THE EFFECT OF ECCENTRIC HAMSTRING STRENGTH TRAINING ON MUSCLE FUNCTION

by

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The high prevalence of hamstring strain injury in sports, coupled with detrimental performance and financial effects of hamstring injuries, stress the necessity to implement an intervention capable of minimizing hamstring injuries for athletes. Nordic Hamstring eccentric strength training has shown itself to be an effective method of preventing hamstring injury. Eccentric strength training has also been shown to alter muscle architecture, joint stiffness, improve strength, and enhance dynamic performance, specifically vertical jump height. While there is limited research investigating the adaptations of the hamstrings to Nordic Hamstring training, determining these adaptations would allow for a better understanding of how the body responds to this injury-preventing stimulus. The purpose of this study was to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance. We hypothesized that Nordic Hamstring eccentric strength training will increase hamstring fascicle lengths and cross-sectional area, properties of muscle stiffness as measured by shear modulus and passive knee flexor torque, maximum torque and angle of max peak torque, and vertical jump height.

A total of 17 recreationally active, adult participants between the age of 18 and 21 were randomly assigned to control or experimental groups. Control subjects (n=7) performed a warm-up and static stretching for 6 weeks while experimental subjects (n=10) performed a warm-up, static stretching, and progressive Nordic Hamstring strength training for 6 weeks. Pre- and post-intervention measurements included: muscle architecture and stiffness of the biceps femoris long head using ultrasound imaging, maximal isokinetic and isometric hamstring strength measured on a dynamometer, and vertical jump height performance. Muscle volume and physiological cross-sectional area (PSCA) were calculated from the ultrasound measurements. Within and between groups two-way repeated measures ANOVAs were used to determine significant interactions and main effects with an alpha level of $p<0.05$.

The experimental group increased volume in both hamstring muscles (biceps femoris 11%, semitendinosus 20%), with a 12% increase in PCSA for the biceps femoris long head muscle but not the semitendinosus ($p<0.05$). There were no changes to fascicle length, pennation angle, or stiffness that were unique to the experimental group. The 6-week intervention did not produce any significant group by time interactions for concentric, isometric, eccentric strength measurements or peak passive torque measurements. Vertical jump height was also not affected by the intervention. Overall, the 6-week Nordic Hamstring training intervention was a good training method for muscle growth and this adaptation in architecture translated to changes in eccentric hamstring muscle strength, although these changes did not reach statistical significance largely due to the dichotomy of responses in our training group. A sub-group analysis of the experimental subjects revealed apparent “responders” and “non-responders” to the training stimulus. From a clinically-relevant standpoint, the Nordic Hamstring training was 70% effective at improving muscle function for participants in this study. Future exploration of the mechanics behind the Nordic Hamstring strength training exercise, shown to reduce hamstring injury, is a necessary step in understanding muscular adaptations to resistance exercise and enhancing training effectiveness on hamstring muscle function.

The Effect of Eccentric Hamstring Strength Training on Muscle Function

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Chapter I. Introduction

Hamstring strains, accounting for over 12% of all lower extremity sport injuries, are among the highest occurring injuries in soccer, rugby, American football, Australian rules football, and sprinting (Ekstrand et al, 2011; Brooks et al, 2005; Feeley et al, 2008; Orchard et al, 2013; Alonso et al, 2012). This type of injury occurs when a muscle is overstretched during an eccentric or lengthening contraction, common during the swing phase of sprinting (Chumanov et al, 2007), resulting in injury. Once injured, hamstring re-injuries occur at an even higher rate of over 20% and are often more severe than initial injuries, resulting in longer absences from sport (Brooks et al, 2006; Ekstrand et al, 2012; Elliott et al, 2011; Orchard et al, 2013). Hamstring strain has also been show to decrease strength in the injured leg by 8-9%, compared to the uninjured leg, even after a year of recovery (Sugiura et al, 2008). Despite nearly two decades of scientific research on hamstring injury, sport epidemiological data indicates that rate of hamstring injury has not declined in recent decades (Brooks et al, 2006; Ekstrand et al, 2011; Ekstrand et al, 2013; Orchard et al, 2013). Clearly, the need exists for developing effective prevention and rehabilitation programs to diminish the rate of hamstring strain injury.

Eccentric strength training has shown itself to be an effective method of building strength and preventing hamstring injury (Askling et al, 2003; Brooks et al, 2006; Arnason et al, 2008; Tansel et al, 2008). The Nordic Hamstring curl is a highly effective eccentric strengthening exercise, which has been shown to reduce initial and recurrent hamstring injury rate by 60% and 80%, respectively, in professional soccer athletes (Petersen et al, 2011). While the Nordic Hamstring exercise does reduce hamstring injuries, the mechanism behind these injury reductions is unclear.

Eccentric strength training alters hamstring muscle architecture (Potier et al, 2009). In addition, mechanical adaptations to eccentric training have also been shown to increase joint stiffness (Fouré et al, 2013). Eccentric exercise induces muscle damage that triggers regeneration of more muscle fibers that allow the hamstrings to stretch further, sequentially, increasing the angle of maximum torque production and total muscle power output (Lieber & Bodine-Fowler, 1993; Brughelli & Cronin, 2007). These biomechanical changes from eccentric exercise can have performance benefits, as seen in vertical jump height (Clark et al, 2005; Tansel et al, 2008; Anastasi et al, 2011).

Eccentric strength training has been shown to alter hamstring muscle architecture and stiffness. Together these adaptations create a biomechanical change that can improve strength and dynamic performance, specifically vertical jump height. However, no study in the literature has examined all four of these variables together. By using an exercise that has been shown to reduce initial and recurrent hamstring strains, comprehensively evaluating the biomechanical and architectural adaptations of hamstring muscles to the Nordic Hamstring exercise could lead to better and more efficient methods of developing injury-resistant tissues.

Statement of Purpose

The purpose of this study was to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance.

Hypothesis

Nordic Hamstring eccentric strength training will cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance.

Significance

A comprehensive approach to understanding the adaptations of the hamstring muscles to eccentric strength training that reduces the risk of injury is essential to further prevention efforts. Broadly, understanding the adaptations of muscle to a stimulus that minimizes injury could lead to better and more efficient methods of developing injury-resistant tissues. Thus, while the focus of this study was the hamstring muscles, namely adaptations to the biceps femoris and semitendinosus, information gained here would help with the general understanding of skeletal muscle adaptations to specialized resistance exercise.

Delimitations

1. All subjects were healthy, with no history of hamstring or major lower limb damage.
2. Subjects were young, college-aged adults between the ages of 18 and 21.
3. Obese individuals, categorized as a BMI > 30, were excluded from the study.
4. Training was done in a controlled laboratory environment.

Limitations

1. Nordic Hamstring training could cause adaptations to the other hip extensor or knee extensor muscles. We only took measurements from the biceps femoris and semitendinosus muscle.
2. Muscle damage, and subsequent pain of eccentric exercise could decrease compliance to the intervention study.

Operational Definitions

1. Muscle Fascicle - Several muscle fibers bundled together and surrounded by perimysium. Fascicles are measured from the insertion to origin.
2. Pennation Angle - The angle at which muscle fascicles insert onto the deep aponeurotic tendon.
3. Physiological Cross-sectional Area - The volume of a muscle divided by the fascicle length, corrected for pennation angle.
4. Aponeurotic Tendon - A deep fibrous connective tissue that acts as an extension of the external tendon and located within the muscle belly.
5. Musculotendinous Junction - The connection between a muscle and tendon.
6. Muscle Belly - The thickest part of a muscle, from musculotendinous junction to musculotendinous junction; encapsulates all the fascicles, excluding external tendons.
7. Shear modulus – The rate of sound wave propagation along muscle fascicles.
8. Stiffness – The shear modulus of a muscle.
9. Joint stiffness – The change in torque per change in joint angular position.
10. Muscle-tendon complex stiffness – Combined stiffness of the muscle and tendon.
11. Passive torque – Moment of force produced when a non-contracting muscle changes length; attributed to the tendon.
12. Eccentric exercise – An exercise that lengthens the muscle.
13. Distal - Further away from a point of reference or place of origin.
14. Proximal - Closer to a point of reference of point of origin.
15. Prone - Lying face down.

Chapter II. Review of The Literature

Introduction

The purpose of this study was to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance. The epidemiology of hamstring injury, the effect of eccentric strength training, muscle adaptations to eccentric training, strength adaptations to eccentric training, dynamic performance adaptations to eccentric training, and a summary of discussed information will be section titles of this review of literature, respectively.

Epidemiology of Hamstring Muscle Injury

Hamstring strains, accounting for over 12% of all lower extremity injuries, are among the highest occurring injuries in American football, Australian rules football, rugby, soccer, and sprinting (Feeley et al, 2008; Orchard et al, 2013; Brooks et al, 2005; Hawkins et al, 2001; Ekstrand et al, 2011; Alonso et al, 2012). This type of injury occurs when a muscle/tendon is overstretched during an eccentric, or lengthening, muscle contraction (Kirkendall et al, 2002). The biceps femoris is the most commonly injured hamstring muscle (De Smet et al, 2000; Ekstrand et al, 2012), followed by the semimembranosus and semitendinosus, respectively.

Once injured, hamstring strain is also one of the most recurrent lower limb injuries in sports (Ekstrand et al, 2012; Orchard et al, 2013). On average, hamstring injuries result in 1,700 days absent from sport per year (Elliott et al, 2011; Orchard et al, 2013; Brooks et al, 2006; Ekstrand et al, 2012), which is a considerable amount of time lost from training and competition. This consequently causes financial cost to teams, with American and Australian football averaging to $300,000 in hamstring injury annually and soccer injuries costing well over $2M per year (Elliott et al, 2011; Hickey et al, 2013; Ekstrand et al, 2011). In addition, diminishing strength to the lower extremity has been shown as a result of hamstring injury. After a year of injury recovery, Sugiura et al (2008) showed a 9% decrease in peak eccentric torque at the knee and an 8% decrease in peak concentric torque at the hip in the injured leg compared to the uninjured leg ($p < 0.05$).

Australian football, rugby union, and soccer epidemiological data indicates that rate of hamstring injury has not declined in recent decades (Brooks et al, 2006; Ekstrand et al, 2011; Ekstrand et al, 2013; Orchard et al, 2013). This is particularly surprising considering the vast amount of attention and documentation that hamstring injury has received in the literature; over 1,500 published articles in two decades. The lack of decline in hamstring injury rates highlights that it is necessary to find and implement an intervention capable of minimizing hamstring injuries for athletes.

Effect of Eccentric Strength Training on Injury Prevention

Eccentric strength training has shown itself to be an effective method of building strength and preventing hamstring injury. In a study conducted by Askling et al (2003) investigating eccentric hamstring overload training on an ergometer over 10 weeks, muscle strength increased by 19% in the training group ($p < 0.05$). Eccentric training also reduced the rate of new injury by 57% and recurring injury by 67% ($p < 0.05$). There are many ways to conduct eccentric training; eccentric cycling (Askling et al, 2003; Elmer et al, 2012), isokinetic eccentric training (Da Silva et al, 2005), eccentric "foot catches" (Sherry and Best, 2004), and eccentric hamstring curls (Arnason et al, 2008; Petersen et al, 2011). Although there are several ways to eccentrically train, to accurately interpret and compare study results in regards to injury prevention, it is most beneficial to focus on a practical and effective training that has been shown to reduce hamstring injuries.

Of the various eccentric training methods, the Nordic Hamstring curl (NH) has been frequently used as an intervention for athletes. The Nordic Hamstring exercise consists of the athlete starting in a kneeling position, with their torso from the knees upwards held rigid and straight. A training partner applies pressure to the athletes' heels/lower legs to ensure the feet stay in contact with the ground throughout the movement. The participant then attempts to resist gravity as they fall forward, using their hamstring muscles to control descent into the prone position (Petersen et al, 2011). This eccentric exercise training is simple to learn and has minimal time requirements; making it an ideal training intervention.

As well as its easy implementation, NH training has been highly effective as an intervention method to increase strength and reduce injury in the hamstrings. A significant eccentric strength increase of 12.6% was shown in 10–12 year old male basketball players who underwent 5 weeks of NH training in addition to basketball training compared to those who did basketball training alone (Tansel et al, 2008). Brooks et al (2006) examined the effect of hamstring strengthening and stretching exercises on reduction of injury rate in rugby. Subjects were divided into three training groups: normal strengthening (concentric and eccentric exercises), strengthening and static stretching, and strengthening/stretching/eccentric NH training. After two full seasons, the incidence of injury per player hour was significantly lower with Nordic Hamstring training compare to the other strengthening and stretching groups (1.1, 0.59, 0.39, respectively; $p < 0.05$).

Arnason et al (2008) investigated the effect of eccentric strength training and flexibility training on the incidence of hamstring strains in soccer. Subjects were instructed to perform Nordic hamstring or flexibility training over the course of two seasons. Results indicated that the incidence of hamstring strains was 65% lower in teams who used the NH training program compared to teams that had flexibility training. Similarly, Petersen et al (2011) investigated the effect of eccentric strengthening of the hamstring muscles compared to no hamstring exercise on the proportion of hamstring injuries in soccer players after Nordic Hamstring training over a 10-week period. Results of the study showed a reduced rate of new injuries by more than 60% and a reduced rate of recurring injuries by about 85% compared to the control group who performed no additional hamstring training.

The Nordic Hamstring exercise resembles the typical hamstring injury situation, which occurs during eccentric muscle contraction. Application of the Nordic Hamstring exercise is fairly easy to learn and requires minimal time to conduct, which is the ideal kind of training intervention for athletic teams. Throughout the literature, eccentric training, specifically the NH, has also been identified as a highly effective method to strengthen the hamstring muscles and prevent hamstring injury. A comprehensive approach to understanding the adaptations of the hamstring muscles to eccentric strength training that reduces the risk of injury is essential to further prevention efforts and the development of injury-resistant tissues.

Muscle Adaptations to Eccentric Strength Training

Eccentric strength training causes adaptations to muscle architecture (Potier et al, 2009). Increased muscle fascicle lengths, cross-section area, and muscle thickness have all been shown as a result of eccentric training. While there is less evidence in adaptations to eccentric strength training in the hamstrings, previous studies focused on quadriceps muscle architecture and resistance training have shown adaptive responses. Alegre et al (2006) found architectural adaptations with the vastus lateralis during eccentric training of half-squat lifts for thirteen weeks. The training group significantly increased vastus lateralis muscle thickness (6.9%, $p < 0.001$) and fascicle length (10.3%, $p < 0.05$), with a non-significant decrease in pennation angle. After training, there was a significant positive correlation between 1-RM and muscle thickness ($r=0.54$, $p < 0.05$), pennation angle and peak isometric force ($r=0.57$, $p < 0.05$), as well as pennation angle and rate of force development ($r=0.55$, $p < 0.05$). Researchers speculated that increases in muscle thickness and fascicle length from resistance training might correlate to more efficient transmission of fiber force to the muscle tendon. Blazevich et al (2007) showed significant pennation angle changes in the vastus lateralis while examining the influence of contraction mode on muscle architectural change. Slow-speed concentric isokinetic knee extensor training was compared to eccentric isokinetic knee extensor training for ten weeks. Although fascicle length increased similarly in both training groups, fascicle angles of the eccentric group increased by 21.4 ± 7.3% ($p = 0.03$) compared to concentric group's fascicle angles which did not reach statistical significance.

A more recent study by Baroni et al (2013) focused on changes in muscle architecture induced by eccentric training of synergist quadriceps muscles. Subjects went through a 12-week knee extensor eccentric training intervention, performed on an isokinetic dynamometer. Both rectus femoris and vastus lateralis fascicle lengths increased by 17–19% ($p < 0.05$), with a muscle thickness increase of approximately 7–10% ($p < 0.05$). Researchers concluded that increased muscle thickness due to eccentric training was related to an increase in fascicle lengths. Also, the difference in muscle fiber pennation of the rectus femoris and vastus lateralis had no effect on the architectural adaptations to eccentric training.

In a pioneer study conducted by Potier et al (2009), change in muscle architecture of the biceps femoris long head after eight weeks of eccentric hamstring curl training was examined.

Eccentric training increased biceps femoris fascicle lengths by 34% ($p = 0.01$), one-repetition maximum strength by 34% ($p < 0.01$), and knee joint range of motion by 5% ($p = 0.01$). These were the first results of biceps femoris long head architectural adaptation as a result of eccentric strength training.

In addition to architectural adaptations, eccentric training also increases muscle and joint stiffness. Fouré et al (2013) determined the specific effects of eccentric training on muscle and tendon mechanical properties assessed in active and passive conditions in vivo. Eleven male subjects completed fourteen weeks of eccentric plantar flexor training. Achilles tendon stiffness was calculated during isometric plantar flexion on an isokinetic dynamometer and passive stiffness of gastrocnemii muscles and Achilles tendon were determined using ultrasound probe strapped to the skin while ankle joint was passively moved. After eccentric training, ankle joint stiffness at low levels of torque significantly increased ($p < 0.01$). This increase was attributed to the 22% increase ($p < 0.05$) in passive Achilles tendon stiffness seen after eccentric training. The difference in joint stiffness increase and tendon stiffness increase was likely due to the 5% decrease ($p < 0.05$) in muscle stiffness seen in the gastrocnemius. Researchers concluded that specific changes in muscle and tendon involved in plantar flexion are mainly due to changes in intrinsic mechanical properties of muscle and tendon tissues.

Eccentric strength training causes adaptations to muscle architecture, with specific increases to fascicle lengths and muscle thickness. Although limited work has been done on hamstrings, there is data to support similar increases to hamstring muscle architecture as a result of eccentric training. Along with architectural adaptations, eccentric training has shown stiffness adaptations in the muscle-tendon complex. Together, these muscular adaptations to eccentric strength training may help to improve muscle function.

Strength Adaptations to Eccentric Strength Training

Eccentric exercise induces muscle damage that triggers regeneration of more sarcomeres that allow the muscle fibers to lengthen and hamstrings to stretch further, sequentially, increasing the angle of maximum torque production and total muscle force output (Lieber & Bodine-Fowler, 1993; Brughelli & Cronin, 2007). Brockett et al (2001) provided evidence for this training effect in human hamstring muscles. Twelve untrained subjects, male and female, performed NH training for two weeks. Hamstring angle-torque curves were constructed as subjects performed maximum voluntary knee extension and flexion movements on an isokinetic dynamometer. Muscle soreness ratings and leg girth measurements were also taken from each subject. Results of the study revealed a significant shift in the optimum angle for knee flexor torque generation to longer muscle lengths immediately post exercise ($7.7° \pm 2.1°$, $p < 0.01$), suggestive of an increase in sarcomeres within the muscle fibers. Post-measurements showed an increase in leg girth and reports of muscle soreness, suggesting exercise-induced muscle damage.

Blazevich et al (2007) showed a similar shift in optimum torque angle in the vastus lateralis while examining the influence of contraction mode on muscle architectural change. Subjects performed slow-speed concentric or eccentric isokinetic knee extensor training for ten weeks. After training, both groups were able to produce greater torque at longer muscle lengths ($p < 0.05$), with peak eccentric torques exceeding concentric torques at larger knee angles. Alegre et al (2006) assessed changes in isometric and dynamic strength of the vastus lateralis. Sixteen male physical education students performed concentric resistance exercises for 13 weeks. The training group significant increased one-repetition maximum (8.2%, $p < 0.05$), rate of force development (23.8%, $p < 0.05$), and average force production (11.7%, $p < 0.05$).

Although the quadriceps respond well to strength training, increased hamstring torque after eccentric training may decrease the opposing torque output of the quadriceps. Clark et al (2005) examined isokinetic peak torques and positions of peak torque were assessed for both the quadriceps and hamstrings after four weeks of NH strength training. Results indicated a significant 11.3% reduction in quadriceps peak torque ($p = 0.01$) and analysis of the position of hamstring peak torque data indicated a significant 19.4% increase in knee flexion angle towards full extension ($p = 0.01$). This decrease in quadriceps peak torque may be a result of more co-contraction by the hamstrings.

Mjølsnes et al (2004) compared the effects of a 10-week training program with traditional hamstring curl (HC) and Nordic hamstrings (NH) on muscle strength among soccer players. Norwegian male competitive soccer players ($n = 11$) completed 10 weeks of a NH training program. Results indicated that there was an 11% increase in eccentric hamstring torque ($p = 0.001$), as well as a 7% increase in isometric hamstring strength in the NH group ($p < 0.05$), compared to the non-significant changes in the HC group. Naclerio et al (2013) found more specific strength increases when the training group performed NH exercises, as well as forward lunges on a balance trainer, and eccentric single leg dead lifts for 4 weeks. Results of the lower body injury prevention program only showed a significant torque increase at 80º knee flexion (15%, $p = .001$). The use of quadriceps eccentric contractions during lunging could be one explanation for these opposite changes in the knee flexor-torque relationship, as well as that the eccentric training was done before predominantly concentric regular season training.

Eccentric hamstring training induces muscle damage that triggers regeneration of more sarcomeres that allow the muscle fibers to lengthen and hamstrings to stretch further, sequentially, shifting the angle of maximum torque production and increasing total muscle torque. Compared to concentric work, this response to eccentric training may enable better co-contraction of the quadriceps and hamstrings, increasing overall muscle strength. Strength adaptations to eccentric hamstring training are desirable outcomes for athletes; however, the lack of research relating these strength parameters to dynamic performance or injury risk leaves the relationships between them unclear.

Dynamic Performance Adaptations to Eccentric Strength Training

The muscular adaptations of architecture, stiffness, and strength in response to eccentric training appear to translate to functional adaptations in whole-body, or dynamic, performance. Recently, increases in vertical jump height have been shown as a performance benefit of eccentric hamstring training. Elmer et al (2012) evaluated changes in leg spring stiffness following eccentric and concentric cycling training for seven weeks. Vertical ground reaction force data were used to calculate the vertical spring stiffness of the whole body during hopping and maximum jump power. Results indicated significant increases in leg spring stiffness (10%, $p = 0.05$) in the eccentric training group, while the concentric group remained unchanged. There was also an increase in maximum jump power (7%, $p = 0.05$) in the eccentric training group, compared to a non-significant change to the concentric group. Increased leg spring stiffness and maximum jump power was suggested to have been due to adaptations in muscle architecture and/or neural adaptations of stretch reflex mechanisms. Researchers concluded that eccentric cycling is an effective method for improving leg spring stiffness and maximum power during multi-joint tasks that include stretch-shortening cycles, such as jumping.

Clark et al (2005) examined the effects of NH strength training on strength measures and vertical jumping performance in amateur athletes. Results indicated a significant increase in vertical jump (6.6%, $p < 0.05$) after four weeks of NH training. Tansel et al (2008) conducted a similar NH training study with youth athletes over five weeks. The NH group demonstrated a significant increase in eccentric hamstring strength (12.6%, $p < 0.05$) and vertical jumping ability (10.3%, $p < 0.01$), whereas the performance of the control group remained unchanged. Anastasi et al (2011) showed a 15% increase in vertical jump height ($p < 0.05$) in professional athletes after ten weeks of NH training, compared to the non-significant vertical jump height change in the control group. Researchers speculated that change in hamstring position of peak torque, the shift to a more extended knee angle, most likely contributed to the increase in vertical jump height due to increased knee joint stability. This allowed for a more efficient transfer of force through the joint during the final takeoff phase of jumping. Thus, it was concluded that a NH strength training program is effective in increasing dynamic performance, specifically, vertical jump height.

The muscular adaptations of architecture, stiffness, and strength in response to eccentric training appear to translate to functional adaptations in dynamic performance. Recent studies have shown increased vertical jump height as a performance benefit of eccentric hamstring training. Yet, again, the lack of research relating the change in dynamic performance or injury risk to the mechanisms of these improvements leaves the relationships between them unclear.

Summary

The high prevalence, coupled with reduced performance and detrimental financial effects of hamstring injuries in numerous sports, stress the necessity to find and implement an intervention capable of minimizing hamstring injuries for athletes. Nordic Hamstring eccentric strength training overall has shown itself to be an effective method of preventing hamstring injury. Eccentric strength training has also been shown to alter hamstring muscle architecture, increase strength by shifting peak torque angles to longer lengths, and improve dynamic performance of vertical jump height. However, no study in the literature has examined all four of these variables together. Comprehensively evaluating muscle-tendon complex adaptations from eccentric Nordic Hamstring training could potentially elucidate the mechanism of how the muscle-tendon complex influences clinically meaningful improvements in performance of strength and vertical jump height. By using an exercise that has been shown to reduce initial and recurrent hamstring strains, comprehensively evaluating the architectural and biomechanical adaptations of hamstring muscles to the Nordic Hamstring exercise could lead to better and more efficient methods of developing injury-resistant tissues. The purpose of this study was to examine the adaptations that occur to the hamstring muscles as a result of the Nordic Hamstring eccentric strength training program. We hypothesized that Nordic Hamstring eccentric strength training would cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance.

Chapter III. Methods

Design

This study aimed to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance. We hypothesized that the Nordic Hamstring eccentric strength training would cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance. A prospective controlled design was employed.

Subjects

Participants in this study were 17 college-aged individuals between the ages of 18 and 25. Previous level of physical activity was documented and examined. Only subjects who were categorized as being recreationally active, had experience with traditional resistance training, and could perform the NH exercise effectively were allowed to participate. Also, only subjects with a BMI below 30 were enrolled. BMI was used in the inclusion criteria to ensure that ultrasound and muscle activation measurements were not affected by excess adipose tissue. Subjects had no known history of hamstring injuries. All subjects were provided and required to sign a consent form, approved by the IRB, prior to participation in this study.

Measurement Reliability

Adaptations to hamstring muscle architecture and stiffness in this study were assessed with ultrasound imaging and elastography. Ultrasound imaging has been used for measuring muscle properties in-vivo, and increasingly, to determine muscle behavior under resting and contracting conditions (Magnusson et al, 2008). Systematic reviews have shown that ultrasound is a valid and reliable method to measure skeletal muscle architecture (ICC > 0.7 and $r > 0.5$; Kwah et al, 2013). Comparing ultrasound to direct cadavers measurements of the hamstring muscle, Chleboun et al (2001) and Kellis et al (2009) found no significant difference between ultrasound and dissection measurements of fascicle length and pennation angle ($p < 0.05$), with intra-rater and comparative ICCs of 0.87 and 0.77, respectively.

Additionally, ultrasound elastography has been validated as a real-time, direct method of measuring in-vivo skeletal muscle stiffness. Assessing the elasticity of the upper trapezius, Leong et al (2013) found high intra-rater (ICC = 0.87–0.97) and inter-rater (ICC = 0.78–0.83) reliability with the arm at rest and 30° abduction. Comparing elastograms of medial gastrocnemius muscle and tissue-mimicking materials, Chino et al (2012) found a high correlation between measurements (ICC ≥ 0.77). In addition, elastography was highly correlated to a mechanical method of stiffness measurement on tissue-mimicking materials ($r = 0.996$).
To determine reliability for this study, muscle stiffness was assessed by shear modulus of the biceps femoris long head and semitendinosus from 12 recreationally active participants (4 male, 8 female, 19.58yrs± 0.67, 1.68m±0.06, 66.3kg±7.96) using ultrasound elastography. ICCs (0.89, 0.78) and SEMs (5.78%, 9.61%) for the biceps femoris long head and semitendinosus, respectively, supported the reliability and precision of shear modulus measurements.

Procedure

The intervention training and data collection for this study were in the Biomechanics Lab, Ward Sports Medicine. Subjects reported for baseline testing, 6 consecutive weeks of training, and post-training assessment.

Baseline Assessments

Muscle Architecture & Stiffness

After completing the informed consent process, subjects had anthropometric characteristics of height and weight assessed using a standard scale and/or tape measure as appropriate. Following anthropometric assessment, subjects laid prone (hip flexion at 0°, knee flexion at 0°, and ankle in relaxed position) on a standard treatment table. Panoramic ultrasound images of the long head of the biceps femoris and semitendinosus were obtained using an ultrasound unit (SuperSonic Imagine, Aixplorer, Bothell, WA). Aquasonic Ultrasound Gel (Parker Laboratories, Aquasonic 100, Fairfield, NJ) was used in conjunction with the ultrasound probe as a lubricant and image enhancer.

The biceps femoris long head and semitendinosus muscle of the right hamstring were imaged from their distal musculotendinous junction to their proximal musculotendinous junction, where all hamstring muscles form one common tendon just inferior to the gluteal fold; these locations were verified via ultrasound image. Once these boundaries of the biceps femoris long head and semitendinosus muscle were identified, eleven equidistant points along the length of each muscle were marked on the skin for cross-sectional and panoramic images of entire muscle lengths, encapsulating the proximal and distal fascicles to be taken and recorded. In addition, shear modulus of the biceps femoris long head and semitendinosus muscle were measured using ultrasound elastography, which measures wave propagation along the fascicles of the muscle to obtain stiffness values. From each muscle belly, the average mean and standard deviation from the central region of interest of two elastograms were recorded. This provided a measure of passive muscle property stiffness.

Dynamic Performance

Vertical jump height was then assessed using a Vertec Device (Gill Athletics, Champaign, IL). Subjects performed 2 vertical jump protocols: a maximum jump with and without a countermovement. For each protocol, subjects were allowed to practice 2 jumps before maximal performance. Three maximal jumps for each jump style were recorded.

Passive Knee Flexor Torque & Muscle Strength

All muscle contractions were performed on a HUMAC NORM Dynamometer (CSMI, model 502140, Stoughton, MA). A Myopac unit (RUN Technologies, model MPRD-101 Receiver/Decoder Unit, Mission Viejo, CA) was run through a computer and utilized to monitor muscle activation.

Subjects' hips were flexed to 90°. The lateral epicondyle of the knee was lined up with the axis of rotation of the dynamometer arm. Then the right lower leg was secured to the dynamometer arm and chair. The leg was not weighed for gravity correction purposes before any protocol, as to not confound the passive and active components of muscle contraction. The weight of the dynamometer arm, lower limb length, and dynamometer arm length were measured and recorded to correct for gravity off-line. Subjects went through three protocols: 4 consecutive passive knee extensions at 5º per second to measure the passive knee flexor torque (primarily using the hamstring muscles), 3 repetitions of maximal isokinetic knee extension-flexion contractions at 60° per second to identify peak torque angle and peak torque, and 3 repetitions of maximum isometric contractions with the knee flexed at 45°. All maximal isokinetic and isometric contractions began with a familiarization trial at 50% of the subject's expected maximum effort, with a 1 minute rest in between each trail.

Intervention and Control Training Sessions

Intervention sessions began on a separate day after baseline measurements. Subjects were randomly assigned into two groups: intervention or control. The control group warmed up on a stationary cycle ergometer and performed static stretching for 6 consecutive weeks. The intervention group warmed up and performed static stretching in addition to 6 consecutive weeks of Nordic Hamstring training.

The Nordic Hamstring training corresponded to the injury-prevention protocol of Petersen et al (2011), with a progressive eccentric hamstring overload over the course of 6 weeks (Table 1). Nordic Hamstring training sessions began with a warm up for 5 minutes on a cycle ergometer at a brisk pace, then three sets of static stretches. Following a 5 minute break, subjects completed the prescribed Nordic Hamstring exercise (Fig. 1) according to the training schedule. After all sets were completed, subjects closed the session with the same three sets of static stretches (Table 2). To facilitate compliance with the strength training protocol, participants in intervention group were also counseled that the exercise would likely produce some muscle soreness after each session similar to soreness experienced following an intense resistance training workout in a gym. Prior to each

Table 1: Nordic Hamstring

Week #	Sessions/week	Sets X repetitions
1	1	2 X 5
2	2	2 X 6
3	3	3 X 6-8
4	3	3 X 8-10
5	3	3 X 12-10-8
6	3	3 X 12-10-8

Figure 1: Nordic Hamstring curl

week of training, subjects filled out the Hamstring Function Survey (adapted from Oslo Sports Trauma Research Center, Oslo, Norway) in order to maintain a record of muscle soreness, pain, and any impediments to functions of daily living throughout the intervention.

The control group sessions began with a warm up for 5 minutes on a cycle ergometer at a brisk pace, then three sets of static stretches. Following a 5 minute break, subjects closed the session with the same three sets of static stretches (Table 2). The control group followed the same schedule of sessions as the training group. With the exception of the actual strength training performed by participants in the intervention group, both groups were matched in terms of training frequency and volume over the 6 weeks. Thus, any differences occurring between the two groups over the course of the training period would be attributable to the strength training protocol.

Table 2: Training session components

Control Group	5min. warm-up on stationary bike, 5min. static stretching, **5min. break**, 5min static stretching
Strength Group	5min. warm-up on stationary bike, 5min. static stretching, **Strengthening**, 5min static stretching

Compliance

In order for a subject to be included in the final analysis, a subject must not have missed any training sessions in weeks 1 and 2, no more than 1 session in weeks 3-6, and no more than 3 sessions total; a compliance of 80%, similar to Petersen et al (2011). These criteria were applied to both the intervention and control subjects.

Post-Training Assessments

Post-training assessments was conducted on a separate day after the conclusion of training and was performed identically to baseline assessments. After completion of these assessments, the data collection protocol for the participant was completed and he/she was thanked for his/her time.

Data Reduction

Analysis of architectural ultrasound images took place on OsiriX DICOM Viewer software (Pixmeo, Bernex, Switzerland). Fascicle length, pennation angle, and physiological cross-sectional area (PCSA) was assessed for the biceps femoris and semitendinosus (Fig. 2, 3). The average of three fascicle lengths (distal, middle, proximal) and three pennation angles (distal, middle, proximal) were recorded for analysis. Muscle volume was calculated by averaging two cross-sectional images at each equidistant point on the muscle, then integrating the areas under the cross sectional area vs. muscle curve. Using these architectural measurements, we computed physiological cross sectional area, defined as the muscle volume

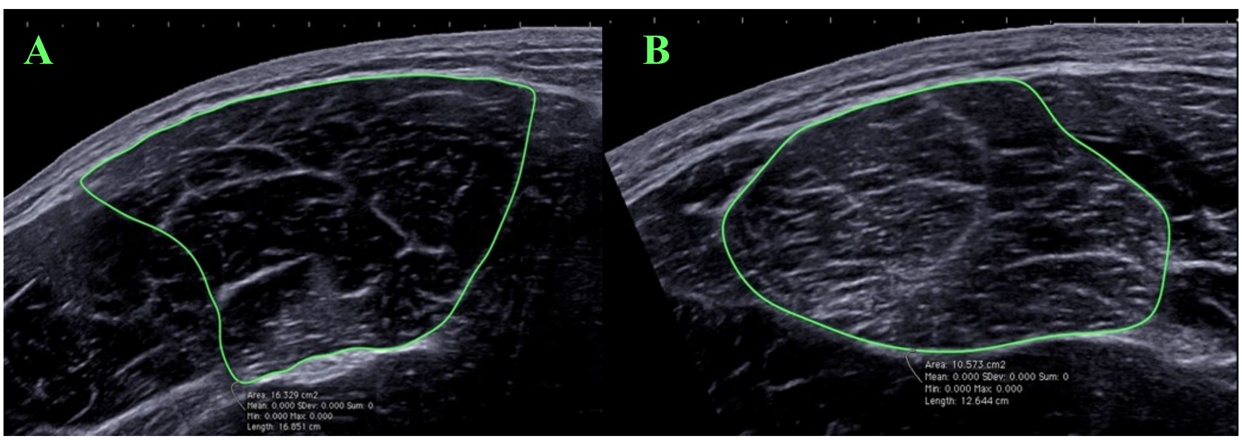

Figure 2: Cross-section area of biceps femoris (A) and semitendinosus (B)

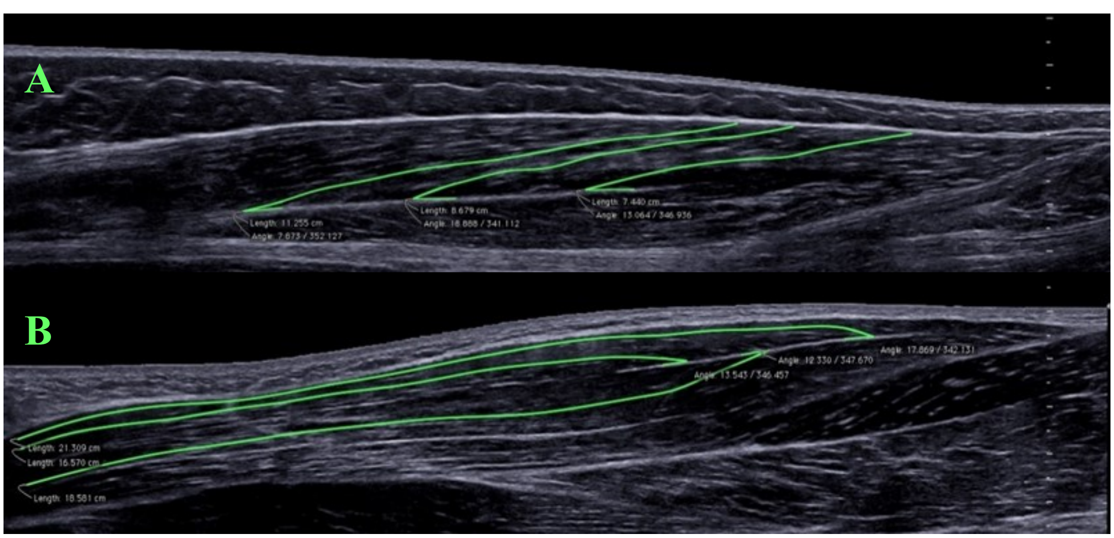

Figure 3: Fascicle lengths and pennation angles of biceps femoris (A) and semitendinosus (B)

divided by the fascicle length corrected for pennation angle. In addition, the fascicle length to muscle length ratio was also computed. Muscle stiffness was analyzed using a Supersonic Ultrasound unit (SuperSonic Imagine, Aixplorer, Bothell, WA) to measure shear modulus. From each muscle, the average mean and standard deviation from the central region of interest of two elastograms was recorded (Fig. 4).

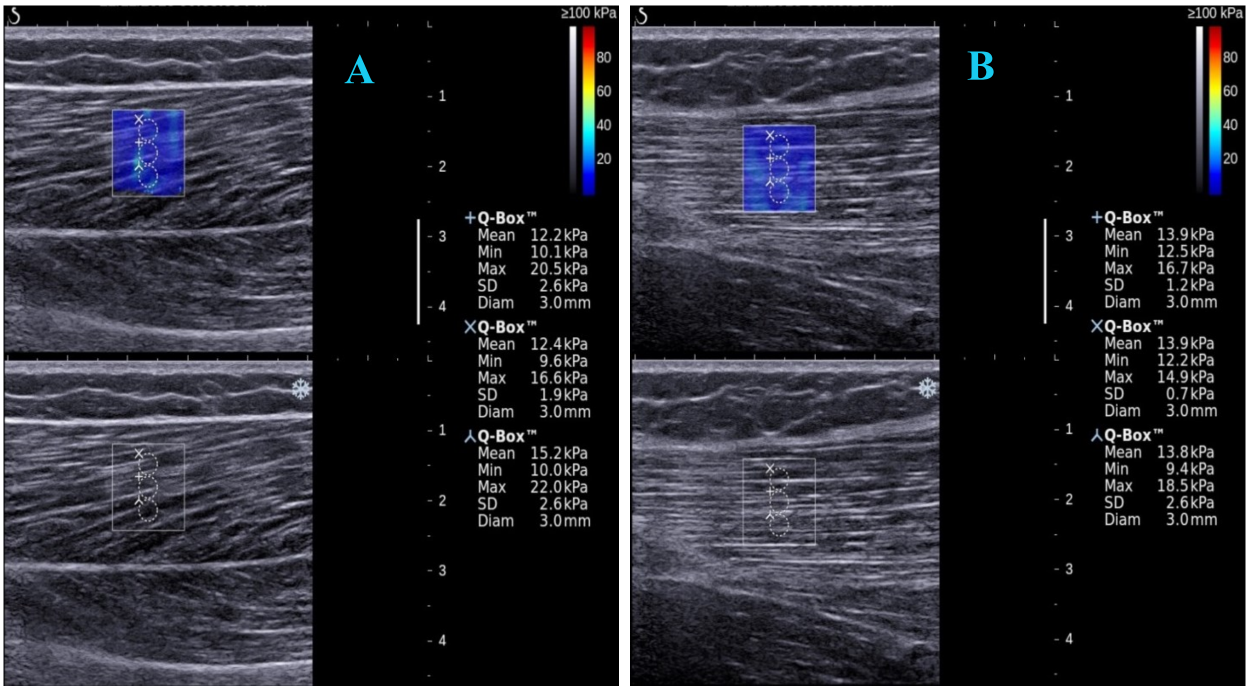

Figure 4: Regions of interest of biceps femoris (A) and semitendinosus (B) elastograms

Peak torque and knee angle at peak torque for the hamstring and quadriceps during the concentric/concentric isokinetic torque curves at $60°s^{-1}$ was recorded. Passive torque across the full knee angle range was plotted over the course of 4 consecutive flexion-extension trials. Peak passive torque was calculated as the average passive torque in the last 5º of terminal extension (0-5º). Peak torque from the isometric conditions was also determined. All strength data was normalized to body mass for analysis.

Data Analysis

We tested the hypothesis that an eccentric strength training program would cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance. From this mixed-model designed study, within (pre & post intervention) and between (control vs intervention) groups two-way repeated measures ANOVAs were performed from data collected before and after the 6-week intervention period on these dependent variables. Statistical significance was set at $p < 0.05$.

Chapter IV. Results

The purpose of this study was to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance. We hypothesized that Nordic Hamstring eccentric strength training would cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance. This chapter is divided into the following sections: 1) Subject Characteristics, 2) Muscle Architecture & Stiffness, 3) Passive Knee Flexor Torque & Muscle Strength, 4) Dynamic Performance, and 5) Summary.

Subject Characteristics

Descriptive statistics for the sample are presented in Table 3. Participants were 18.9±1.2 years old, with an average body-mass index (BMI) of 24.1±3.9kg/m^2. All participants self-reported as being recreationally active recreationally active (5+ hours of physical activity per week), experienced with traditional resistance training (2+ hours per week), and had no known history of hamstring injuries. No difference in height, mass, or BMI was observed between the NH training and control group before the intervention. With the exception of age and male-to-female ratio, the random assignment procedure produced groups that were fairly equal in terms of general anthropometrics.

Table 3: Descriptive statistics for the NH training and control group

	Male/Female Ratio	Age	Height (m)	Mass (kg)	BMI
NH Training	4/6	18.3 ± 0.48	1.7 ± 0.15	71.3 ± 15.86	25.5 ± 3.94
Control	1/6	19.7 ± 1.38	1.7 ± 0.16	63.5 ± 14.71	23.5 ± 3.15

Compliance

To be included in data analysis, subjects must have complied with the intervention protocol. Compliance for the intervention was established as not missing any training sessions in weeks 1 and 2, no more than 1 session in weeks 3-6, and no more than 3 sessions total. The NH group had 100% compliance with the training schedule, with no participants missing any training days. The control group had 100% compliance with the training schedule, with 2 participants missing 1 day of week 4 and 5, respectively.

Muscle Architecture & Stiffness

Biceps Femoris

Biceps femoris muscle architecture and stiffness measurements of the sample are presented in Table 4. After the 6-week intervention, muscle fascicle pennation angle significantly increased from 12.4° to 14.2° (main effect, $p<.05$, Fig. 5A). Muscle volume increased by 11% in the NH training group but not in the control group compared to their respective baseline measurements (group by time interaction, $p<.001$, Fig. 5B). There was also a significant interaction for physiological cross-sectional area (PCSA) which significantly increased in the NH training group by 12%, with no change in the control group (group by time interaction, $p<.05$, Fig. 5C). There were no group or time main effects or interactions for fascicle length ($p>.05$, Fig. 6A). Muscle stiffness, as measured by shear modulus, showed no significant change from baseline measurements in either group (Fig. 6B). However, the NH training group's mean stiffness (12.9kPa) was significantly lower than the control group's mean stiffness (16.6kPa) regardless of time point assessed (main effect for group, $p<.001$, Table 4).

Table 4: Architectural and stiffness measurements of the biceps femoris muscle

	NH Training				Control			
	Baseline		Post		Baseline		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Fascicle Length (cm)	8.96	1.23	9.07	1.73	8.17	0.82	8.11	1.09
Pennation Angle (°)	13.59	3.23	14.86*	2.69	12.07	3.15	12.69*	3.04
Volume (cm^3)	131.46	43.31	145.20*	46.42	124.34	30.37	120.36	25.90
PCSA (cm^2)	15.59	6.21	17.40*	7.01	15.72	4.28	15.45	3.97
Stiffness (kPa)	13.13†	2.29	12.61	3.18	15.39	3.81	17.84	2.49

**indicates significant change from baseline (p<0.05), †indicates significant difference from control group (p<0.05)*

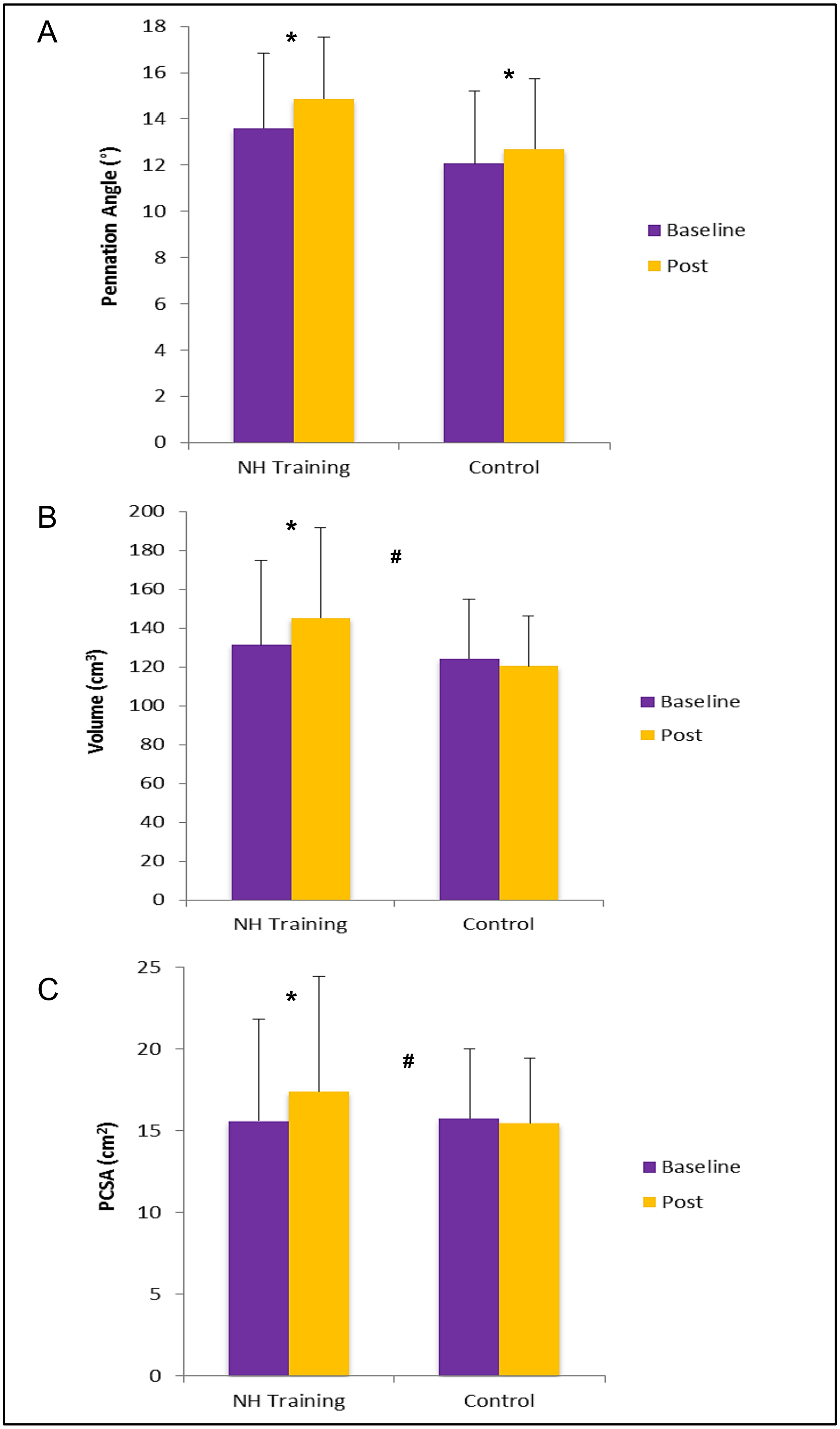

Figure 5: Biceps femoris muscle pennation angle (A), volume (B), and physiological cross-sectional area (PCSA) (C) before and after intervention. (*p<0.05; #significant interaction effect)

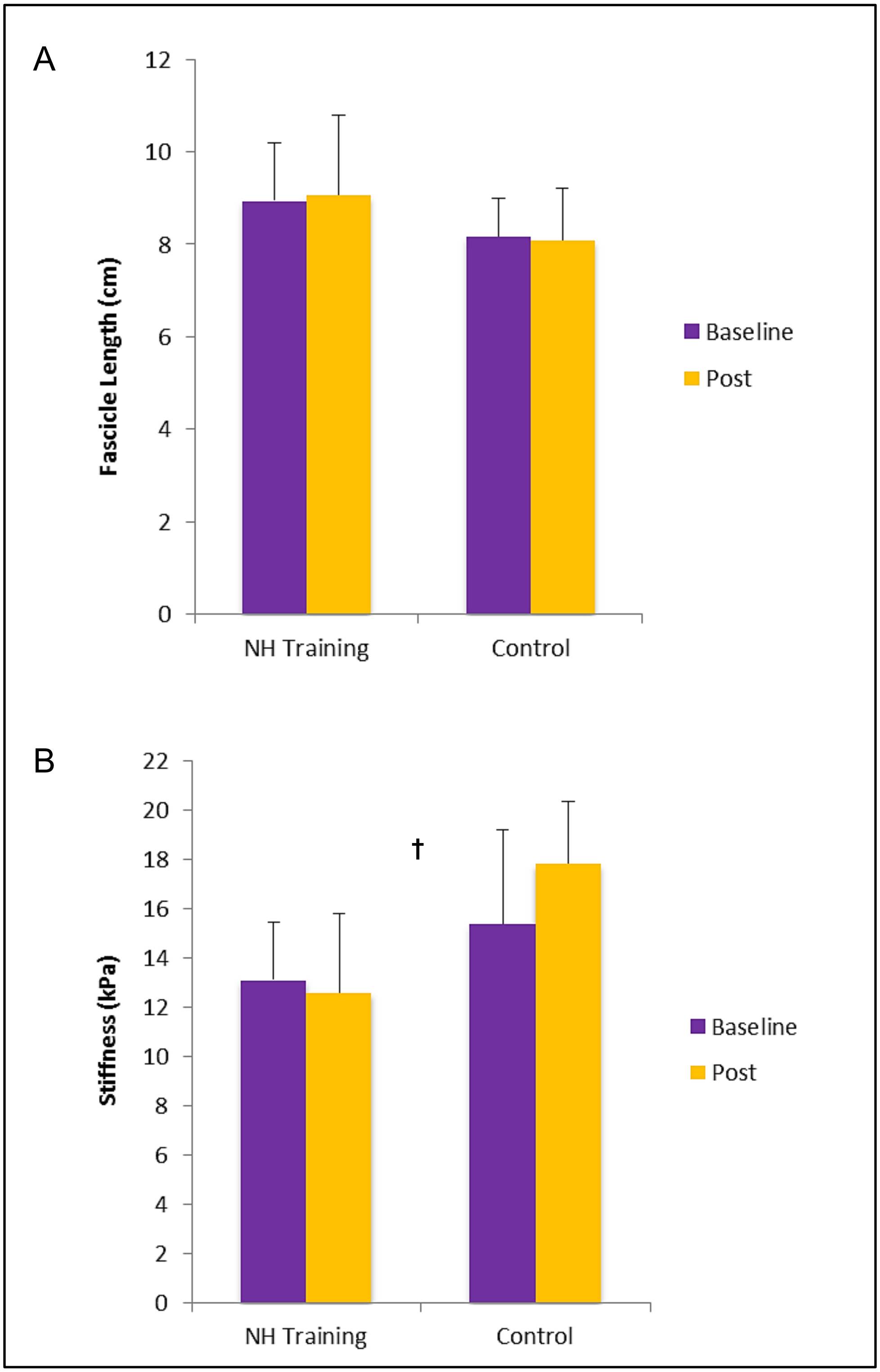

Figure 6: Biceps femoris muscle fascicle length (A) and stiffness (B) before and after intervention. (†significant difference from control group)

Semitendinosus

Semitendinosus muscle architecture and stiffness measurements of the sample are presented in Table 5. Muscle fascicle pennation angle showed no significant change in the NH training or control group after the intervention (Fig. 7A). However, the NH training group's mean pennation angle (12.0°) was significantly higher than the control group's mean pennation angle (9.8°) regardless of time point assessed (main effect for group, $p<.01$). Muscle volume significantly increased in the NH training group after the intervention by 20% while no changes occurred in the control group (group by time interaction, $p<.05$, Fig. 7B). Muscle fascicle length and PCSA showed no significant change in either group after the intervention nor were there any group main effects ($p>.05$, Fig. 7C, 8A). Muscle stiffness, as measured by shear modulus, did not change as a result of the intervention, nor were there any differences between groups (Fig. 8B).

Table 5: Architectural and stiffness measurements of the semitendinosus muscle

	NH Training				Control			
	Baseline		Post		Baseline		Post	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Fascicle Length (cm)	17.48	2.30	17.46	1.23	18.21	1.82	17.74	1.45
Pennation Angle (°)	11.88†	1.11	12.11	2.55	9.32	0.91	10.20	2.07
Volume (cm^3)	134.81	35.14	161.71*	49.64	123.31	35.39	117.24	23.12
PCSA (cm^2)	7.92	1.93	9.46	2.74	6.90	1.96	6.80	1.63
Stiffness (kPa)	17.52	4.89	17.71	4.59	18.03	4.91	19.56	6.27

**indicates significant change from baseline (p<0.05), †indicates significant difference from control group (p<0.05)*

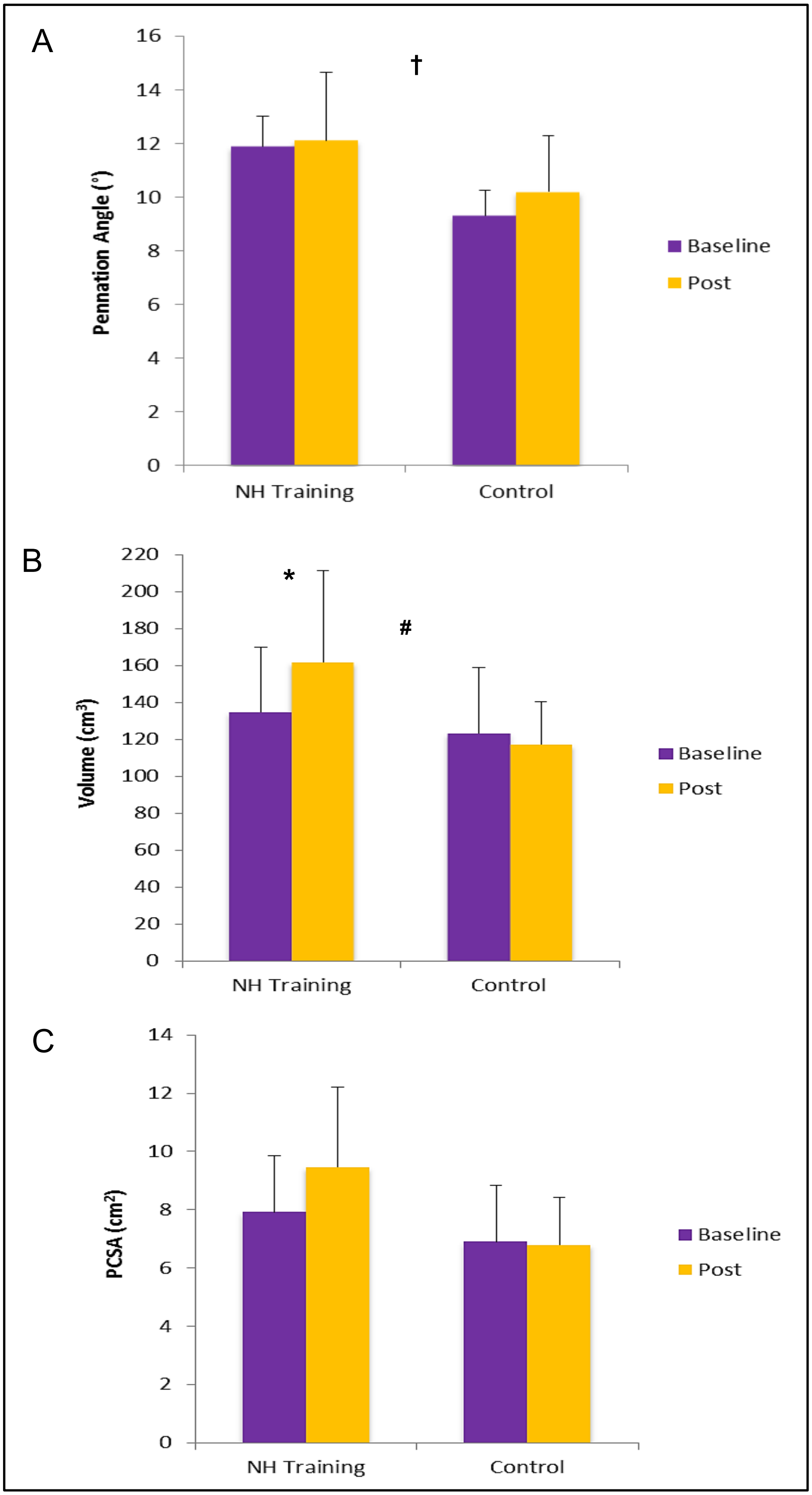

Figure 7: Semitendinosus muscle pennation angle (A), volume (B), and physiological cross-sectional area (PCSA) (C) before and after intervention. (*p<0.05; #significant interaction effect, †significant difference from control group)

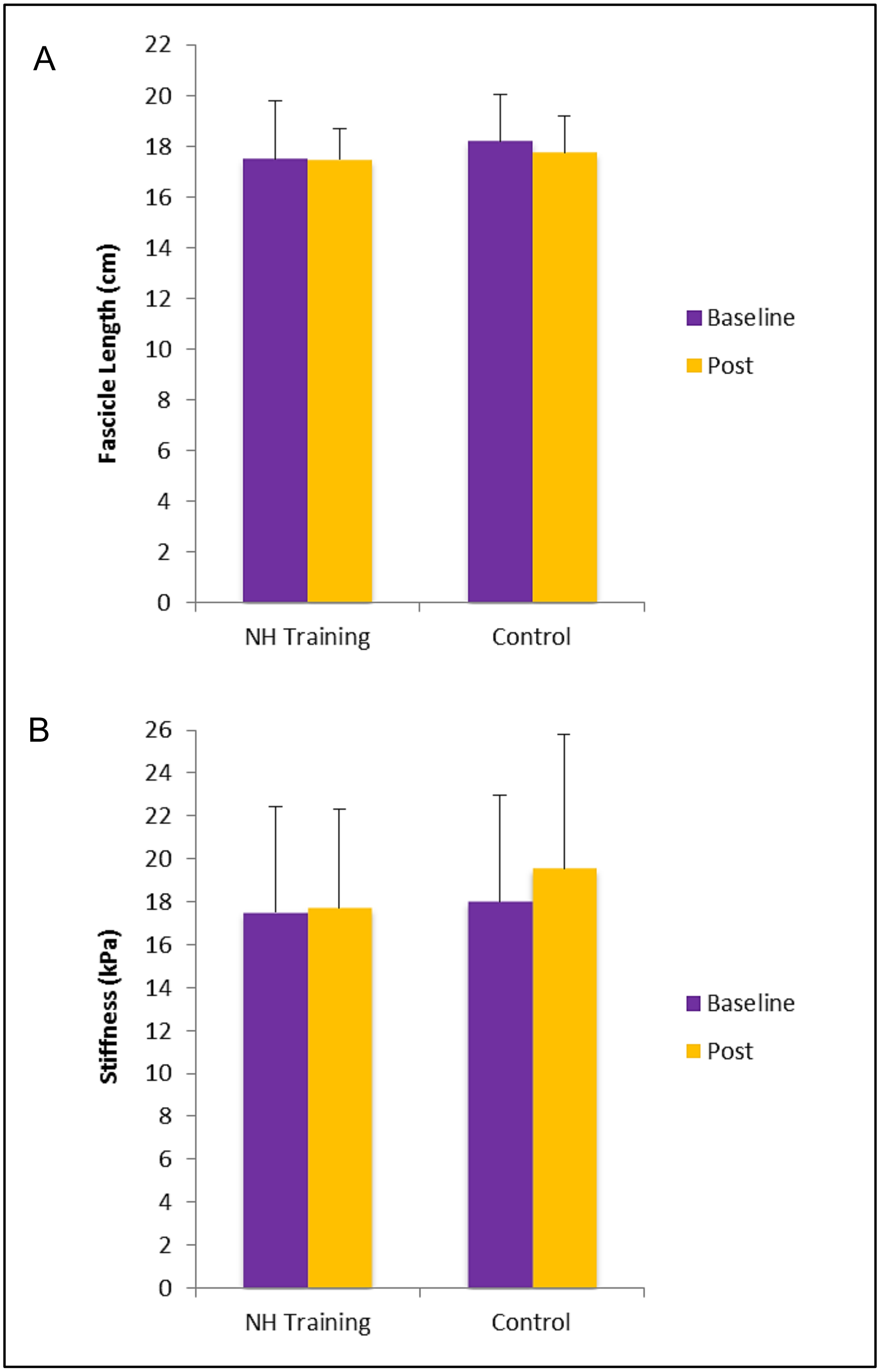

Figure 8: Semitendinosus muscle fascicle length (A) and stiffness (B) before and after intervention.

Passive Knee Flexor Torque & Muscle Strength

After the 6-week intervention, no significant changes in peak passive knee torque were seen in the NH training or control group ($p>.05$, Fig. 9).

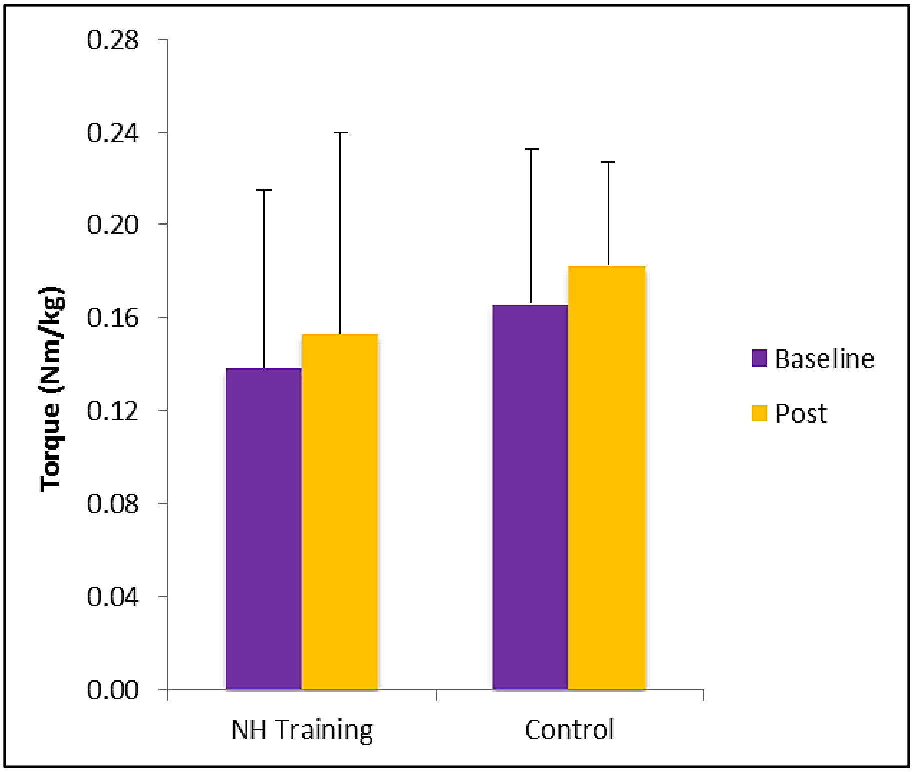

Figure 9: Peak passive knee torque before and after intervention.

Peak concentric hamstring torque increased from 1.03Nm/kg to 1.18Nm/kg after the intervention; a 15% increase regardless of group assessed (main effect for time, $p<.05$) (Fig. 10A). Knee angle at peak hamstring torque showed no significant change in the NH training or control group after the intervention (Fig. 10B). No significant change across time or group was seen in peak concentric quadriceps torque or knee angle at peak quadriceps torque in either group ($p>.05$, Fig. 11).

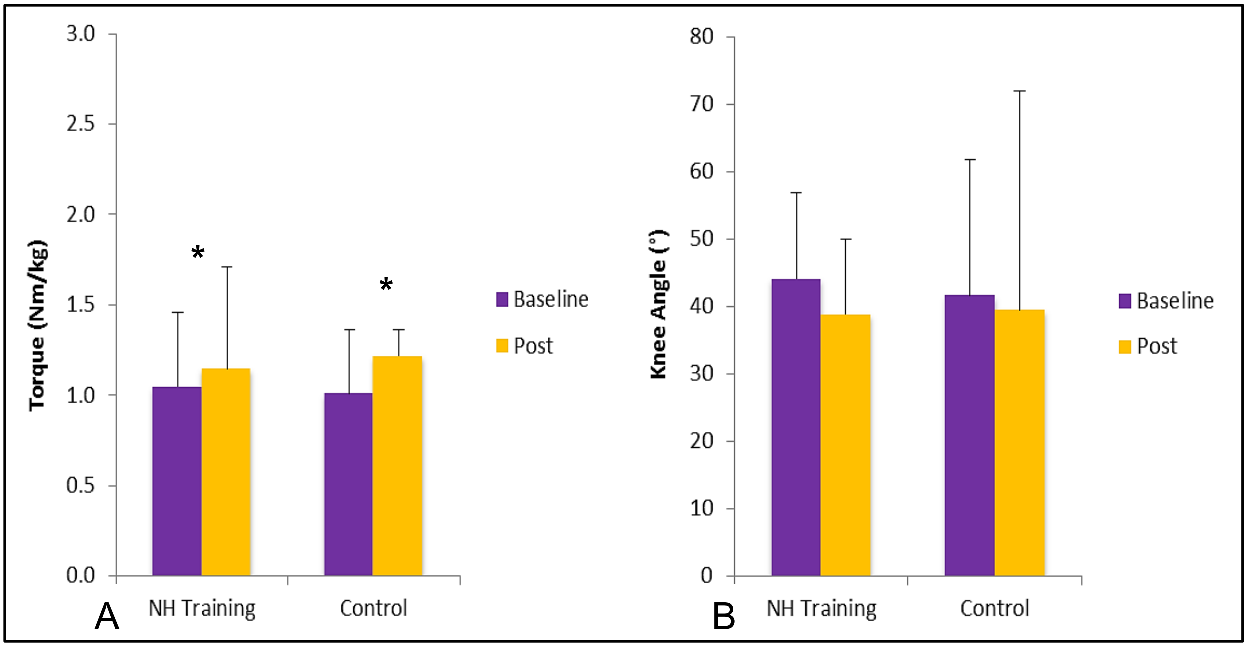

Figure 10: (A) Peak concentric hamstring torque and (B) knee angle at peak torque before and after intervention. (*p<0.05)

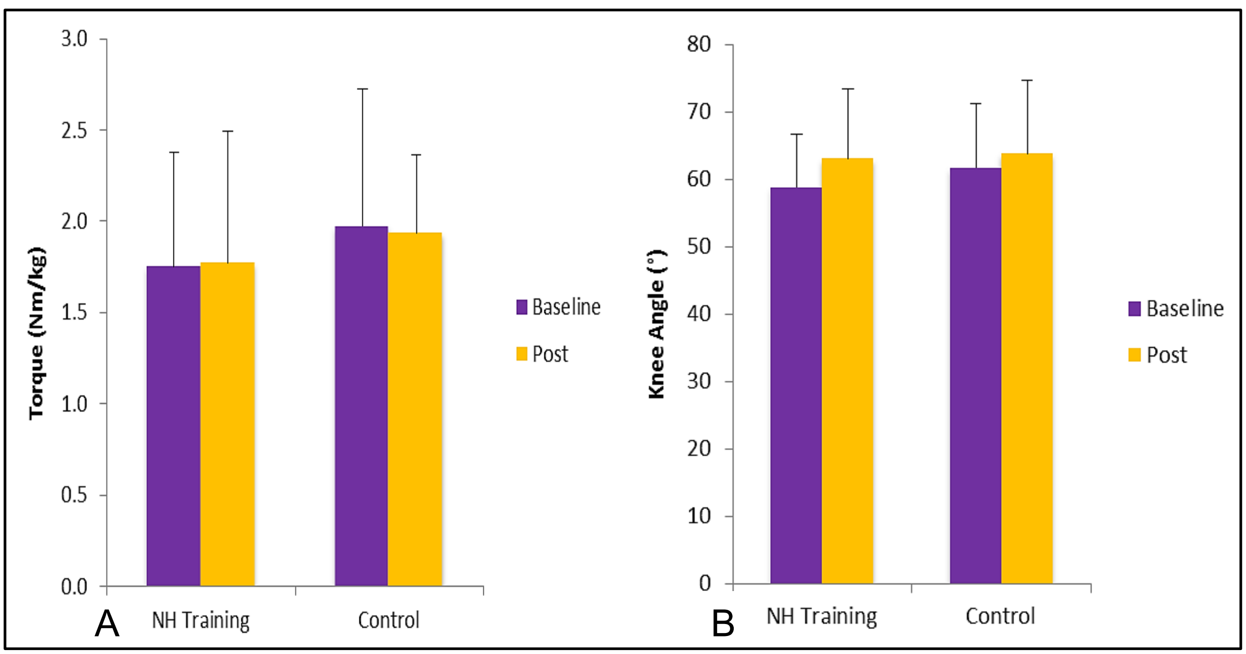

Figure 11: (A) Peak concentric quadriceps torque and (B) knee angle at peak torque before and after intervention.

There were no significant changes seen in peak eccentric hamstring torque or knee angle at peak torque in the NH training or control group after the 6-week intervention ($p > .05$, Fig. 12). Similar to the concentric strength results, there was a main effect for time where the isometric hamstring torque measured at 45° of knee flexion increased from 1.26 Nm/kg to 1.41 Nm/kg, a 12% increase ($p < .05$, Fig. 13A). Peak isometric quadriceps torque was not affected by the intervention nor were there any group differences ($p > .05$, Fig. 13B).

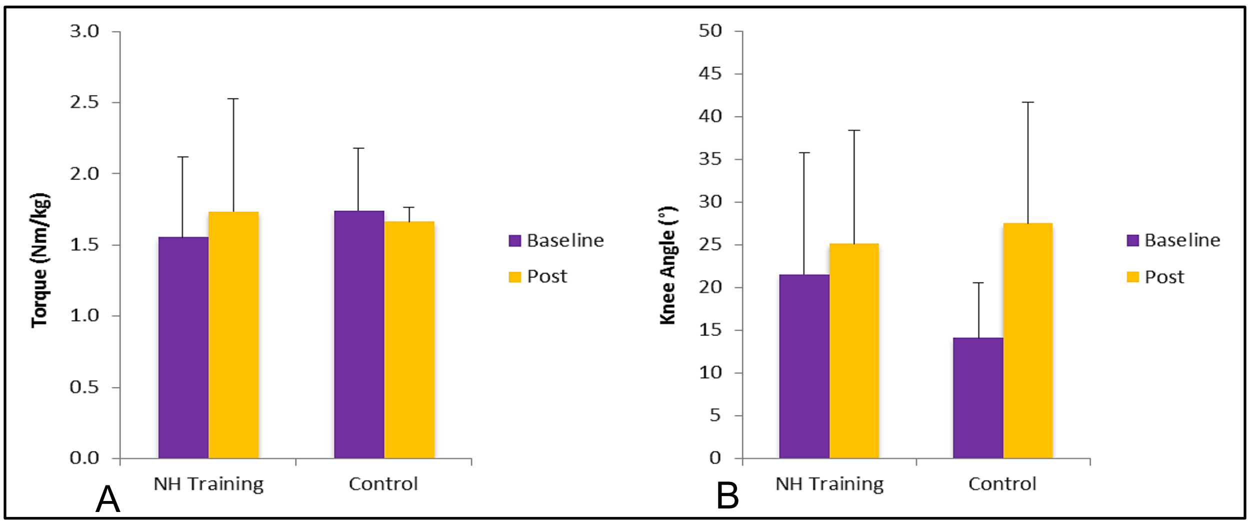

Figure 12: (A) Peak eccentric hamstring torque and (B) knee angle at peak torque before and after intervention.

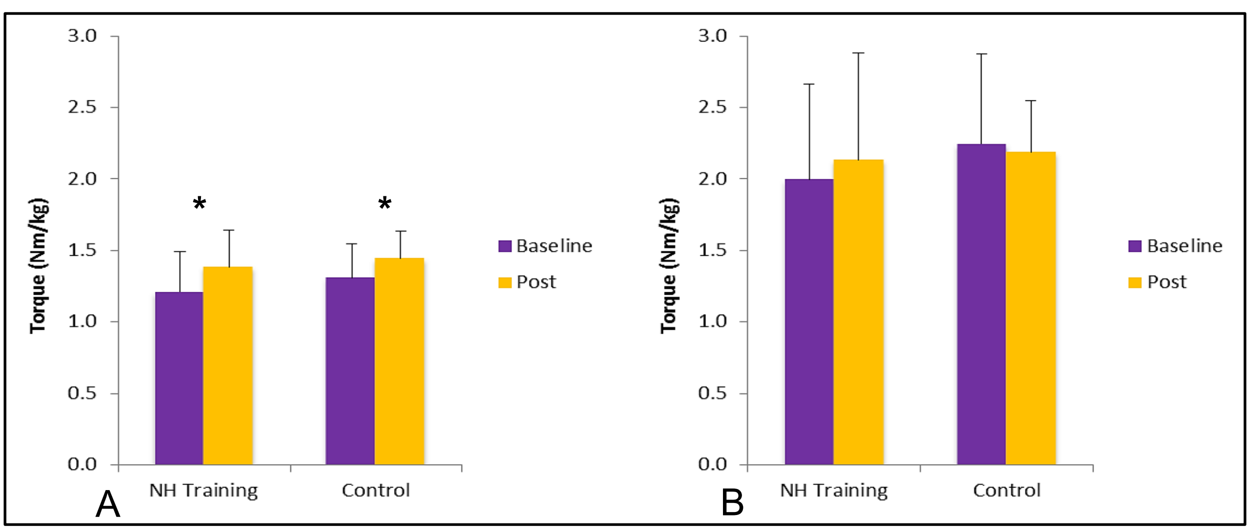

Figure 13: (A) Maximum isometric hamstring and (B) quadriceps torque before and after intervention. (*p<0.05)

Dynamic Performance

After the 6-week intervention, there were no significant changes to vertical jump height, with or without a counter-movement, in the NH training or control group (Fig. 14). There were also no group differences p>.05.

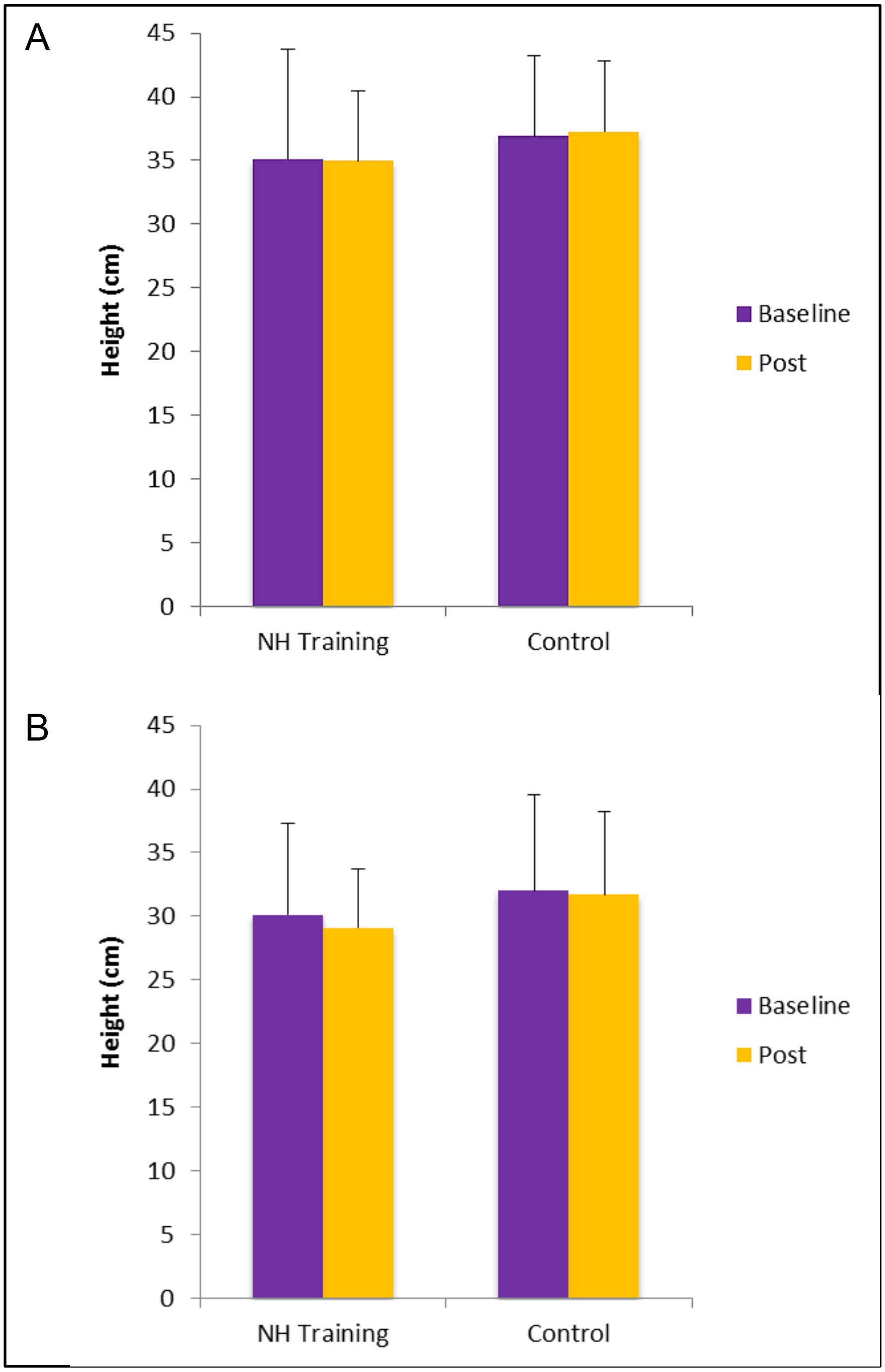

Figure 14: Vertical jump height with (A) and without a counter-movement (B) before and after intervention.

Summary

Overall, the 6-week Nordic Hamstring strength training intervention produced some architectural adaptations in the experimental group that were not present in the control group: volume increased in both hamstring muscles, with concomitant increases in the PCSA for the biceps femoris long head muscle but not the semitendinosus. There were no changes to fascicle length, pennation angle, or stiffness that were unique to the experimental group. The 6-week intervention did not produce any significant group by time interactions for concentric, isometric, eccentric strength measurements or peak passive torque measurements. Vertical jump height was also not affected by the intervention.

Chapter V. Discussion

The purpose of this study was to examine the effects of Nordic Hamstring eccentric strength training on hamstring muscle architecture, stiffness, strength, and dynamic performance. We hypothesized that Nordic Hamstring eccentric strength training would cause adaptations in hamstring muscle architecture, stiffness, strength, and vertical jump height performance. This chapter will discuss the methods and results in comparison to current literature and our hypothesis. This chapter is divided into the following sections: 1) Effects of Eccentric Hamstring Strength Training on Muscle Function, 2) Individualistic Responses to Strength Training, 3) Future Considerations, and 4) Conclusions.

Effects of Eccentric Hamstring Strength Training on Muscle Function

Nordic Hamstring (NH) training has been shown to reduce hamstring strain injury (Arnason et al, 2008; Brooks et al, 2006; Petersen et al, 2011). However, there is limited data in the literature to explain how the hamstring muscle-tendon complex adapts to this training stimulus and develops a more injury-resistant tissue. Therefore, this study attempted to comprehensively evaluate the biomechanical and architectural adaptations of hamstring muscles to the NH exercise through a 6-week eccentric training intervention.

Training Stimulus

The architectural measurements of muscle size, volume and physiological cross-sectional area (PCSA), are strongly associated with muscle strength (Lieber & Bodine-Fowler, 1993). Eccentric training, specifically the NH curl, has been shown to improve hamstring muscle strength, even more so than traditional concentric training exercises (Mjølsnes et al, 2004). While there are no current hamstring studies that have examined muscle volume or PCSA after eccentric training, volume gains in the quadriceps and gastrocnemius muscles have been well documented (Alegre et al, 2006; Baroni et al, 2013; Franchi et al, 2014; Duclay et al, 2009). Blazevich et al's 10-week eccentric quadriceps training intervention reported an 11% and 15% increase in vastus lateralis and vastus medius muscle volume, respectively (2007). The muscle volume increase (11%, 20%) and PCSA increase (12%) seen in the biceps femoris and semitendinosus, respectively, are comparable to eccentric training muscle volume gains in the literature. The eccentric NH curl does seem to be a good stimulus for growth in muscle size, however, other architectural measurements related to muscle strength were not equally affected after this intervention.

Based on previous literature, it was hypothesized that eccentric NH strength training would cause increases to hamstring muscle fascicle length (Alegre et al, 2006; Baroni et al, 2013; Blazevich et al, 2007; Potier et al, 2009). Such results were not found in this study, as no significant increase to fascicle length was seen in the NH training group after the intervention. One explanation for unseen adaptations could be joint positions during training. Research has shown that changes in biceps femoris fascicle length are more sensitive to changes in hip position than changes in knee position when the knee and hip position, respectively, are held constant (Hawkins & Hull, 1990). This difference is most likely related to a larger hamstring moment arm at the hip resulting in greater excursion of the muscle with altered hip angles, compared to the knee (Visser et al, 1990). Previous studies showing increased muscle fascicle lengths after eccentric training have all used dynamometry-based training interventions, with the hip at 90° and resistance through full knee extension (Potier et al, 2009; Blazevich et al, 2007). This study used NH eccentric training, which required the hip to be at 0° and only provided resistance through a partial knee range of motion and biased towards shorter musculotendon lengths; as participants were able to release their muscle contractions at the point they could no longer controllably lower their torso to the ground. Comparatively, subjects in this intervention were training at shorter muscle lengths. Based on the measured biceps femoris muscle lengths of our subjects, this would equate to average training lengths of 25cm during NH curls versus 33cm during eccentric hamstring curls on a dynamometer. Sharifnezhad et al (2014) confirmed this architectural adaptation difference after a 10-week eccentric intervention. Vastus lateralis muscle fascicle lengths increased in the leg that exercised at a longer muscle length (25-100° knee flexion), with no change to the leg exercised at a shorter muscle length (25-65° knee flexion) after training. Thus, the joint positions during the NH curl training may have contributed to the lack of fascicle length change seen after the intervention.

Strength adaptations seen after resistance training are highly dependent on the specificity of training (Morrissey et al, 1995). That is, training exercises must be specific to the type of strength desired. The non-significant strength adaptations observed after this intervention could be due to difference in training exercises (dynamometry versus NH curls), more specially, the resistance or load applied during the exercise and the range of motion tested. Dynamometry-based training interventions provide variable resistance through full knee extension at constant speeds, compared to NH training interventions, which provides increasing resistance from the beginning of the movement as the knee extension extends but also depend on how far the participant can lower themselves to the ground. Increasing load with progression of the movement is what makes the NH curl an overload stimulus.

Opar et al quantified the NH curl stimulus by recording forces, via load cells attached to ankle cuffs, required to stabilize the distal lower leg during the exercise (2013). On average, each lower leg recorded 340N of force. Assuming an average lower leg length of 40cm and the load cells located just proximal to the ankle (~32cm distal to the knee joint), this load would equate to approximately 240Nm, with 120Nm of knee flexor torque for each leg. Normalized to an average body mass of 71.3kg (not reported in the Opar manuscript) the average flexor torque experienced during the NH curl exercise is 3.37Nm/kg. Given the average peak eccentric torque for a single leg for our experimental group at baseline was 110±45Nm, the NH stimulus approaches the maximum eccentric strength (on average) of the hamstring muscles.

Sharifnezhad et al (2014) confirmed training stimulus differences effect on knee extensor strength. Maximum knee joint moment increased significantly more in the leg that exercised at a higher load magnitude (100% of maximum voluntary contraction), compared to the leg exercised at a lower load magnitude (65% of maximum voluntary contraction) after eccentric training. The amount and/or consistency of resistance during our NH training intervention may not have been sufficient for changes in eccentric hamstring strength. In addition to resistance differences, there are notable training and testing mode differences between this study and the literature. Subjects in our study were tested for eccentric on a dynamometer, performed eccentric strength training using NH curls, and then re-tested for eccentric strength on a dynamometer. The consistency of the training and testing modes may play a role in the significant eccentric strength gains seen with dynamometry-based training interventions.

When assessing muscle stiffness adaptations, it is important to understand whether the stiffness measurements are more reflective of the muscle material or structural property changes; as both adaptations can influence the shear modulus of a muscle. Structural properties of muscle can be affected by changes to the size, thickness, or length of a muscle. Material properties of muscle can be affected by changes to the collagen content, collagen linking, or tissue fluid in a muscle. Increases in muscle stiffness due to structural property changes have been shown after increased loading and resistance training (Basford et al, 2002; Fouré et al, 2013; Green et al, 2012). Decreases in muscle stiffness due to material property changes have been shown after stretching interventions (Akagi & Takahashi, 2014). Our study used both increased eccentric loading and passive stretching as part of the intervention protocol. Therefore, the effects of the NH training may have been negated by the addition of a stretching warm-up. Fouré et al's 14-week eccentric plantar flexor training revealed a significant increase in Achilles tendon stiffness and a decrease in gastrocnemius muscle stiffness after the intervention. However, this result is does not make much sense when considering the tissue stiffness of muscle is much lower compared to tendon. As shear modulus and passive resistance are highly related (Koo et al, 2013), lengthening a stiff tissue would not cause as much of a change to passive stiffness as lengthening a less stiff tissue. Lack of literature on low-extremity stiffness adaptations to resistance training leave it unclear whether training more prominently affects properties of muscle material or structural stiffness properties, however, non-significant changes to hamstrings muscle stiffness seen in this study may be a result of the effect of stretching on material properties counteracting the effect of resistance training on structural properties of the muscles.

Length of Intervention

The length of our intervention, 6 weeks, might also explain some of the non-adaptations of muscle architecture and dynamic performance. It is important to note that this was an abbreviated version of a 10-week eccentric NH strength training intervention, previously shown to prevent hamstring injury (Petersen et al, 2011). The current literature provides evidence of muscle fascicle length increases after eccentric training interventions 8-13 weeks in length. Although each study had substantial lengths of time for muscular adaptations to be documented, only Blazevich et al (2007) reported fascicle length measurements during an eccentric training intervention. Researchers were able to show significant increases in vastus lateralis muscle fascicle lengths after only five weeks of eccentric training, however, these rapid changes cannot be assumed to hold true for muscle of different architecture, length, and function; such as the biceps femoris. Again, it is noted that this architectural adaptation occurred after dynamometry training the muscle through a full knee range of motion. Kawakami et al (1995) showed similar results to the current study after a lengthy 16-week eccentric triceps brachii training intervention. Significant increases to muscle volume and PCSA were seen, with no significant changes to muscle fascicle length. Potier et al (2009) have been the only researchers to show hamstring muscle fascicle length change after eccentric training, with an intervention lasting eight weeks. Therefore, it is not implausible that significant increases to hamstring muscle fascicle lengths require a longer training protocol than the six weeks given for this study.

Recently, dynamic performance measurements of vertical jump height have shown improvement after eccentric NH strength training. However, no such vertical jump height increases were seen after our 6-week intervention. Anastasi et al (2011) showed an increase in vertical jump height after a 10-week NH training, compared to the non-significant change in the control group. Results were linked to the change in hamstring position of peak torque seen after NH training, allowed for a more efficient transfer of force during the final takeoff phase of jumping. After only five weeks of NH training, Tansel et al (2008) showed a significant increase to vertical jump height in the training group compared to non-significant changes to the control group. Once again, it was suggested that strength adaptations at longer muscle lengths allowed for enhance jump performance. Clark et al (2005) were able to show a small, but significant increase in vertical jump height after a 4-week NH intervention. However, the lack of a control group leaves some skepticism to the results being a resultant of the eccentric training, and not just the regular season training athletes also underwent.

The hamstrings role in increasing vertical jumping can easily be explained by its contribution to hip extension and knee stabilization while jumping. Along with the gluteal muscles, the hamstrings play a vital role in extending the hip maximally upon the final take-off phase of jumping. Greater hamstring strength could increase acceleration of the hip into extension, thus increasing hip torque, power (Jakobsen et al, 2011), and ultimately, vertical jump height. Additionally, co-activation of the hamstrings helps to stabilize knee joint during final phase of jump, when knee is fully extended before take-off. This knee stabilization may allow for a more efficient transfer of force through the joint (Baratta et al, 1988), resulting in an increased jump performance. The length of an eccentric NH training may be a factor in vertical jump height outcomes due to the initial muscle architecture and strength changes that seem to supersede dynamic performance adaptations.

Study Population

The varying populations used in the literature may have additionally contributed to inconsistencies in muscle strength and dynamic performance adaptations seen in this study. Many of the strength adaptations to eccentric strength training have been seen in the highly/regularly-trained, elite/competitive athletes (Anastasi et al, 2011; Clark et al, 2005; Fouré et al, 2013; Mjølsnes et al, 2014; Naclerio et al, 2013; Potier et al, 2009; Tansel et al, 2008). Well-trained athletes would have more exposure to resistance training, particularly eccentric training, than any other population. Thus, performing eccentric training and strength testing movements more appropriately and readily compared to the recreationally active, non-elite athletes. Less variance in the strength training movements and testing measurements could have attributed to the significant eccentric muscle strength increases seen in previous studies after an eccentric training intervention.

Although some previous studies may have used the same training stimulus (NH curl) and comparable training intervention lengths (4-5 weeks), there were some population differences that may have influenced vertical jump height results. Clark et al (2005) saw increased vertical jump height in competitive youth athletes, who performed regular season training in addition to the NH training intervention. Yet, again, the lack of a control group in this study design casts doubt on whether the increased vertical jump height was truly due to the intervention or other factors. In another youth-athlete study, Tansel et al (2008) showed significant increases in vertical jump height after a 5-week NH training intervention. Authors made no mention of compliance or adequate performance of the NH exercise. Given the age bracket (10 to12-year-olds), and the difficulty of the exercise movement, it is questionable whether training protocols were following effectively by all participants. Regularly-trained, professional female rugby players participated in Anastasi et al's 10-week NH training intervention during their regular season (2011). After training, athletes significantly increased their vertical jump height compared to control athletes who only received regular season training. Comparatively, our study participants were recreationally active, non-elite athletes, who had not necessarily been through a resistance training program previously, and some of whom had never been maximally tested for vertical jump height before.

In addition to subject characteristics, many of the studies recruited larger sample sizes for their interventions (9+ per group), which boosts the statistical power of differences in independent variables found between and within groups. This study had a limited sample of 17 subjects, which were sub-divided into groups for purpose of a randomized controlled intervention study; a necessary study design, however, it left many group differences seen after the intervention underpowered and non-significant.

Individualistic Responses to Strength Training

Although it is common for training intervention studies to present changes to experimental subjects as a group, there is evidence of individualistic responses to the same training stimulus (Erskine et al, 2010). Erskine et al (2010) examined subject-specific responses in maximum knee joint torque, quadriceps femoris muscle force, and physiological cross-sectional area (PCSA) after nine weeks of concentric strength training. While all three variables significantly increased after training as a group, the adaptations were not uniform for all 53 subjects. In fact, when each subject's pre-post percent change was plotted out, each variable had a wide spectrum of responses; max knee joint torque increases ranged from -1 to 52%, quadriceps force from -1 to 44%, and PCSA from -3 to 18%. Authors concluded that the varied training adaptations to muscle force and PCSA gave rise to the greater variability seen in max knee joint torque. These results shed more light onto the true nature of strength training adaptations. Individuals can display unique responses to the same training stimulus and adaptations to resistance training interventions may not be uniform even within the same experimental group. Therefore, it is important to look at strength training outcome variables on the subject-specific level, as well as the group level.

The benefits of most exercises are dependent on the dedication and effort of the individual being trained. Although not quantitative in our study, the quality of effort put forth by each experimental subject was apparent while training. Again, it is noted that the resistance during a NH curl is self-imposed. All subjects were instructed to lower their torso as far as they could to the ground in a controlled manner. Once they no longer felt they could hold the eccentric contraction, they were instructed to release and catch themselves before hitting the ground. Some individuals were inherently better at performing the exercise and/or more motivated to improve their technique than others. These individuals were able to lower themselves slower, hold their contractions longer, and reach a more extended knee angle before releasing. These subjects who appeared to maximize their efforts throughout the intervention also experienced the highest increases in eccentric hamstring torque. Subjectively, effort during the NH exercise was a major determinant of individualistic responses to this training intervention.

Sub-Group Analysis

From this study's results it was clear that adaptations to NH training were variable and not uniform within the experimental group, 3 out of 10 subjects did not respond as anticipated to the stimulus. Therefore, a qualitative sub-group analysis was performed on the experimental group to gain a better understanding of individualistic responses to the training stimulus. PCSA and strength are known to be strongly related (Lieber & Bodine-Fowler, 1993). Regression analysis revealed a strong relationship between the changes in PCSA and eccentric hamstring strength (r^2=0.85) within this experimental group (Fig. 15). The variation of adaptations seen in the control group could be a result of error in measurement repeatability; as no changes were expected from this group (Fig. 15). It is possible, but unlikely, that ultrasound architectural measurements taken 6-weeks apart were not assessed in the same areas of the muscle. A more likely explanation is that the eccentric contraction efforts given by the subjects during baseline assessments were different from the efforts given during post-test assessments. In any case, from this figure, it is clear that any subject in the experimental group demonstrating an increase in eccentric strength also experienced concomitant increases in biceps femoris PCSA. Thus, the 3 subjects located in the lower left quadrant were classified as "non-responders" and the 7 subjects in the upper right quadrant were classified as "responders".

When the independent variables of this study are observed separately, the responders' adaptations were fairly in line with our hypothesis (Table 6). Nordic Hamstring eccentric strength training increased architectural measurements of biceps femoris (BF) muscle pennation angle and PCSA (Fig. 16). Given the increase in muscle volume (11%) and PCSA (18%) without changes to fascicle length or muscle length seen in the responders, a change to fascicle pennation angle is necessary to maintain structure in a muscle. Passive knee flexor torque and eccentric hamstring torque increased in the responders, compared to a decrease seen in the non-responders (Fig. 17, 18). Hamstring fascicle length and knee angle at peak eccentric torque changes after the intervention were most likely a result of training at shorter muscle lengths (Table 6).

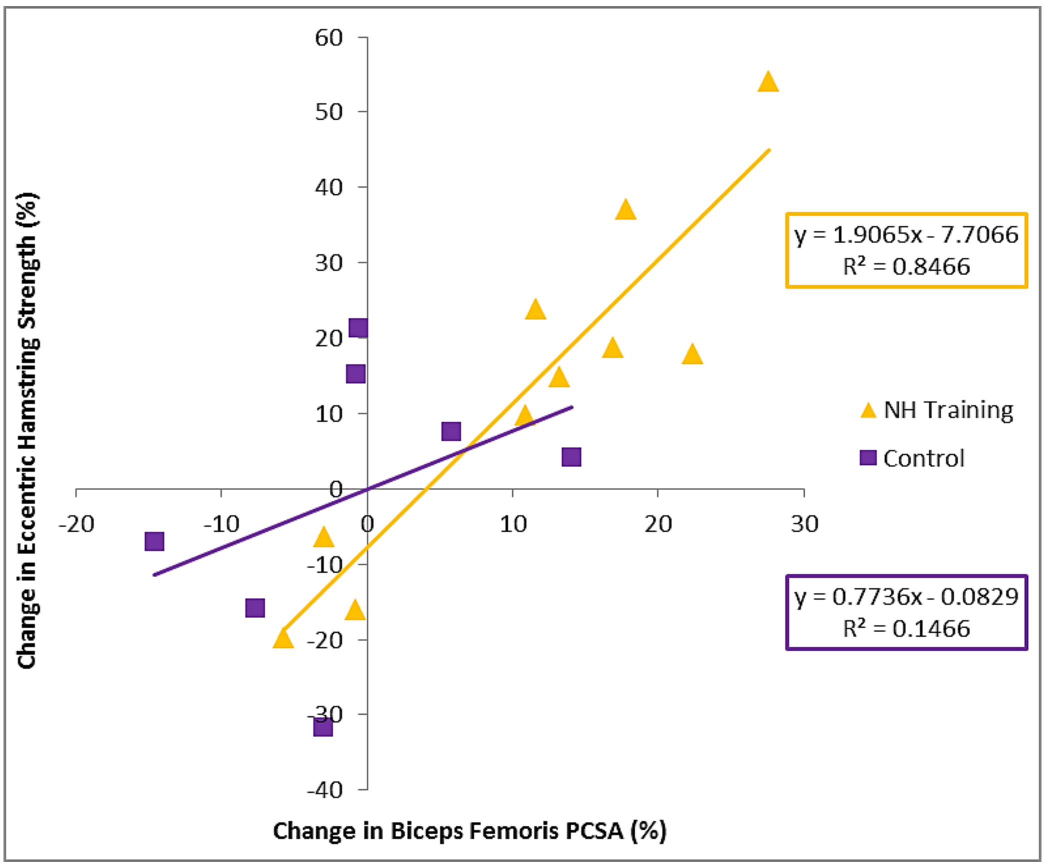

Figure 15: Regression of percent change in biceps femoris PCSA and percent change in eccentric hamstring strength after intervention.

To better understand potentially why several individuals did not respond to the NH curl as we hypothesized, training stimulus magnitude was also assessed for the experimental sub-groups. To estimate the overall knee flexor torque during the NH curl, anthropometric assumptions of location of the combined center of masses and segment masses of both thighs and head, arms and trunk segment (HAT) were estimated from Winter (1990). Also, we assumed that all individuals were able to sustain a zero degree hip joint position effectively modeling the HAT and thighs as one rigid segment and consisting of 88% of the total body mass. The average knee flexor torque stimulus was estimated at 230Nm (3.27Nm/kg) for the responders and 250Nm (3.29Nm/kg) for non-responders. After computing each subjects measured peak eccentric strength (assuming symmetry between limbs) relative to the estimated average NH torque stimulus, these ratios did not appear to be drastically different (0.90Nm and 1.04Nm for responders and non-responders, respectively). With comparable stimulus magnitudes for both sub-groups, the differences in training responses were most likely due to effort exerted by each subject during the NH exercise. Results of our 6-week intervention study confirm Erskine et al's findings (2010). Individualistic responses to strength training do occur and can be highly variable depending on the sample.

To comprehensively summarize the eccentric NH training intervention on hamstring muscle function, it appears that eccentric NH curls are a sufficient loading stimulus to cause muscle hypertrophy. The increase in muscle volume, but not fascicle length, resulted in a larger fascicle pennation angle. Larger pennation angles in addition to muscle volume ultimately increased hamstring PCSA. As muscle PSCA is highly related to strength, there were concomitant increases to eccentric hamstring strength after the intervention seen in our responsive experimental group. Additionally, peak passive knee torque increased in our responsive experimental group, likely due to the increase in hamstring muscle size and strength, which would increase the resistance of passive extension at the knee joint. NH training did not lengthen hamstring muscles fascicle lengths or shift knee angles of peak torque to longer muscle lengths, because the muscles were not trained at long excursion lengths. The training intervention protocol, which included stretching exercises, may have masked the increases in passive muscle stiffness from our resistance training; as stretching has been shown to decrease muscle stiffness. Thus, from results of the current study, the mechanism behind eccentric NH strength training mitigating hamstring injury may be its ability to robustly increase hamstring muscle size and eccentric strength.

Table 6: Hamstring function measurements of the experimental responders

	Baseline		Post		Mean Difference	(95% CI of Difference)
	Mean	SD	Mean	SD		
BF Fascicle Length (cm)	8.88	1.18	8.59	1.50	-0.29	(-0.93, 0.36)
BF Pennation Angle (°)	13.39	3.79	15.12	3.05	1.72	(0.65, 2.80)
BF Volume (cm^3)	127.49	37.78	141.67	37.75	14.18	(7.56, 20.80)
BF PCSA (cm^2)	15.09	4.88	17.82	6.27	2.73	(1.27, 4.19)
BF Stiffness (kPa)	13.46	2.42	12.07	2.83	-1.39	(-4.36, 1.59)
Peak Passive Knee Torque (Nm/kg)	0.12	0.08	0.16	0.10	0.04	(0.01, 0.06)
Peak Eccentric Hamstring Torque (Nm/kg)	1.49	0.68	1.87	0.93	0.38	(0.11, 0.65)
Knee Angle at Peak Eccentric Hamstring Torque (°)	21.03	17.45	18.48	14.86	-2.55	(-16.60, 11.50)
Vertical Jump Height-Countermovement (cm)	33.99	8.61	33.99	5.44	0.00	(4.11, 4.11)

Table 7: Hamstring function measurements of the experimental non-responders

	Baseline		Post		Mean Difference	(95% CI of Difference)
	Mean	SD	Mean	SD		
BF Fascicle Length (cm)	9.15	1.59	10.19	2.01	1.05	(-0.37, 2.47)
BF Pennation Angle (°)	14.07	1.86	14.28	1.95	0.21	(-4.83, 5.25)
BF Volume (cm^3)	140.73	63.04	153.44	72.63	12.71	(-12.21, 37.63)
BF PCSA (cm^2)	16.78	9.94	16.41	10.07	-0.37	(-0.71, -0.02)
BF Stiffness (kPa)	12.37	2.15	13.85	4.26	1.48	(-4.76, 7.73)
Peak Passive Knee Torque (Nm/kg)	0.18	0.04	0.14	0.03	-0.04	(-0.13, 0.06)
Peak Eccentric Hamstring Torque (Nm/kg)	1.70	0.14	1.42	0.24	-0.28	(-0.72, 0.16)
Knee Angle at Peak Eccentric Hamstring Torque (°)	22.70	14.86	40.61	5.47	17.91	(-42.31, 78.13)
Vertical Jump Height-Countermovement (cm)	37.82	9.81	37.25	6.15	-0.56	(-9.75, 8.62)

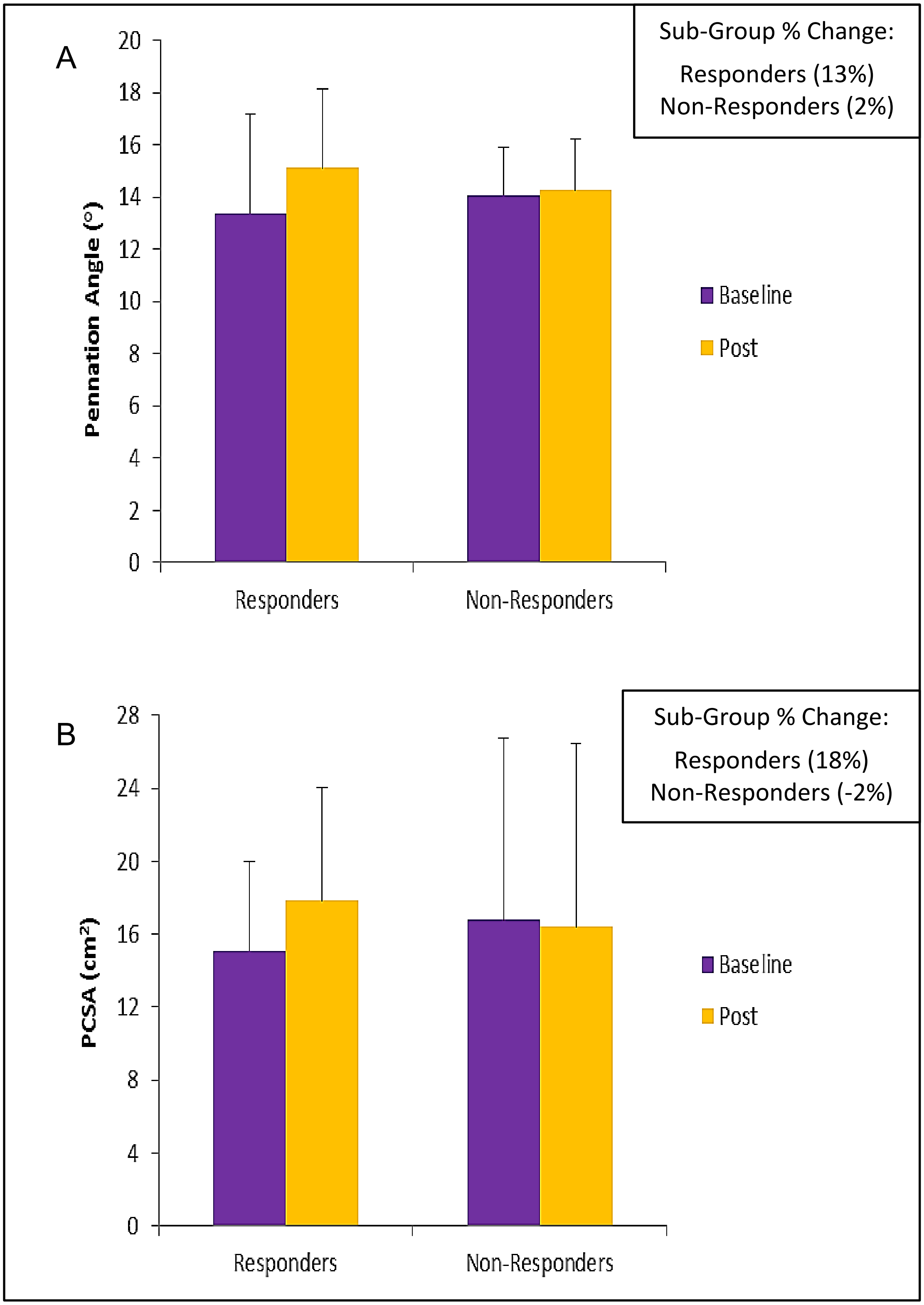

Figure 16: Biceps femoris muscle pennation angle (A) and physiological cross-sectional area (PCSA) (B) before and after intervention.

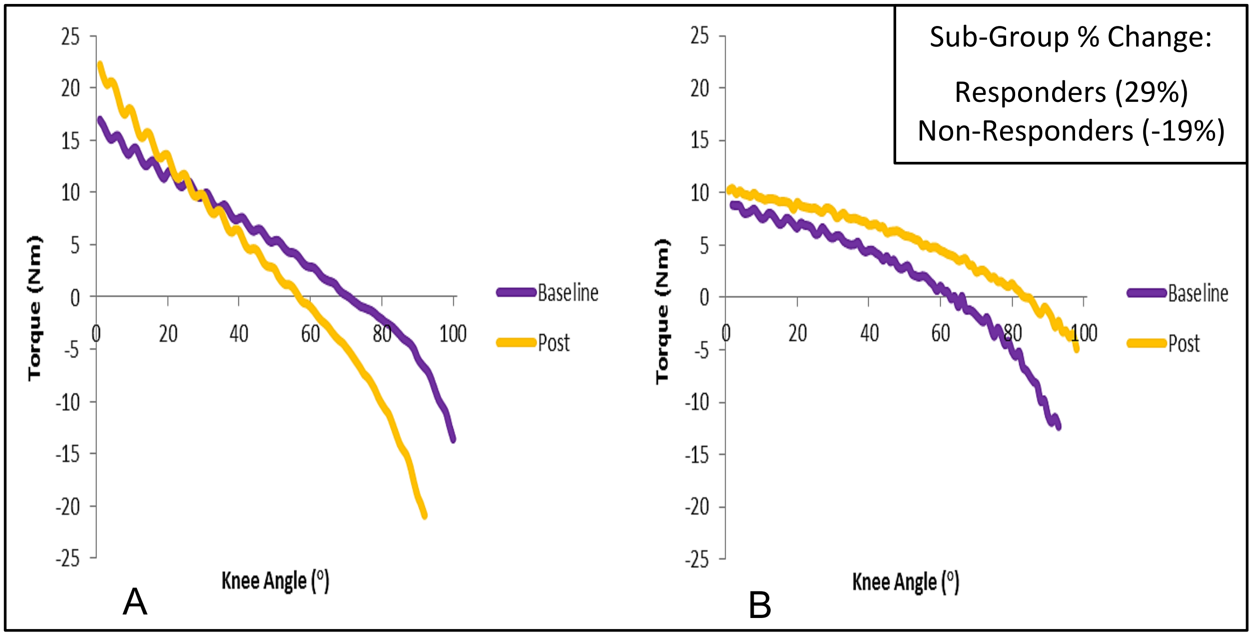

Figure 17: Passive knee flexor torque of a representative responder (A) and non-responder (B) before and after intervention.

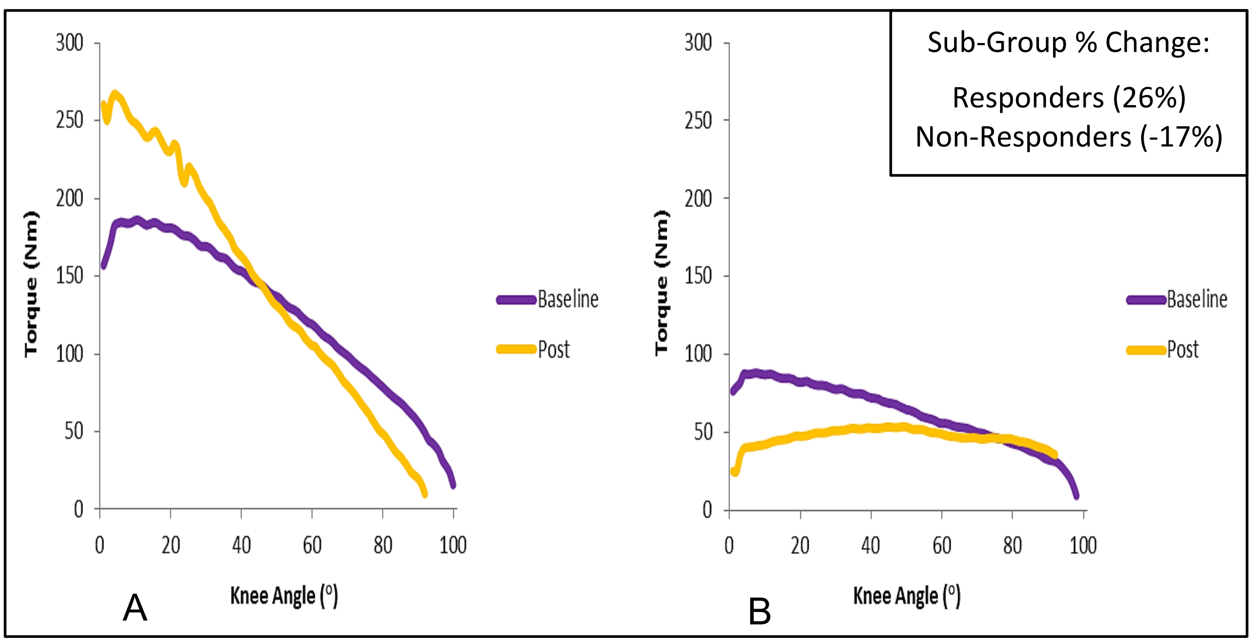

Figure 18: Eccentric hamstring torque of a representative responder (A) and non-responder (B) before and after intervention.

Future Considerations

This study was the first attempt at comprehensively evaluating the effects of a NH strength training intervention on hamstring muscle architecture and function. While training and evaluation methods were based on previous eccentric training protocols, there were several limitations of the current study that may have contributed to the lack of muscle adaptation differences. The length of this intervention and recruited sample size were limited by the university's schedule and the practical time allotted for data collection, reduction, and analysis of each independent variable. Both may have contributed to the non-significant and statistically underpowered results in the NH training group.

Although subjects came in weekly for training, there was no assessment of physical activity outside of the study. It is possible that some subjects did additional resistance training on their own during the duration of the intervention. There was also no assessment of effort given during the NH curl or stretching exercises. Participants were encouraged to perform to the best of their ability; however, there were observable differences in effort, particularly amongst the experimental subjects. In terms of independent variables, we did not measure hamstring tendon tissue stiffness or assess its contribution to passive knee torque. This information may have proved beneficial in connecting muscle architecture and material property adaptations to eccentric training. We also were not able to measure the total semitendinosus muscle volume using ultrasound imaging techniques. Therefore, assumptions made about hamstring muscle architecture can only be confidently made for the biceps femoris long head muscle.

The next steps in eccentric NH training research are to extend the intervention length and recruit a larger sample size of more resistance-trained subjects, to more closely replicate previous studies that have shown significant hamstring muscle function adaptations. Additionally, it would be beneficial to take pre-, mid-, and post-intervention measurements of hamstring muscle architecture and strength to gain a better understanding of the phase relationship between variables. Based on the identification of “responders” and “non-responders” in the current study, continued work to determine why certain individuals may not respond well to this intervention is warranted to ultimately further prevention efforts. Future research is needed to establish a connection between hamstring muscle architecture, stiffness, and strength adaptations to eccentric NH strength training, a stimulus that has shown across several studies to reduce the incidence of initial and recurrent hamstring injuries.

Conclusions

After a 6-week eccentric Nordic Hamstring strength training intervention, the training group significantly increased hamstring muscle volume and PCSA after the intervention, compared to no change in the control group. No significant changes to hamstring muscle fascicle length, pennation angle, stiffness, passive knee torque, eccentric or concentric strength were seen after the intervention that were unique to the training group. Thus our hypothesis was not fully supported. Although our adaptation results were not concurrent with the previous eccentric strength training literature, there was still knowledge gained from this comprehensive study. The Nordic Hamstring exercise was a good training method for muscle growth and this adaptation in architecture translated to changes in eccentric hamstring muscle strength, although these changes did not reach statistical significance largely due to the dichotomy of responses in our training group. A sub-group analysis of the experimental subjects revealed apparent “responders” and “non-responders” to the training stimulus. From a clinically-relevant standpoint, the Nordic Hamstring training was 70% effective at improving muscle function for participants in this study.

Exploring the mechanics behind the Nordic Hamstring strength training exercise, shown to reduce hamstring injury, is a necessary step in understanding muscular adaptations to resistance exercise and enhancing training effectiveness on hamstring muscle function.

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Appendix A

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building · Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · **www.ecu.edu/irb**

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: Anthony Kulas
CC:
Date: 8/29/2014
Re: UMCIRB 14-001266
Biomechanical Effects of Hamstring Strengthening

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 8/28/2014 to 8/27/2015. The research study is eligible for review under expedited category #4,7. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Name	Description
Hamstring Function Survey	Surveys and Questionnaires
Informed Consent	Consent Forms
Recruitment Announcement.docx	Recruitment Documents/Scripts
Study Protocol	Study Protocol or Grant Application

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418