Q VAS | 1.6 (1.0-2.2) | Moderate ↑** | 2.4 (1.0-3.8) | Very large ↑*** | 2.5 (1.3-3.6) | Very large ↑*** | 1.4 (0.3-2.5) | Large ↑* |
| **Nordic Hamstrings (n=8)** | | | | | | | | |
| Girth 1 (cm) | 0.13 (0.07-0.20) | Trivial*** | 0.16 (0.12-0.21) | Unclear | 0.18 (0.12-0.23) | Unclear | 0.18 (0.13-0.24) | Unclear |
| Girth 2 (cm) | 0.15 (0.09-0.21) | Trivial** | 0.16 (0.09-0.24) | Unclear | 0.24 (0.18-0.29) | Unclear | 0.25 (0.14-0.36) | Unclear |
| H VAS | 2.0 (0.6-3.4) | Very large ↑** | 1.8 (0.9-2.6) | Large ↑** | 2.0 (0.8-3.3) | Very large ↑** | 0.7 (0.2-1.2) | Trivial** |
| Q VAS | 0.7 (0.0-1.3) | Trivial** | 1.4 (0.3-2.4) | Large↑* | 0.8 (0.1-1.6) | Moderate ↑* | 0.3 (0.0-0.6) | Trivial**** |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely. H=hamstrings; Q=quadriceps; VAS=visual analogue scale.

***Table 12: Mean difference between the change in girth and VAS and magnitude based inferences for the difference in the changes following the drop lunge and the Nordic hamstrings exercise***

| | Immediate post | | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| Girth 1 (cm) | 0.03 (-0.05-0.11) | Trivial*** | 0.07 (0.01-0.16) | Trivial*** | 0.09 (-0.01-0.19) | Trivial*** | 0.03 (-0.06-0.13) | Trivial*** |
| Girth 2 (cm) | -0.06 (-0.15-0.04) | Trivial*** | -0.01 (-0.13-0.10) | Trivial*** | 0.06 (-0.06-0.17) | Trivial*** | -0.04 (-0.20-0.12) | Trivial** |
| H VAS | 0.6 (-1.1-2.2) | Unclear | -0.7 (-1.8-0.4) | Moderate ↓* | -0.1 (-1.7-1.5) | Unclear | -1.0 (-2.2-0.3) | Moderate ↓* |
| Q VAS | -1.0 (-1.9--0.2 | Moderate ↓* | -1.2 (-2.8-0.4) | Large ↓* | -1.8 (-3.0--0.5) | Large ↓** | -1.2 (-2.4-0.0) | Large ↓* |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely. H=hamstrings; Q=quadriceps; VAS=visual analogue scale.

*Table 13: Changes (standardised Cohen units) in echo intensity and cross sectional area between pre exercise and day 3 post exercise and magnitude-based inferences for the changes following the drop lunge and Nordic hamstrings exercise*

| Hamstring location | Drop Lunge (n=8) | | Nordic Hamstrings (n=8) | |
|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| **Echo intensity** | | | | |
| BFL1 | 0.76 (0.30-1.23) | Moderate ↑*** | 0.41 (-0.10-0.92) | Small ↑** |
| BFL2 | 0.20 (-0.43-0.82) | Unclear | 0.19 (-0.20-0.59) | Unclear |
| BFS | 0.17 (-0.42-0.76) | Unclear | 0.28 (-0.29-0.86) | Unclear |
| SM1 | 0.52 (0.10-0.94) | Small ↑** | 0.38 (-0.07-0.82) | Small ↑** |
| SM2 | 0.45 (-0.13-1.02) | Small ↑** | 0.50 (0.11-0.90) | Small ↑** |
| ST1 | 0.92 (0.46-1.37) | Moderate ↑*** | 0.56 (-0.06-1.17) | Small ↑** |
| ST2 | -0.57 (-1.56-0.42) | Unclear | 0.58 (0.05-1.11) | Small ↑** |
| **Cross sectional area** | | | | |
| BFL1 | 0.12 (-0.15-0.40) | Trivial ↑* | -0.09 (-0.30-0.12) | Trivial*** |
| BFL2 | 0.44 (0.28-0.60) | Small ↑*** | 0.20 (-0.07-0.47) | Small ↑* |
| BFS | 0.85 (0.02-1.67) | Moderate ↑** | -0.29 (-0.53--0.05) | Small ↓** |
| SM1 | -0.38 (-1.00-0.25) | Unclear | -0.21 (-0.59-0.16) | Small ↓* |
| SM2 | -0.08 (-0.27-0.12) | Trivial ↓** | -0.42 (-0.91-0.08) | Small ↓** |
| ST1 | 0.03 (-0.10-0.16) | Trivial*** | 0.25 (-0.21-0.71) | Unclear |
| ST2 | 0.25 (0.06-0.44) | Small ↑* | 0.40 (-0.05-0.85) | Small ↑** |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely.

A moderate difference in mean change in echo intensity was observed at ST2 (ES=0.96) indicating greater damage following the NH (Table 14). There were trivial or no clear differences between the changes in mean echo intensity at the other measured sites. A small difference in mean change in cross sectional area was observed at BFL1 (ES=0.20), BFL2 (ES=0.37) and BFS (ES=0.47) indicating greater change following the DL. There were no clear differences between the changes in mean cross sectional area at the other measured sites.

*Table 14: Mean difference (standardised Cohen units) between the change in echo intensity and cross sectional area and magnitude-based inferences for the difference in the changes following the drop lunge and the Nordic hamstrings exercise*

| | Echo intensity | | Cross sectional area | |
|---|---|---|---|---|
| | Mean; ±90%CL | Inference[a] | Mean; ±90%CL | Inference[a] |
| BFL1 | -0.16 (-0.63-0.96) | Unclear | -0.20 (-0.55-0.14) | Small* ↓ |
| BFL2 | 0.29 (-0.18-0.77) | Trivial* ↑ | -0.37 (-0.69--0.05) | Small** ↓ |
| BFS | 0.11 (-0.77-0.99) | Unclear | -0.47 (-1.06-0.11) | Small** ↓ |
| SM1 | -0.21 (-0.50-0.93) | Unclear | 0.07 (-0.66-0.80) | Unclear |
| SM2 | 0.36 (-0.34-1.07) | Unclear | -0.22 (-0.64-0.21) | Unclear |
| ST1 | -0.06 (-0.78-0.89) | Unclear | 0.12 (-0.26-0.50) | Unclear |
| ST2 | 0.96 (0.11-1.80) | Moderate*** ↑ | -0.07 (-0.44-0.31) | Unclear |

[a]Magnitude thresholds: <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; 1.2-1.99 (large), 2.0-3.99 (very large), ≥4.0 (extremely large) and their inverse. Asterisks indicate effects clear at the 90% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely.

## Discussion

To our knowledge this is the first study to compare the acute effects of two lower body eccentric exercises and to attempt to describe the location of the eccentric damage that occurred.

***Peak torque and angle of peak torque***

Findings from this study provide some evidence of hamstring muscle damage following both the DL and NH exercises as shown by small to moderate immediate decreases in knee flexion peak torque of 6% and 14.6% respectively. The NH caused a greater decrease in hamstring PT immediately and at day 1. This may have been because the hamstrings act as the agonist to eccentrically control knee extension during the NH whereas during the DL the hamstrings and gluteals worked eccentrically to control hip flexion and the quadriceps worked eccentrically to control knee flexion. Therefore, the total load is dispersed over a greater number of muscle fibers during the DL.

Small decreases in knee extension PT were also seen immediately following the DL (10.5%) and up to day 2 (7.3%). This was expected because the quadriceps was contracting eccentrically to decelerate knee flexion. Previous studies using a stepping down exercise have found greater decreases in quadriceps peak torque (25-29%) (Alemany, et al., 2014; Bowers, et al., 2004). However, these studies used a greater volume of eccentric exercise (200-240 repetitions). (Alemany, et al., 2014). It has been shown that as you increase the number of eccentric contractions the extent of muscle damage increases (Brown, et al., 1997; Howatson, et al., 2007). The exercise prescription in the current study was chosen based on replicating a realistic training load. Also previous studies have used maximal isokinetic eccentric contractions (Hody, et al., 2013). Greater damage occured following contractions of greater intensity even when total work was equated (Nosaka & Newton, 2002a; Paschalis, Koutedakis, Jamurtas, et al., 2005; Peake, et al., 2006). Another factor that influences the degree of muscle damage is muscle length during eccentric contraction. As a muscle lengthens into the descending limb of its length tension curve, the degree of actin and myosin overlap decreases and therefore the ability of the muscle to generate active tension decreases. At the same time the tension on the parallel elastic components is increasing consequently passive tension is increasing. Therefore the length of the muscle during eccentric contractions influences the degree of muscle damage (Child, et al., 1998; Nosaka & Sakamoto, 2001). The hamstrings are in a lengthened position during knee extension and hip flexion. The NH finishes in full knee extension and hip extension therefore the hamstrings are not in a lengthened position. Whereas the DL finishes with the hip and knee flexed therefore neither exercise finishes in a lengthened position. This may have contributed to smaller reductions in peak torque compared to previous studies.

Surprisingly, the participants who completed the NH also showed decreased knee extension PT immediately (8.8%) and 1 day post exercise (5.4%).This was unexpected because there was no eccentric loading of the quadriceps during the NH. The decrease in PT may have been due to excessive co-contraction during an unfamiliar exercise. The decrease in knee extension PT didn’t last as long as following the DL potentially because it wasn’t from eccentric induced delayed onset of muscle damage. However, there were no clear differences between exercises in the changes in mean knee extension PT at any time points. Although the DL may offer less training stimulus to the hamstrings it could potentially confer an injury prevention training stimulus to the quadriceps if it reached a sufficient threshold. To increase the loading on the hamstrings the intensity of the DL may need to be increased by elevating the height of the drop or adding weight.

This is the first study to our knowledge to report changes in hip extension peak torque post eccentric exercise. There were no clear changes in hip extension PT following either exercise. This suggests neither exercise caused significant damage to the gluteal musculature because there was insufficient volume, the exercise wasn't performed at a long enough muscle length, and/or the intensity of loading was insufficient.

In the current study there was a lengthening of the APT for knee flexion at all time points following the DL but no clear changes were observed following the NH. The NH is performed at relatively short muscle lengths for the hamstrings. Greater shifts are observed when eccentrics are performed at longer muscle lengths (ie: beyond optimal length) (Child, et al., 1998). Potentially, the DL may have cause greater lengthening of the hamstrings as the participants tired especially as their form deteriorated and their trunk fell forward causing greater hip flexion. However, there were no clear differences in the change in APT between the exercises. In a previous study, a 7.7 degree shift was observed immediately in the optimal angle of torque generation for the hamstrings following 12 sets of 6 repetitions of the NH (Brockett, et al., 2001). Potentially the lower volume of repetitions that were used in our study could explain the lack of change in the NH group and also our participants were all female whereas the Brockett et al, (2001) study was on a predominately male cohort.

There were no clear changes in APT for knee extension or hip extension that indicated muscle damage following either exercise. There was a small difference in the changes in knee extension APT immediately (ES=0.47) and a small difference in change in hip extension APT immediately (ES=0.47) and at day 1 (ES=0.39) with a moderate difference at day 2 (ES=0.60). However, neither of these measures showed clear changes when the within group data was analysed. Therefore the difference between the changes between the groups may have little practical relevance. This contrasts with a 15.6 degree lengthening of knee extension APT observed following a step down exercise (Bowers, et al., 2004). Eccentric contractions performed at muscle lengths on the descending limb cause overstretching of some sarcomeres (Morgan, 1990). A consequence of overstretched popped sarcomeres is that force must be transmitted through the elastic non contractile component of these sarcomeres. This increases the series compliance of the myofibril and therefore the optimal angle of force production will be shifted to longer muscle lengths (Morgan & Allen, 1999). Potential reasons why this was not observed in the quadriceps or hip extensors in this study may be because these muscles were not eccentrically loaded far enough into the descending limb of their length-tension relationship, the intensity of loading or number of repetitions wasn't sufficient.

Decreases in peak torque and lengthening of the APT commonly occur together as markers of muscle damage (Philippou, et al., 2009). Interestingly, the knee flexion peak torque decreases that were shown at all time points following the NH did not correspond to a clear change in APT. This was the opposite following the DL where a small lengthening of APT was observed at all time points but only a small decrease in peak torque occurred immediately. Therefore, peak torque and APT could be thought of as separate markers of damage and thus both should be considered in future studies. Risk factors for hamstring strain injury include hamstring weakness and low hamstrings:quadriceps ratio (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008). Athletes with good hamstrings:quadriceps ratios may benefit from either exercise to maintain this ratio and offer eccentric training to both the quadriceps and hamstrings. However, athletes with limb strength asymmetry may benefit from a unilateral dominant exercise such as the DL as opposed to the bilateral NH.

***Girth***

There was an increase in girth 2 following the DL but no clear changes in girth at any time point following the NH. The observed increase in girth 2 following the DL but not the NH may be attributed to both the hamstrings and quadriceps having to eccentrically decelerate knee flexion and hip flexion whereas the NH only requires the hamstrings to decelerate knee extension. The lack of change at girth 1 following both exercises may be attributed to gravitational drainage of fluid rather than a localisation of the eccentric damage. Previous studies have demonstrated greater increases in girth at the distal site (Howell, et al., 1993).

Muscle damage following exercise induces an inflammatory response and local swelling which peaks between 3-6 days (Bowers, et al., 2004; Brockett, et al., 2001). The only area where we did observe small increases in girth suggestive of swelling was following the DL at girth 2 (0.43cm increase). The increases were similar to the 0.6 ±0.06cm mean changes reported by Bowers et al. (2004) following 12 sets of 20 eccentric step downs even though our volume of exercises was less.

***Soreness***

Following the DL peak mean quadriceps soreness was 2.5. This compared to 1.4 following the NH in this study. Whereas peak hamstring soreness reached 3.0 following the DL and 2.0 following the NH. When comparing between groups there was a moderately greater difference in change in hamstring soreness following the DL on day 1 and day 3 and a moderately greater difference in the change in quadriceps soreness on day 1 and a large difference in the change in soreness on day 1,2 and 3 following the DL. This suggests greater damage occurred in both the hamstrings and the quadriceps following the DL compared to the NH. After eccentric exercise there tends to be a progressive increase in muscle soreness that peaks 24-48 hours post exercise (Sbriccoli, et al., 2001). Previous studies using an eccentric stepping exercise or isokinetics have reported peak mean quadriceps soreness on a VAS scale of between 5.2-8.6 (Akdeniz, Karli, Dasdemir, Yarar, & Yilmaz, 2012; Bowers, et al., 2004; Hortobágyi, et al., 1998; Magal, et al., 2010). These higher quadriceps VAS scores have been reported following much greater volumes of eccentric exercise. Hamstring VAS scores were not reported. Previous studies using the NH have reported peak mean hamstring soreness at 5.55 following 12 sets of 6 repetitions (Brockett, et al., 2001). Less soreness in our study may be explained by the differences between the Brockett et al (2001) study that have been discussed previously.

***Echo intensity and cross sectional area***

A previous study on eccentric hamstring exercise measured hamstring echo intensity changes at a single site (T. C. Chen, et al., 2011). The potential advantage of measuring ultrasound changes (EI and CSA) at numerus sites is the ability to tailor prevention and rehabilitation exercises to common injury sites. The NH which is commonly used in hamstring injury prevention programs, has been shown by MRI to stress the proximal Biceps Femoris short head (BFSH) of the hamstrings (Mendiguchia, Arcos, et al., 2013). This was not observed in our participants with unclear findings in BFS echo intensity for both the DL and NH and no increase in BFS cross sectional area following the NH. The DL group did show a moderate increase in cross sectional area at BFS. This is counterintuitive because the BFS is a uniarticular muscle which only crosses the knee. During the DL the knee is eccentrically flexing and therefore should not require a strong contraction of BFS.

Atrophy of the BFLH has been found on MRI at long term follow up of participants post hamstring injury, whereas hypertrophy of the BFSH was observed (Silder, et al., 2008). Both exercises showed potential to address this atrophy of BFLH with a moderate increase in echo intensity at BFL1 following the DL and a small increase following the NH. The moderate increase in echo intensity observed at the proximal aspect of BFL1 following the DL agrees with a previous MRI study that reported the lunge exercise loads the proximal regions of the BFLH (Mendiguchia, Garrues, et al., 2013). However, when the differences in the change in mean echo intensity were compared, there were no clear differences between the exercises except at ST2 which showed a moderately greater change following the NH. The differences in the mean change in cross sectional area between exercises were either unclear or small.

Rehabilitation programmes need to be better targeted to focus on individual muscles if possible to avoid strength imbalances continuing post injury which could predispose the athlete to further hamstring strains. Therefore, a better understanding of which area of the hamstrings is stressed by different exercises will help inform clinicians, coaches and trainers when prescribing rehabilitation and training programmes. The results from the ultrasound measures show little difference between the exercises. Also some hamstring areas showed markers of damage being evident in one measure but not the other and this raises the question as to whether or not they are measuring the same thing.

**Limitations**

There are number of limitations in the current study that need to be considered. There were small baseline differences in absolute peak torque between groups which may have influenced the propensity for muscle damage. However, measures of baseline angle of peak torque were well matched and this was probably the most important factor when considering the effect of eccentric exercise. A lack of clarity in some results may be due to the small sample size and the error of measurement in a number of the ultrasound measures. Future studies could use MRI to assess changes in muscle size and/or the ultrasound technique could be improved and a greater number of participants could be used to increase the power of the study. Another limitation of this study is that the participants were all healthy female recreationally trained tertiary students, menstrual cycle and use of oral contraceptives were not recorded. Therefore any effects these factors may have on indicators of muscle damage may have confounded the results. Also the height of the box used for the drop jump was standardised which potentially may have affected the load and therefore the damage each participant sustained. Further studies could investigate the effects on a male population, a highly trained population and different age groups using a drop height relative to the participants' height.

**Conclusion**

Changes in markers of muscle damage were observed following both exercises and there were few clear differences in the magnitude of these changes between the exercises. This suggests the DL provides a similar eccentric stimulus to the NH and should be considered as an alternate unilateral eccentric hamstring exercise for hamstring strain injury prevention and rehabilitation. The DL may be especially beneficial for addressing limb asymmetries. Future studies are needed to investigate if the DL can reduce the risk of HS injury and to investigate other forms of eccentric hamstring training that may place greater stress on the biceps femoris long head.

# CHAPTER 5

## DISCUSSION AND CONCLUSIONS

The prevention and treatment of hamstring strain injury (HSI) is important because HSI is the most common non-contact injury in sports involving stretch shorten cycle activities. HSIs have high risk of re-injury and can result in prolonged time away from training and competing. Training studies involving the Nordic hamstrings exercise (NH) have shown eccentric exercise can decrease the incidence of HSI. However, the NH has limitations such as it is a bilateral exercise and it doesn't mimic the biomechanics or neuromuscular constraints associated with the mechanism of HSI. Additionally, the most commonly strained location in the hamstrings group (biceps femoris long head) is not the area that is stressed and that undergoes hypertrophy following NH training (biceps femoris short head). Therefore, there is some debate over whether a different form of eccentric training that is unilateral and involves greater hip flexion may confer greater protection from HSI. This thesis sought to compare the acute effects of the NH with the drop lunge DL, an additional eccentric hamstring exercise.

Before attempting to compare the acute effects of the NH and DL, a literature review on the acute effects of eccentric exercise was conducted. It was established that eccentric exercise causes significant decreases in torque and shifts the angle of peak torque to longer muscle lengths. Limb circumference also increases and there is an associated increase in ultrasound echo intensity and muscle size (cross sectional area and muscle thickness). The factors that influence these changes were also reviewed and it was found that greater intensity of loading is more important than total work done and as the number of repetitions increase over 30, greater damage is done by high velocity eccentric exercise. Additionally greater damage is done when exercise is performed at longer muscle lengths and power athletes have greater protection from eccentric muscle damage than endurance athletes. Limitations of the current research included a lack of studies focusing on the hamstrings and therefore a lack of detail as to the specific location of eccentric damage and a lack of reliability data on the measurement of ultrasound echo intensity and cross sectional area of the hamstrings.

To compare the acute effects of the NH and DL and to localise which area in the hamstrings each exercise would stress, an ultrasound protocol was created. Chapter 3 sought to establish the within session and between session reliability of this protocol. Based on our criteria (ICC $\geq 0.75$) both EI and CSA were found to have high within-session reliability for all areas. However, between-session measurement reliability was high for some but not all measures. Therefore, this protocol has merit as a reliable within-session measure of hamstring CSA and EI at 7 different locations when use by an experienced clinician with an appropriate length of time to become familiar with the testing protocol. However, to ensure adequate between session reliability when determining EI and CSA for some areas, more investigation is required. This gives some confidence for researchers to use this protocol when identifying areas of hamstring muscle damage following eccentric hamstring exercise at certain locations.

The aim of the intervention study was to compare the acute effects of the DL and NH on markers of eccentric muscle damage. A greater decrease in hamstring PT was seen following the NH. This may be because the load is distributed more evenly between muscle groups during the DL. Potentially this could confer an injury prevention training stimulus for the quadriceps if it reached a sufficient threshold. However there were no clear differences between the changes in knee extension PT so therefore greater intensity may be needed for the DL. This could be achieved by increasing the height of the drop, adding weight or increasing the sets or repetitions. Although there were changes in hamstring PT following both exercises, hamstring APT shifted to longer muscle lengths for the hamstrings following the DL, but not NH, however the difference between exercises wasn't clear. This may have been due to the muscle length at which each exercise is performed because greater changes in APT are seen following exercise at longer muscle lengths. The NH finishes in a mid-range position for the hamstrings. It is hard to quantify hamstring muscle length during the DL because the hamstrings are being lengthened over the hip and shortened over the thigh. However as our participants form deteriorated they tended to complete the DL in greater trunk and hip flexion which causes lengthening of the hamstrings. Although, PT and APT changes indicative of damage were seen following both exercises sometimes a change indicative of damage in one measure didn't correspond with a change in the other. A similar situation occurred where there were some small to moderate changes in echo intensity and CSA for both exercises and the locations were similar. However echo intensity changes indicative of damage didn't necessarily correspond with CSA changes indicative of damage. This could reflect that PT and APT, and EI and CSA are independent measures of muscle damage and should be considered separately or there was measurement error.

Magnetic resonance imaging of the hamstrings of elite male athletes acutely following NH showed a non-uniform response in signal intensity with greater signal intensity change in the biceps femoris short head. However, in this study of recreationally active females there were unclear findings in bicep femoris short head EI following both exercises and no increase in CSA following the NH but a moderate increase following the DL. This difference may be due to the different participant populations or measurement error. A small difference in change in CSA was observed at both the proximal and distal biceps femoris long head which showed greater change following the DL. As the most commonly strained hamstring muscle is the biceps femoris long head, a long term DL training program may offer greater injury prevention.

The only girth changes were observed at the distal measurement site following the DL. This may be due to the DL requiring eccentric control at both the hip and knee as opposed to the NH requiring eccentric control only at the knee. Gravitational drainage may explain the lack of change at the proximal site because muscle CSA was seen to increase at the proximal biceps femoris long head site. Finally, when comparing changes in muscle soreness, the DL moderate to large greater changes in quadriceps soreness and moderately greater changes in hamstring soreness suggesting greater damage.

**Thesis limitations**

The studies presented in this thesis were at times limited by methodological constraints, and it is important to be cognizant of the following limitations when interpreting the results. Due to logistical constraints participant numbers were generally lower than would be ideal, potentially compromising statistical power. Also, the participants in this study were all healthy, recreationally active female tertiary students and stage of menstrual cycle and oral contraceptive use was not recorded, therefore the findings may not be transferable to a general or athletic population. Additionally there were small baseline differences in absolute peak torque between groups. Another limitation is the error of measurement in a number of the ultrasound measures which may explain the lack of clarity in some results. There are also limitations to peak torque and angle of peak torque assessment via dynamometry, and limb circumference measurement. These limitations are mostly due to the technique and experience of the tester. The same assessor was used to perform these measures in an effort to minimise these limitations.

Another factor that may have limited the clarity of the results was the choice of exercise prescription. The volume of exercise was chosen to be reflective of a training load. However, greater volume of exercise may have caused greater damage which could have added more clarity to the results. Furthermore, the participants were unaccustomed to both exercises and as they began to fatigue their technique deteriorated, potentially altering the effectiveness of the exercise. Also, the height of the box used for the drop lunge was at a standard height rather than relative to the participants' height, which may have affected the amount of muscle damage the participants received. Familiarization and crossover were not possible due to the repeated bout effect of eccentric exercise. Therefore, an athletic population who were familiar with the DL and NH or a sedentary population may produce different results.

**Future directions**

This thesis reported reliability statistics for ultrasound echo intensity and cross sectional area measurement for seven areas the hamstrings. Future research with more trials and involving greater numbers of participants is required to establish higher precision for estimates of reliability of this protocol. The reliability of this protocol should also be investigated for participants of different genders, ages and fitness levels. Also a different location for the scanning of BFS should be investigated because the between-session reliability of CSA was low. Furthermore, if this protocol is to be used for research without utilising an experienced musculoskeletal sonographer then the reliability will need to be established for these researchers. Also future studies should compare the ultrasound results from this protocol with MRI. The ultrasound technique could be improved.

The main intervention study (chapter 4) found both exercises showed markers of eccentric muscle damage, however there were few clear differences between the magnitude of change. This indicates the DL could be considered as an alternative to the NH. However, future research with greater participant numbers, a higher volume of repetitions and utilising MRI may uncover greater differences. Moreover, the chronic effects of the DL should now be investigated to establish if the acute effects of the exercise correspond to the chronic effects of a training program and whether this does confer a protective effect on hamstring strain injury.

**Conclusion**

This thesis consists of a literature review of the acute effects of eccentric exercise, and a study evaluating the reliability of a new protocol for measuring the ultrasound echo intensity and cross sectional area of the hamstrings. It culminates in an intervention study comparing the acute effects of the NH and DL. The ultrasound measures showed acceptable within session reliability but some measures lacked high between session reliability. The NH and DL both showed markers of eccentric muscle damage with few clear differences between them. Therefore, the DL could be considered as an addition to the NH for hamstring strain injury rehabilitation and prevention. Further research needs to investigate the DL's influence on HSI through longitudinal studies following athletes throughout a competitive season.

# REFERENCES


Ahmadi, S., Sinclair, P. J., Foroughi, N., & Davis, G. M. (2008). Monitoring muscle oxygenation after eccentric exercise-induced muscle damage using near-infrared spectroscopy. *Applied Physiology, Nutrition, and Metabolism, 33*(4), 743-752.

Akdeniz, Ş., Karli, Ü., Dasdemir, T., Yarar, H., & Yilmaz, B. (2012). Impact of exercise induced muscle damage on sprint and agility performance. *Journal Physical Education and Sports Science, 6*(2), 152-160.

Alemany, J. A., Delgado-Díaz, D. C., Mathews, H., Davis, J. M., & Kostek, M. C. (2014). Comparison of acute responses to isotonic or isokinetic eccentric muscle action: Differential outcomes in skeletal muscle damage and implications for rehabilitation. *International Journal of Sports Medicine, 35*, 1-7.

Alonso, J. M., Junge, A., Renström, P., Engebretsen, L., Mountjoy, M., & Dvorak, J. (2009). Sports injuries surveillance during the 2007 IAAF World Athletics Championships. *Clinical Journal of Sport Medicine, 19*(1), 26-32.

Armstrong, R. B. (1986). Muscle damage and endurance events. *Sports Medicine, 3*, 370-381.

Arnason, A., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2008). Prevention of hamstring strains in elite soccer: an intervention study. *Scandinavian Journal of Medicine and Science in Sports, 18*(1), 40-48.

Bahr, R., Thorborg, K., & Ekstrand, J. (2015). Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. *British Journal of Sports Medicine*, bjsports-2015-094826.

Barroso, R., Roschel, H., Ugrinowitsch, C., Araujo, R., Nosaka, K., & Tricoli, V. (2010). Effect of eccentric contraction velocity on muscle damage in repeated bouts of elbow flexor exercise. *Applied Physiology, Nutrition, and Metabolism, 35*(4), 534-540.

Batterham, A. M., & Hopkins, W. G. (2006). Making meaningful inferences about magnitudes. *International Journal of Sports Physiology and Performance, 1*, 50-57.

Bemben, M. G. (2002). Use of diagnostic ultrasound for assessing muscle size. *The Journal of Strength & Conditioning Research, 16*(1), 103-108.

Black, C. D., & McCully, K. K. (2008). Muscle injury after repeated bouts of voluntary and electrically stimulated exercise. *Medicine and Science in Sports and Exercise, 40*(9), 1605.

Bogdanis, G. C., Nevill, M. E., Boobis, L. H., & Lakomy, H. K. A. (1996). Contribution of phosphocreatine and aerobic metabolism to energy supply during repeated sprint exercise. *Journal of Applied Physiology, 80*(3), 876-884.

Bottas, R., Miettunen, K., Komi, P. V., & Linnamo, V. (2010). Disturbed motor control of rhythmic movement at 2 h and delayed after maximal eccentric actions. *Journal of Electromyography and Kinesiology, 20*(4), 608-618.

Bourne, M. N., Opar, D. A., Williams, M. D., & Shield, A. J. (2015). Eccentric knee flexor strength and risk of hamstring injuries in rugby union: A prospective study. *The American Journal of Sports Medicine*, 1-8.

Bowers, E. J., Morgan, D. L., & Proske, U. (2004). Damage to the human quadriceps muscle from eccentric exercise and the training effect. *Journal of Sports Sciences, 22*(11-12), 1005-1014.

Brockett, C. L., Morgan, D. L., & Proske, U. (2004). Predicting hamstring strain injury in elite athletes. *Medicine & Science in Sports & Exercise, 36*(3), 379.

Brockett, C. L., Morgan, D. L., & Proske, U. W. E. (2001). Human hamstring muscles adapt to eccentric exercise by changing optimum length. *Medicine & Science in Sports & Exercise, 33*(5), 783.

Brooks, J. H. M., Fuller, C. W., Kemp, S., & Reddin, D. B. (2006). Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *The American Journal of Sports Medicine, 34*(8), 1297.

Brown, S. J., Child, R. B., Day, S. H., & Donnelly, A. E. (1997). Exercise-induced skeletal muscle damage and adaptation following repeated bouts of eccentric muscle contractions. *Journal of Sports Sciences, 15*(2), 215-222.

Brughelli, M., & Cronin, J. (2008). Preventing hamstring injuries in sport. *Strength & Conditioning Journal, 30*(1), 55.

Byrne, C., & Eston, R. (2002). The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance. *Journal of Sports Sciences, 20*(5), 417-425.

Byrne, C., Eston, R., & Edwards, R. (2001). Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage. *Scandinavian Journal of Medicine & cience in Sports, 11*(3), 134-140.

Byrne, C., & Eston, R. G. (2002). Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions. *Journal of Sports Sciences, 20*(12), 951-959.

Cabello, E. N., Hernández, D. C., Márquez, G. T., González, C. G., Navandar, A., & González, S. V. (2015). A review of risk factors for hamstring injury in soccer: A biomechanical approach. *European Journal of Human Movement, 34*, 52-74.

Chapman, D., Newton, M., Mcguigan, M., & Nosaka, K. (2008). Effect of lengthening contraction velocity on muscle damage of the elbow flexors. *Medicine and Science in Sports and Exercise, 40*(5), 926.

Chapman, D., Newton, M., McGuigan, M., & Nosaka, K. (2011). Effect of slow-velocity lengthening contractions on muscle damage induced by fast-velocity lengthening contractions. *The Journal of Strength & Conditioning Research, 25*(1), 211-219.

Chapman, D., Newton, M., Sacco, P., & Nosaka, K. (2006). Greater muscle damage induced by fast versus slow velocity eccentric exercise. *International Journal of Sports Medicine, 27*(8), 591-598.

Chapman, D., Newton, M., Zainuddin, Z., Sacco, P., & Nosaka, K. (2008). Work and peak torque during eccentric exercise do not predict changes in markers of muscle damage. *British Journal of Sports Medicine, 42*(7), 585-591.

Chapman, D., Simpson, J., Iscoe, S., Robins, T., & Nosaka, K. (2013). Changes in serum fast and slow skeletal troponin I concentration following maximal eccentric contractions. *Journal of Science and Medicine in Sport, 16*, 82-85.

Chen, H.-L., Nosaka, K., & Chen, T. C. (2012). Muscle damage protection by low-intensity eccentric contractions remains for 2 weeks but not 3 weeks. *European Journal of Applied Physiology, 112*(2), 555-565.

Chen, T. C. (2003). Effects of a second bout of maximal eccentric exercise on muscle damage and electromyographic activity. *European Journal of Applied Physiology, 89*(2), 115-121.

Chen, T. C., Chen, H.-L., Lin, M.-J., Wu, C.-J., & Nosaka, K. (2009). Muscle damage responses of the elbow flexors to four maximal eccentric exercise bouts performed every 4 weeks. *European Journal of Applied Physiology, 106*(2), 267-275.

Chen, T. C., Lin, K., Chen, H., Lin, M., & Nosaka, K. (2011). Comparison in eccentric-induced muscle damage among four limb muscles. *European Journal of Applied Physiology, 111*, 211-223. doi: 10.1007/s00421-010-1648-7

Chen, T. C., & Nosaka, K. (2006). Effects of number of eccentric muscle actions on first and second bouts of eccentric exercise of the elbow flexors. *Journal of Science and Medicine in Sport, 9*(1), 57-66.

Chen, T. C., Nosaka, K., & Sacco, P. (2007). Intensity of eccentric exercise, shift of optimum angle, and the magnitude of repeated-bout effect. *Journal of Applied Physiology, 102*(3), 992-999.

Child, R. B., Saxton, J. M., & Donnelly, A. E. (1998). Comparison of eccentric knee extensor muscle actions at two muscle lengths on indices of damage and angle specific force production in humans. *Journal of Sports Sciences, 16*(4), 301-308.

Chleboun, G. S., France, A. R., Crill, M. T., Braddock, H. K., & Howell, J. N. (2001). In vivo measurement of fascicle length and pennation angle of the human biceps femoris muscle. *Cells Tissues Organs, 169*(4), 401-409.

Clark, R., Bryant, A., Culgan, J. P., & Hartley, B. (2005). The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Physical Therapy in Sport, 6*(2), 67-73.

Cleak, M. J., & Eston, R. G. (1992). Muscle soreness, swelling, stiffness and strength loss after intense eccentric exercise. *British Journal of Sports Medicine, 26*(4), 267-272.

Coole, W. G., & Gieck, J. H. (1987). An analysis of hamstring strains and their rehabilitation. *Journal of Orthopaedic and Sports Physical Therapy, 9*(2), 77-85.

Crameri, R., Aagaard, P., Qvortrup, K., Langberg, H., Olesen, J., & Kjær, M. (2007). Myofibre damage in human skeletal muscle: effects of electrical stimulation versus voluntary contraction. *The Journal of Physiology, 583*(1), 365-380.

Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., & Ferret, J. M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players. *The American Journal of Sports Medicine, 36*(8), 1469.

Dannecker, E. A., Liu, Y., Rector, R. S., Thomas, T. R., Fillingim, R. B., & Robinson, M. E. (2012). Sex Differences in Exercise-Induced Muscle Pain and Muscle Damage. *The Journal of Pain, 13*(12), 1242-1249.

Ekstrand, J., Hägglund, M., & Waldén, M. (2011). Injury incidence and injury patterns in professional football: the UEFA injury study. *British Journal of Sports Medicine, 45*(7), 553-558.

Engebretsen, A. H., Myklebust, G., Holme, I., Engebretsen, L., & Bahr, R. (2008). Prevention of injuries among male soccer players. *The American Journal of Sports Medicine, 36*(6), 1052.

Engebretsen, A. H., Myklebust, G., Holme, I., Engebretsen, L., & Bahr, R. (2010). Intrinsic Risk Factors for Hamstring Injuries Among Male Soccer Players. *The American Journal of Sports Medicine, 38*(6), 1147.

Feeley, B. T., Kennelly, S., Barnes, R. P., Muller, M. S., Kelly, B. T., Rodeo, S. A., & Warren, R. F. (2008). Epidemiology of National Football League training camp injuries from 1998 to 2007. *The American Journal of Sports Medicine, 36*(8), 1597.

Flitney, F. W., & Hirst, D. G. (1978). Cross-bridge detachment and sarcomere 'give' during stretch of active frog's muscle. *The Journal of Physiology, 276*(1), 449-465.

Franklin, M. E., Chamness, M. S., Chenier, T. C., Mosteller, G. C., & Barrow, L. A. (1993). A comparison of isokinetic eccentric exercise on delayed-onset muscle soreness and creatine kinase in the quadriceps versus the hamstrings. *Isokinetics and Exercise Science, 3*(2), 68-73.

Fridén, J., Sjöström, M., & Ekblom, B. (1983). Myofibrillar damage following intense eccentric exercise in man. *International Journal of Sports Medicine, 4*(3), 170-176.

Fukumoto, Y., Ikezoe, T., Yamada, Y., Tsukagoshi, R., Nakamura, M., Mori, N., . . . Ichihashi, N. (2012). Skeletal muscle quality assessed from echo intensity is associated with muscle strength of middle-aged and elderly persons. *European Journal of Applied Physiology, 112*(4), 1519-1525.

Gabbe, B. J., Branson, R., & Bennell, K. L. (2006). A pilot randomised controlled trial of eccentric exercise to prevent hamstring injuries in community-level Australian Football. *Journal of Science and Medicine in Sport, 9*(1), 103-109.

Gambetta, V., & Benton, D. (2008). A systematic approach to hamstring prevention and rehabilitation. *Sports Coach, 28*, 1-6.

Golden, C. L., & Dudley, G. A. (1992). Strength after bouts of eccentric or concentric actions. *Medicine and Science in Sports and Exercise, 24*(8), 926-933.

Gonzalez-Izal, M., Cadore, E. L., & Izquierdo, M. (2014). Muscle conduction velocity, surface electromyography variables, and echo intensity during concentric and eccentric fatigue. *Muscle & Nerve, 49*(3), 389-397.

Greenstein, J. S., Bishop, B. N., Edward, J. S., & Topp, R. V. (2011). The effects of a closed-chain, eccentric training program on hamstring injuries of a professional football cheerleading team. *Journal of Manipulative and Physiological Therapeutics, 34*(3), 195-200.

Guex, K., Degache, F., Gremion, G., & Millet, G. (2013). Effect of hip flexion angle on hamstring optimum length after a single set of concentric contractions. *Journal of Sports Sciences*(ahead-of-print), 1-8.

Hamlin, M. J., & Quigley, B. M. (2001a). Quadriceps concentric and eccentric exercise 1: Changes in contractile and electrical activity following eccentric and concentric exercise. *Journal of Science and Medicine in Sport, 4*(1), 88-103.

Hamlin, M. J., & Quigley, B. M. (2001b). Quadriceps concentric and eccentric exercise 2: Differences in muscle strength, fatigue and EMG activity in eccentrically-exercised sore and non-sore muscles. *Journal of Science and Medicine in Sport, 4*(1), 104-115.

Henderson, G., Barnes, C. A., & Portas, M. D. (2010). Factors associated with increased propensity for hamstring injury in English Premier League soccer players. *Journal of Science and Medicine in Sport, 13*(4), 397-402.

Hinckson, E. A., Hopkins, W. G., Aminian, S., & Ross, K. (2013). Week-to-week differences of children's habitual activity and postural allocation as measured by the ActivPAL monitor. *Gait & posture, 38*(4), 663-667.

Hody, S., Rogister, B., Leprince, P., Laglaine, T., & Croisier, J. L. (2013). The susceptibility of the knee extensors to eccentric exercise-induced muscle damage is not affected by leg dominance but by exercise order. *Clinical Physiology and Functional Imaging, 33*(5), 373-380.

Hoeger, W. W., Hopkins, D. R., Barette, S. L., & Hale, D. F. (1990). Relationship between repetitions and selected percentages of one repetition maximum: a comparison

between untrained and trained males and females. *The Journal of Strength & Conditioning Research, 4*(2), 47-54.
Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.
Hopkins, W. G. (2006). Spreadsheets for analysis of controlled trials, with adjustment for a subject characteristic. *Sportscience, 10*, 46-50.
Hopkins, W. G. (2007a). A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a P value. *Sportscience 11*, 16-20.
Hopkins, W. G. (2007b). A spreadsheet to compare means of two groups. *Sportscience, 11*, 22-23.
Hopkins, W. G. (2015). Spreadsheets for analysis of validity and reliability. *Sportscience, 19*, 36-42.
Hopkins, W. G., Batterham, A. M., Marshall, S. W., & Hanin, J. (2009). Progressive statistics. *Sportscience, 13*, 55-70.
Hortobágyi, T., Houmard, J., Fraser, D., Dudek, R., Lambert, J., & Tracy, J. (1998). Normal forces and myofibrillar disruption after repeated eccentric exercise. *Journal of Applied Physiology, 84*(2), 492-498.
Howatson, G., & Van Someren, K. A. (2007). Evidence of a contralateral repeated bout effect after maximal eccentric contractions. *European Journal of Applied Physiology, 101*(2), 207-214.
Howatson, G., Van Someren, K. A., & Hortobagyi, T. (2007). Repeated bout effect after maximal eccentric exercise. *International Journal of Sports Medicine, 28*(7), 557-563.
Howell, J. N., Chleboun, G., & Conatser, R. (1993). Muscle stiffness, strength loss, swelling and soreness following exercise-induced injury in humans. *The Journal of Physiology, 464*(1), 183-196.
Huang, Q., Li, D., Zhang, Y., Hu, A., Huo, M., & Maruyama, H. (2014). The reliability of rehabilitative ultrasound imaging of the cross-sectional area of the lumbar multifidus muscles in the PNF pattern. *Journal of Physical Therapy Science, 26*(10), 1539.
Hunter, A. M., Galloway, S. D. R., Smith, I. J., Tallent, J., Ditroilo, M., Fairweather, M. M., & Howatson, G. (2012). Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. *Journal of Electromyography and Kinesiology, 22*(3), 334-341.
Huxley, A. F. (2000). Cross-bridge action: present views, prospects, and unknowns. *Journal of Biomechanics, 33*(10), 1189-1195.
Jamurtas, A. Z., Theocharis, V., Tofas, T., Tsiokanos, A., Yfanti, C., Paschalis, V., . . . Nosaka, K. (2005). Comparison between leg and arm eccentric exercises of the same relative intensity on indices of muscle damage. *European Journal of Applied Physiology, 95*(2-3), 179-185.
Jenkins, N. D., Miller, J. M., Buckner, S. L., Cochrane, K. C., Bergstrom, H. C., Hill, E. C., . . . Cramer, J. T. (2015). Test–retest reliability of single transverse versus panoramic ultrasound imaging for muscle size and echo intensity of the biceps brachii. *Ultrasound in Medicine & Biology, 41*(6), 1584-1591.
Johnson, M. A., Polgar, J., Weightman, D., & Appleton, D. (1973). Data on the distribution of fibre types in thirty-six human muscles: an autopsy study. *Journal of the Neurological Sciences, 18*(1), 111-129.
Jones, D. A., Newham, D. J., Round, J. M., & Tolfree, S. E. (1986). Experimental human muscle damage: morphological changes in relation to other indices of damage. *The Journal of Physiology, 375*(1), 435-448.
Jones, D. A., Newham, D. J., & Torgan, C. (1989). Mechanical influences on long-lasting human muscle fatigue and delayed-onset pain. *The Journal of Physiology, 412*(1), 415-427.
Juul-Kristensen, B., Bojsen-Møller, F., Holst, E., & Ekdahl, C. (2000). Comparison of muscle sizes and moment arms of two rotator cuff muscles measured by ultrasonography and magnetic resonance imaging. *European Journal of Ultrasound, 11*(3), 161-173.
Kerkhoffs, G. M., van Es, N., Wieldraaijer, T., Sierevelt, I. N., Ekstrand, J., & van Dijk, C. N. (2013). Diagnosis and prognosis of acute hamstring injuries in athletes. *Knee Surgery, Sports Traumatology, Arthroscopy, 21*(2), 500-509.
Kubota, J., Ono, T., Araki, M., Tawara, N., Torii, S., Okuwaki, T., & Fukubayashi, T. (2009). Relationship between the MRI and EMG measurements. *International Journal of Sports Medicine, 30*(07), 533-537.
Kubota, J., Ono, T., Araki, M., Torii, S., Okuwaki, T., & Fukubayashi, T. (2007). Non-uniform changes in magnetic resonance measurements of the semitendinosus muscle

following intensive eccentric exercise. *European Journal of Applied Physiology, 101*(6), 713-720.

Larsen, R. G., Ringgaard, S., & Overgaard, K. (2007). Localization and quantification of muscle damage by magnetic resonance imaging following step exercise in young women. *Scandinavian Journal of Medicine & Science in Sports, 17*(1), 76-83.

Lavender, A. P., & Nosaka, K. (2008). Changes in markers of muscle damage of middle-aged and young men following eccentric exercise of the elbow flexors. *Journal of Science and Medicine in Sport, 11*(2), 124-131.

Leach, R. E. (2000). Bigger is better? *The American Journal of Sports Medicine, 28*(1), 1-1.

Lefebvre, H. P., Braun, J. P., Laroute, V., Tripodi, A., Bret, L., & Toutain, P. L. (1995). Non-invasive quantification of organ damage. *Comparative Haematology International, 5*(2), 120-124.

Li, X., Karmakar, M., Lee, A., Kwok, W., Critchley, L., & Gin, T. (2014). Quantitative evaluation of the echo intensity of the median nerve and flexor muscles of the forearm in the young and the elderly. *British Journal of Radiology, 85*(1014), e140-e145.

Lieber, R. L., Shah, S., & Fridén, J. (2002). Cytoskeletal disruption after eccentric contraction-induced muscle injury. *Clinical Orthopaedics and Related Research, 403*, S90-S99.

Maffiuletti, N. A., & Lepers, R. (2003). Quadriceps femoris torque and EMG activity in seated versus supine position. *Medicine and Science in Sports and Exercise, 35*(9), 1511-1516.

Magal, M., Dunmke, C. L., Urbiztondo, Z. G., Cavill, M. J., Triplett, N. T., Quindry, J. C., . . . Epstein, Y. (2010). Relationship between serum creatine kinase activity following exercise-induced muscle damage and muscle fibre composition. *Journal of Sports Sciences, 28*(3), 257-266.

Mair, J., Koller, A., Artner-Dworzak, E., Haid, C., Wicke, K., Judmaier, W., & Puschendorf, B. (1992). Effects of exercise on plasma myosin heavy chain fragments and MRI of skeletal muscle. *Journal of Applied Physiology, 72*(2), 656-663.

Malliaropoulos, N., Isinkaye, T., Tsitas, K., & Maffulli, N. (2011). Reinjury after acute posterior thigh muscle injuries in elite track and field athletes. *The American Journal of Sports Medicine, 39*(2), 304-310.

McHugh, M. P., Connolly, D. A. J., Eston, R. G., Gartman, E. J., & Gleim, G. W. (2001). Electromyographic analysis of repeated bouts of eccentric exercise. *Journal of Sports Sciences, 19*(3), 163-170.

McHugh, M. P., Connolly, D. A. J., Eston, R. G., & Gleim, G. W. (1999). Exercise-induced muscle damage and potential mechanisms for the repeated bout effect. *Sports Medicine, 27*(3), 157-170.

McHugh, M. P., Connolly, D. A. J., Eston, R. G., & Gleim, G. W. (2000). Electromyographic analysis of exercise resulting in symptoms of muscle damage. *Journal of Sports Sciences, 18*(3), 163-172.

McHugh, M. P., & Tetro, D. T. (2003). Changes in the relationship between joint angle and torque production associated with the repeated bout effect. *Journal of Sports Science, 21*(11), 927-932.

McNair, P. J., Marshall, R. N., & Matheson, J. A. (1991). Quadriceps strength deficit associated with rectus fernoris rupture: A case report. *Clinical Biomechanics, 6*(3), 190-192.

Mendiguchia, J., Alentorn-Geli, E., & Brughelli, M. (2011). Hamstring strain injuries: are we heading in the right direction? *British Journal of Sports Medicine*.

Mendiguchia, J., Arcos, A. L., Garrues, M., Myer, G., Yanci, J., & Idoate, F. (2013). The use of MRI to evaluate posterior thigh muscle activity and damage during Nordic Hamstring exercise. *Journal of Strength and Conditioning Research*.

Mendiguchia, J., Garrues, M. A., Cronin, J. B., Contreras, B., Los Arcos, A., Malliaropoulos, N., . . . Idoate, F. (2013). Nonuniform changes in MRI measurements of the thigh muscles after two hamstring strengthening exercises. *The Journal of Strength & Conditioning Research, 27*(3), 574-581.

Mendis, M. D., Wilson, S. J., Stanton, W., & Hides, J. A. (2010). Validity of real-time ultrasound imaging to measure anterior hip muscle size: a comparison with magnetic resonance imaging. *Journal of Orthopaedic & Sports Physical Therapy, 40*(9), 577-581.

Mjolsnes, R., Arnason, A., Raastad, T., & Bahr, R. (2004). A 10 week randomized trial comparing eccentric vs. concentric hamstring strength training in well trained soccer players. *Scandinavian Journal of Medicine and Science in Sports, 14*(5), 311-317.

Mohseny, B., Nijhuis, T. H., Hundepool, C. A., Janssen, W. G., Selles, R. W., & Coert, J. H. (2015). Ultrasonographic quantification of intrinsic hand muscle cross-sectional area; Reliability and validity for predicting muscle strength. *Archives of physical medicine and rehabilitation*(96), 845-853.

Molina, R., & Denadai, B. S. (2012). Dissociated time course recovery between rate of force development and peak torque after eccentric exercise. *Clinical Physiology and Functional Imaging, 32*(3), 179-184.

Morgan, D. L. (1990). New insights into the behavior of muscle during active lengthening. *Biophysical Journal, 57*(2), 209-221.

Morgan, D. L., & Allen, D. G. (1999). Early events in stretch-induced muscle damage. *Journal of Applied Physiology, 87*(6), 2007-2015.

Murayama, M., Nosaka, K., Yoneda, T., & Minamitani, K. (2000). Changes in hardness of the human elbow flexor muscles after eccentric exercise. *European Journal of Applied Physiology, 82*(5-6), 361-367.

Murphy, J. C., O'Malley, E., Gissane, C., & Blake, C. (2012). Incidence of injury in Gaelic Football. A 4-year prospective study. *The American Journal of Sports Medicine, 40*(9), 2113-2120.

Newham, D., Jones, D., & Edwards, R. (1983). Large delayed plasma creatine kinase changes after stepping exercise. *Muscle & Nerve, 6*(5), 380-385.

Newham, D., Jones, D., Ghosh, G., & Aurora, P. (1988). Muscle fatigue and pain after eccentric contractions at long and short length. *Clinical Science, 74*(5), 553-557.

Newton, M. J., Morgan, G. T., Sacco, P., Chapman, D. W., & Nosaka, K. (2008). Comparison of responses to strenuous eccentric exercise of the elbow flexors between resistance-trained and untrained men. *The Journal of Strength & Conditioning Research, 22*(2), 597-607.

Newton, M. J., Sacco, P., Chapman, D., & Nosaka, K. (2013). Do dominant and non-dominant arms respond similarly to maximal eccentric exercise of the elbow flexors? *Journal of Science and Medicine in Sport, 16*, 166-171.

Nosaka, K., Chapman, D., Newton, M., & Sacco, P. (2006). Is isometric strength loss immediately after eccentric exercise related to changes in indirect markers of muscle damage? *Applied Physiology, Nutrition, and Metabolism, 31*(3), 313-319.

Nosaka, K., & Clarkson, P. M. (1996). Changes in indicators of inflammation after eccentric exercise of the elbow flexors. *Medicine and Science in Sports and Exercise, 28*(8), 953-961.

Nosaka, K., & Newton, M. (2002a). Difference in the magnitude of muscle damage between maximal and submaximal eccentric loading. *The Journal of Strength & Conditioning Research, 16*(2), 202-208.

Nosaka, K., & Newton, M. (2002b). Is recovery from muscle damage retarded by a subsequent bout of eccentric exercise inducing larger decreases in force? *Journal of Science and Medicine in Sport, 5*(3), 204-218.

Nosaka, K., Newton, M., & Sacco, P. (2002a). Delayed-onset muscle soreness does not reflect the magnitude of eccentric exercise-induced muscle damage. *Scandinavian Journal of Medicine & Science in Sports, 12*(6), 337-346.

Nosaka, K., Newton, M., & Sacco, P. (2002b). Muscle damage and soreness after endurance exercise of the elbow flexors. *Medicine and Science in Sports and Exercise, 34*(6), 920-927.

Nosaka, K., Newton, M., & Sacco, P. (2002c). Responses of human elbow flexor muscles to electrically stimulated forced lengthening exercise. *Acta Physiologica Scandinavica, 174*(2), 137-145.

Nosaka, K., Newton, M., & Sacco, P. (2005). Attenuation of protective effect against eccentric exercise-induced muscle damage. *Canadian Journal of Applied Physiology, 30*(5), 529-542.

Nosaka, K., Newton, M., Sacco, P., Chapman, D., & Lavender, A. P. (2005). Partial protection against muscle damage by eccentric actions at short muscle lengths. *Medicine and Science in Sports and Exercise, 37*(5), 746-753.

Nosaka, K., & Sakamoto, K. (2001). Effect of elbow joint angle on the magnitude of muscle damage to the elbow flexors. *Medicine and Science in Sports and Exercise, 33*(1), 22-29.

Nosaka, K., Sakamoto, K., Newton, M., & Sacco, P. (2001). The repeated bout effect of reduced-load eccentric exercise on elbow flexor muscle damage. *European Journal of Applied Physiology, 85*(1-2), 34-40.

O'Sullivan, C., Meaney, J., Boyle, G., Gormley, J., & Stokes, M. (2009). The validity of rehabilitative ultrasound imaging for measurement of trapezius muscle thickness. *Manual Therapy, 14*(5), 572-578.
Orchard, J., James, T., Alcott, E., Carter, S., & Farhart, P. (2002). Injuries in Australian cricket at first class level 1995/1996 to 2000/2001. *British Journal of Sports Medicine, 36*(4), 270-274.
Orchard, J., & Seward, H. (2010). Injury Report 2009: Australian Football League. *Sport Health, 28*(2), 10.
Paddon-Jones, D., Keech, A., Lonergan, A., & Abernethy, P. (2005). Differential expression of muscle damage in humans following acute fast and slow velocity eccentric exercise. *Journal of Science and Medicine in Sport, 8*(3), 255-263.
Paschalis, V., Giakas, G., Baltzopoulos, V., Jamurtas, A. Z., Theoharis, V., Kotzamanidis, C., & Koutedakis, Y. (2007). The effects of muscle damage following eccentric exercise on gait biomechanics. *Gait & Posture, 25*(2), 236-242.
Paschalis, V., Koutedakis, Y., Baltzopoulos, V., Mougios, V., Jamurtas, A. Z., & Giakas, G. (2005). Short vs. long length of rectus femoris during eccentric exercise in relation to muscle damage in healthy males. *Clinical Biomechanics, 20*(6), 617-622.
Paschalis, V., Koutedakis, Y., Baltzopoulos, V., Mougios, V., Jamurtas, A. Z., & Theocharis, V. (2005). The effects of muscle damage on running economy in healthy males. *International Journal of Sports Medicine, 26*(10), 827-831.
Paschalis, V., Koutedakis, Y., Jamurtas, A. Z., Mougios, V., & Baltzopoulos, V. (2005). Equal volumes of high and low intensity of eccentric exercise in relation to muscle damage and performance. *The Journal of Strength & Conditioning Research, 19*(1), 184-188.
Paschalis, V., Nikolaidis, M. G., Giakas, G., Jamurtas, A. Z., Pappas, A., & Koutedakis, Y. (2007). The effect of eccentric exercise on position sense and joint reaction angle of the lower limbs. *Muscle & Nerve, 35*(4), 496-503.
Paschalis, V., Nikolaidis, M. G., Theodorou, A. A., Giakas, G., Jamurtas, A. Z., & Koutedakis, Y. (2010). Eccentric exercise affects the upper limbs more than the lower limbs in position sense and reaction angle. *Journal of Sports Sciences, 28*(1), 33-43.
Peake, J., Nosaka, K. K., Muthalib, M., & Suzuki, K. (2006). Systemic inflammatory responses to maximal versus submaximal lengthening contractions of the elbow flexors. *Exercise Immunology Review, 12*, 72-85.
Peñailillo, L., Blazevich, A., Numazawa, H., & Nosaka, K. (2013). Metabolic and muscle damage profiles of concentric versus repeated eccentric cycling. *Medicine and Science in Sports and Exercise, 45*(9), 1773-1781.
Petersen, J., Thorborg, K., Nielsen, M. B., Budtz-Jørgensen, E., & Hölmich, P. (2011). Preventive effect of eccentric training on acute hamstring injuries in men’s soccer. A cluster-randomized controlled trial. *The American Journal of Sports Medicine, 39*(11), 2296-2303.
Petersen, J., Thorborg, K., Nielsen, M. B., & Hölmich, P. (2010). Acute hamstring injuries in Danish elite football: A 12-month prospective registration study among 374 players. *Scandinavian Journal of Medicine & Science in Sports, 20*(4), 588-592.
Pettitt, R. W., Symonds, J. D., Eisenman, P. A., Taylor, J. E., & White, A. T. (2005). Repetitive eccentric strain at long muscle length evokes the repeated bout effect. *The Journal of Strength & Conditioning Research, 19*(4), 918-924.
Philippou, A., Bogdanis, G. C., Nevill, A. M., & Maridaki, M. (2004). Changes in the angle-force curve of human elbow flexors following eccentric and isometric exercise. *European Journal of Applied Physiology, 93*(1-2), 237-244.
Philippou, A., Maridaki, M., Bogdanis, G., Halapas, A., & Koutsilieris, M. (2009). Changes in the mechanical properties of human quadriceps muscle after eccentric exercise. *In Vivo, 23*(5), 859-865.
Philippou, A., Maridaki, M., & Bogdanis, G. C. (2003). Angle-specific impairment of elbow flexors strength after isometric exercise at long muscle length. *Journal of Sports Sciences, 21*(10), 859-865.
Pillen, S., van Keimpema, M., Nievelstein, R. A., Verrips, A., van Kruijsbergen-Raijmann, W., & Zwarts, M. J. (2006). Skeletal muscle ultrasonography: visual versus quantitative evaluation. *Ultrasound in Medicine & Biology, 32*(9), 1315-1321.
Potier, T. G., Alexander, C. M., & Seynnes, O. R. (2009). Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *European Journal of Applied Physiology, 105*(6), 939-944.
Prior, B. M., Jayaraman, R. C., Reid, R. W., Cooper, T. G., Foley, J. M., Dudley, G. A., & Meyer, R. A. (2001). Biarticular and monoarticular muscle activation and injury in

human quadriceps muscle. *European Journal of Applied Physiology, 85*(1-2), 185-190.
Proske, U., & Morgan, D. (2001). Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications. *The Journal of Physiology, 537*(2), 333-345.
Proske, U., Morgan, D., Brockett, C., & Percival, P. (2004). Identifying athletes at risk of hamstring strains and how to protect them. *Clinical and Experimental Pharmacology and Physiology, 31*(8), 546-550.
Radaelli, R., Bottaro, M., Wilhelm, E. N., Wagner, D. R., & Pinto, R. S. (2012). Time course of strength and echo intensity recovery after resistance exercise in women. *The Journal of Strength & Conditioning Research, 26*(9), 2577-2584.
Rodenburg, J. B., De Boer, R. W., Schiereck, P., Van Echteld, C. J. A., & Bär, P. R. (1994). Changes in phosphorus compounds and water content in skeletal muscle due to eccentric exercise. *European Journal of Applied Physiology and Occupational Physiology, 68*(3), 205-213.
Saka, T., Akova, B., Yazici, Z., Sekir, U., Gür, H., & Ozarda, Y. (2009). Difference in the magnitude of muscle damage between elbow flexors and knee extensors eccentric exercises. *Journal of Sports Science and Medicine, 8*(1), 107-115.
Saltin, B., Henriksson, J., Nygaard, E., Andersen, P., & Jansson, E. (1977). Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. *Annals of the New York Academy of Sciences, 301*(1), 3-29.
Sbriccoli, P., Felici, F., Rosponi, A., Aliotta, A., Castellano, V., Mazza, C., . . . Marchetti, M. (2001). Exercise induced muscle damage and recovery assessed by means of linear and non-linear sEMG analysis and ultrasonography. *Journal of Electromyography and Kinesiology, 11*(2), 73-83.
Schache, A. G., Dorn, T. W., Blanch, P. D., Brown, N. A. T., & Pandy, M. G. (2012). Mechanics of the human hamstring muscles during sprinting. *Medicine and Science in Sports and Exercise, 44*(4), 647-658.
Schwane, J. A., Buckley, R. T., Dipaolo, D. P., Atkinson, M., & Shepherd, J. R. (2000). Plasma creatine kinase responses of 18-to 30-yr-old African-American men to eccentric exercise. *Medicine and Science in Sports and Exercise, 32*(2), 370-378.
Shepstone, T. N., Tang, J. E., Dallaire, S., Schuenke, M. D., Staron, R. S., & Phillips, S. M. (2005). Short-term high-vs. low-velocity isokinetic lengthening training results in greater hypertrophy of the elbow flexors in young men. *Journal of Applied Physiology, 98*(5), 1768-1776.
Silder, A., Heiderscheit, B. C., Thelen, D. G., Enright, T., & Tuite, M. J. (2008). MR observations of long-term musculotendon remodeling following a hamstring strain injury. *Skeletal Radiology, 37*(12), 1101-1109.
Skurvydas, A., Brazaitis, M., & Kamandulis, S. (2010). Prolonged muscle damage depends on force variability. *International Journal of Sports Medicine, 31*(2), 77-81.
Skurvydas, A., Brazaitis, M., Kamandulis, S., Mickevičienė, D., & Karanauskienė, D. (2011). Eccentrically-induced fatigue in voluntary muscle performance: the effect of muscle length and contraction type. *Ugdymas Kuno Kultura, 2*, 37-43.
Skurvydas, A., Brazaitis, M., Kamandulis, S., & Sipaviciene, S. (2010). Peripheral and central fatigue after muscle-damaging exercise is muscle length dependent and inversely related. *Journal of Electromyography and Kinesiology, 20*(4), 655-660.
Skurvydas, A., Brazaitis, M., Venckūnas, T., Kamandulis, S., Stanislovaitis, A., & Zuoza, A. (2011). The effect of sports specialization on musculus quadriceps function after exercise-induced muscle damage. *Applied Physiology, Nutrition, and Metabolism, 36*(6), 873-880.
Slavotinek, J. P., Verrall, G. M., & Fon, G. T. (2002). Hamstring injury in athletes: using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *American Journal of Roentgenology, 179*(6), 1621-1628.
Soderlund, K., Greenhaff, P. L., & Hultman, E. (1992). Energy metabolism in type I and type II human muscle fibres during short term electrical stimulation at different frequencies. *Acta Physiologica Scandinavica, 144*(1), 15-22.
Starbuck, C., & Eston, R. G. (2012). Exercise-induced muscle damage and the repeated bout effect: evidence for cross transfer. *European Journal of Applied Physiology, 112*(3), 1005-1013.
Tesch, P., & Karlsson, J. (1985). Muscle fiber types and size in trained and untrained muscles of elite athletes. *Journal of Applied Physiology, 59*(6), 1716-1720.

Thelen, D. G., Chumanov, E. S., Sherry, M. A., & Heiderscheit, B. C. (2006). Neuromusculoskeletal models provide insights into the mechanisms and rehabilitation of hamstring strains. *Exercise and Sport Sciences Reviews, 34*(3), 135-141.

Thorborg, K. (2012). Why hamstring eccentrics are hamstring essentials. *British Journal of Sports Medicine, 46*(7), 463-465.

van der Horst, N., Smits, D. W., Petersen, J., Goedhart, E., & Backx, F. (2015). The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players: A randomized controlled trial. *British Journal of Sports Medicine, 48*(7), 609-610.

Van Holsbeeck, M., & Introcaso, J. (1992). Musculoskeletal ultrasonography. *Radiologic Clinics of North America, 30*(5), 907-925.

Watanabe, Y., Yamada, Y., Fukumoto, Y., Ishihara, T., Yokoyama, K., Yoshida, T., . . . Kimura, M. (2013). Echo intensity obtained from ultrasonography images reflecting muscle strength in elderly men. *Clinical Interventions in Aging, 8*, 993.

Whittaker, J. L., & Stokes, M. (2011). Ultrasound imaging and muscle function. *Journal of Orthopaedic & Sports Physical Therapy, 41*(8), 572-580.

Wickiewicz, T. L., Roy, R. R., Powell, P. L., & Edgerton, V. R. (1983). Muscle architecture of the human lower limb. *Clinical Orthopaedics and Related research, 179*, 275-283.

Yeung, S. S., & Yeung, E. W. (2008). Shift of peak torque angle after eccentric exercise. *International Journal of Sports Medicine, 29*(3), 251-256.

Yu, J., Carlsson, L., & Thornell, L. (2004). Evidence for myofibril remodeling as opposed to myofibril damage in human muscles with DOMS: an ultrastructural and immunoelectron microscopic study. *Histochemistry and Cell Biology, 121*(3), 219-227.

# APPENDIX 1

## AUT ETHICS APPROVAL

**A U T E C**

**S E C R E T A R I A T**

25 June 2013

Chris Whatman

Faculty of Health and Environmental Sciences

Dear Chris

Re Ethics Application: **13/124 A comparison of the effects of two forms of eccentric hamstring training on performance, muscle architecture, flexibility, hamstrings: quadriceps ratio, and optimal angle of torque generation.**

Thank you for providing evidence as requested, which satisfies the points raised by the AUT University Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 24 June 2016.

As part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online throughhttp://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 24 June 2016;
- A brief report on the status of the project using form EA3, which is available online throughhttp://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 24 June 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Madeline Banda

Acting Executive Secretary

**Auckland University of Technology Ethics Committee**

Cc:Ben reynolds ben.reynolds@manukau.ac.nz

# AUT ETHICS AMENDMENT

**A U T E C**

**S E C R E T A R I A T**

12 March 2014

Chris Whatman

Faculty of Health and Environmental Sciences

Dear Chris

Re: Ethics Application: **13/124 The acute effects of two eccentric hamstring exercises on indicators of hamstring muscle damage.**

Thank you for your request for approval of an amendment to your ethics application.

I have approved the minor amendment to your ethics application allowing changes to the testing exercises and also note a change in the title.

I remind you that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 24 June 2016;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 24 June 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O’Connor

Executive Secretary

**Auckland University of Technology Ethics Committee**

Cc:Ben Reynolds ben.reynolds@manukau.ac.nz

**A U T E C**

**S E C R E T A R I A T**

14 October 2013

Chris Whatman

Faculty of Health and Environmental Sciences

Dear Chris

Re: Ethics Application:**13/124 Eccentric induced muscle damage following an acute bout of drop lunges.**

Thank you for your request for approval of amendments to your ethics application.

I have approved minor amendments to your ethics application allowing:

- Change of title
- Change of measurement technique
- Change in the participants being recruited.

I remind you that as part of the ethics approval process, you are required to submit the following to AUTEC:

- A brief annual progress report using form EA2, which is available online through http://www.aut.ac.nz/researchethics. When necessary this form may also be used to request an extension of the approval at least one month prior to its expiry on 24 June 2016;
- A brief report on the status of the project using form EA3, which is available online through http://www.aut.ac.nz/researchethics. This report is to be submitted either when the approval expires on 24 June 2016 or on completion of the project.

It is a condition of approval that AUTEC is notified of any adverse events or if the research does not commence. AUTEC approval needs to be sought for any alteration to the research, including any alteration of or addition to any documents that are provided to participants. You are responsible for ensuring that research undertaken under this approval occurs within the parameters outlined in the approved application.

AUTEC grants ethical approval only. If you require management approval from an institution or organisation for your research, then you will need to obtain this. If your research is undertaken within a jurisdiction outside New Zealand, you will need to make the arrangements necessary to meet the legal and ethical requirements that apply there.

To enable us to provide you with efficient service, please use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

All the very best with your research,

Kate O'Connor

Executive Secretary

**Auckland University of Technology Ethics Committee**

Cc:Ben reynolds ben.reynolds@manukau.ac.nz

# PARTICIPANT INFORMATION SHEET

Date Information Sheet Produced: 13th February 2014

**Project Title:** The acute effects of two eccentric hamstring exercises on indicators of hamstring muscle damage

An Invitation

My name is Ben Reynolds and I am completing a Master of Sport and Exercise at AUT University in Auckland, New Zealand. As part of my qualification I am required to carry out a research project and I would like to invite you to take part in my study.

The study is investigating the effects of the drop lunge and Nordic Hamstring Exercise. The study will include measures of knee strength and optimum angle of torque generation, limb circumference, muscle soreness and echo intensity of B-mode ultrasound images. Together, you and your whanau should decide whether or not you would like to be involved. You don't have to be involved, neither grades nor academic relationships with the department or members of staff of the School of Sport and Recreation will be affected by either your refusal or agreement to participate in this study, and you can stop being involved in the study at any time.

What is the purpose of this research?

The purpose of this research is to help develop knowledge around preventing hamstring injuries and improving athletic performance. The eccentric Nordic Hamstring Exercise has been shown to decrease the incidence of hamstring strains in soccer players. The Drop lunge has been proposed to be more effective. The results of this research could help us improve athletic performance and hamstring injury prevention.

The completed research will result in a published thesis as part of the requirements of the Master of Sport and Exercise at AUT University.

How was I identified and why am I being invited to participate in this research?

You have been identified and invited to take part in this study because you are a student at MIT.

What will happen in this research?

We will ask you to complete an initial assessment of knee strength and optimum angle of torque generation, limb circumference, muscle soreness at M.I.T. and echo intensity of B-mode ultrasound images at UNITEC. This testing will be on a Monday and will take approximately 30 minutes. You will then be randomly assigned to complete either the drop lunge or the Nordic hamstrings exercise before being tested again. You will be tested at the same time for the next 4 days. The drop lunge involves you stepping off a step and lowering into a lunge position. The Nordic hamstrings exercise involves you lowering yourself to the floor from a kneeling position.

What are the discomforts and risks?

There is a minimal level of risk of hamstring injury; no greater than what would be expected in your normal fitness training.

In the unlikely event of a physical injury as a result of your participation in this study, you may be covered by ACC under the Injury Prevention, Rehabilitation, and Compensation Act 2001. ACC cover is not automatic, and your case will need to be assessed by ACC according to the provisions of the Injury Prevention, Rehabilitation, and Compensation Act 2001. If your claim is accepted by ACC, you still might not get any compensation. This depends on a number of factors, such as whether you are an earner or non-earner. ACC usually provides only partial reimbursement of costs and expenses, and there may be no lump sum compensation payable. There is no cover for mental injury unless it is a result of physical injury. If you have ACC cover, generally this will affect your right to sue the investigators. If you have any questions about ACC, contact your nearest ACC office or the investigator. You are also advised to check whether participation in this study would affect any indemnity cover you have or are considering, such as medical insurance, life insurance and superannuation.

How will these discomforts and risks be alleviated?

The level of risk will be no more than what you experience as part of your usual fitness training and less than what would be involved during playing team sport. Before strength testing you will be taken through a warm up and familiarisation period to minimise any potential discomfort and risk.

What are the benefits?

You will receive a copy of your test results and be given the opportunity to undertake an exercise to improve your athletic performance and decrease your hamstring injury risk.

Your contribution to the study will result in helping to develop greater knowledge around athletic performance and hamstring injury prevention.

The completion of this research also contributes to a Masters qualification and upon completion you will be provided the results of the study.

How will my privacy be protected?

All data collected will remain completely anonymous to the researchers throughout the study and at no stage will any individuals be identifiable in any way in any published documents.

What are the costs of participating in this research?

There is no monetary cost to you to be involved in this research, the only cost is time. The testing will be conducted in the MIT High Performance Lab and at UNITEC. You will be given a fuel voucher to assist with your travel costs. This testing will take approximately 90 minutes each day.

How do I agree to participate in this research?

If you agree to take part in the research you will need to fill out a consent form. You will be given a copy of the consent forms with this information sheet. If you do not return a signed consent form you will not be allowed to participate in the study.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor Chris Whatman, chris.whatman@aut.ac.nz, (09) 921 9999 ext 7037

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEC, Dr Rosemary Godbold, *rosemary.godbold@aut.ac.nz* , 921 9999 ext 6902.

Whom do I contact for further information about this research?

## RESEARCHER CONTACT DETAILS:

If you would like any further information about the study at any stage please feel free to contact Primary researcher, Ben Reynolds,ben.reynolds@manukau.ac.nz.

## PROJECT SUPERVISOR CONTACT DETAILS:

**Primary Supervisor**Dr. Chris Whatman

Faculty of Health and Environmental Sciences

AUT University

(09) 921 9999, Ext. 7037

chris.whatman@aut.ac.nz

**Additional Supervisor** Dr. Matt Brughelli

Faculty of Health and Environmental Sciences

AUT University

(09) 921 9999, Ext. 7025

Matt.brughelli@aut.ac.nz

**Thank you for considering participating in this research.**

**Approved by the Auckland University of Technology Ethics Committee on 12 March 2014, AUTEC Reference number 13/124**

# PARTICIPANT CONSENT FORM

*Project title:The acute effects of two eccentric hamstring exercises on indicators of hamstring muscle damage*

*Project Supervisor:* ***Chris Whatman***

*Researcher:* ***Ben Reynolds***

- ○ I have read and understood the information provided about this research project designed to compare the effects of two forms of eccentric hamstring training in the Information Sheet.
- ○ I understand that the duration of this study is 5 days.
- ○ I understand that neither grades nor academic relationships with the department or members of staff of the School of Sport and Recreation will be affected by either your refusal or agreement to participate in this study
- ○ I have had an opportunity to ask questions and am happy with the answers I have received.
- ○ I understand that taking part in the study is entirely my choice and that I may withdraw any information that I have provided for this project at any time prior to completion of data collection, without being disadvantaged in any way.
- ○ I permit the researcher to use the data from testing that is part of this project exclusively for research or educational purposes
- ○ I understand that the results will be used for academic purposes only and will not be published in any form outside of this project without my written permission.
- ○ I understand that any information I give during this study will be confidential and my name will not be recorded on any collected data at any time.
- ○ I agree to take part in this research.
  - ○ I wish to receive a copy of the report from the research (please tick one):

Yes○No○

Participant name:………………………………………………………………..

Participant signature:

.......................................………………………………………………………

Participant Contact Details (if appropriate):

………………………………………………………………………………………..

Date:

***Approved by the Auckland University of Technology Ethics Committee on* 12 March 2014 *AUTEC Reference number* 13/124**

*Note: The Participant should retain a copy of this form.*