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ORIGINAL ARTICLE

The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength

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Abstract

Purpose Hamstring strain injury is a frequent and serious injury in competitive and recreational sports. While Nordic hamstring (NH) eccentric strength training is an effective hamstring injury-prevention method, the protective mechanism of this exercise is not understood. Strength training increases muscle strength, but also alters muscle architecture and stiffness; all three factors may be associated with reducing muscle injuries. The purpose of this study was to examine the effects of NH eccentric strength training on hamstring muscle architecture, stiffness, and strength.
Methods Twenty healthy participants were randomly assigned to an eccentric training group or control group. Control participants performed static stretching, while experimental participants performed static stretching and NH training for 6 weeks. Pre- and post-intervention measurements included: hamstring muscle architecture and stiffness using ultrasound imaging and elastography, and maximal hamstring strength measured on a dynamometer.
Results The experimental group, but not the control group, increased volume (131.5 vs. 145.2 cm^3, $p<0.001$) and physiological cross-sectional area (16.1 vs. 18.1 cm^2, $p=0.032$). There were no significant changes to muscle fascicle length, stiffness, or eccentric hamstring strength.
Conclusions The NH intervention was an effective training method for muscle hypertrophy, but, contrary to common literature findings for other modes of eccentric training, did not increase fascicle length. The data suggest that the mechanism behind NH eccentric strength training mitigating hamstring injury risk could be increasing volume rather than increasing muscle length. Future research is, therefore, warranted to determine if muscle hypertrophy induced by NH training lowers future hamstring strain injury risk.

Keywords Eccentric · Intervention · Injury prevention · Biomechanics · Ultrasound · Dynamometry

Abbreviations

ANOVA	Analyses of variance
BFLH	Biceps femoris long head
ICC	Intraclass correlation
LOA	Limits of agreement
NH	Nordic hamstring
PCSA	Physiological cross-sectional area
ROI	Region of interest
SEM	Standard error of the mean

Introduction

Hamstring strains are among the most frequently occurring injuries in field sports, accounting for over 12% of all lower extremity sport injuries (Brooks et al. 2005; Feeley et al. 2008; Ekstrand et al. 2011a; Alonso et al. 2012; Orchard et al. 2013). This injury occurs when a muscle is eccentrically overstretched, typically during the late swing phase of sprinting (Chumanov et al. 2007). Despite nearly two decades of hamstring injury-prevention research, hamstring

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injury rates have not declined (Brooks et al. 2006; Ekstrand et al. 2011b, 2013; Orchard et al. 2013). Thus, the need to identify and optimize successful hamstring injury-prevention programs is critical.

The Nordic hamstring (NH) curl exercise appears to be effective in reducing hamstring injury rates (Brooks et al. 2006; Arnason et al. 2008; Petersen et al. 2011; van der Horst et al. 2015). This exercise reduces initial and recurrent hamstring injury rates by 60 and 85%, respectively, in professional soccer athletes (Petersen et al. 2011). However, the mechanism behind this reduction remains unclear. A thorough understanding of the adaptations to NH training may provide the theoretical basis for optimizing injury-prevention efforts.

NH strengthening programs are effective in improving eccentric strength, muscle activation, and jump height performance (Mjølsnes et al. 2004; Clark et al. 2005; Tansel et al. 2008; Iga et al. 2012; Delahunt et al. 2016). Eccentric strength gains following NH interventions, 4–10 weeks in length, range from 11 to 21% (Mjølsnes et al. 2004; Iga et al. 2012; Delahunt et al. 2016), with no significant concentric strength gains (Mjølsnes et al. 2004; Clark et al. 2005; Tansel et al. 2008). Neural adaptations also occur following NH programs, with higher hamstring muscle activation during the NH exercise after a 6-week intervention (Delahunt et al. 2016). These improvements in muscle activations combined with no change in quadriceps muscle activation lead to a lower co-contraction index during the NH exercise, suggesting that NH training improves neuromuscular control (Delahunt et al. 2016). Finally, functional performance (vertical jump height) improves after 4–5-week NH interventions (Clark et al. 2005; Tansel et al. 2008), suggesting that strength and neuromuscular improvements do translate to functional activity.

It is implied that if the NH exercise causes a shift in optimum torque production towards longer lengths, this would be “injury-protective”, because the induced muscle damage from eccentric NH training would trigger sarcomerogenesis (increased muscle fiber length) allowing the hamstrings to stretch further (Lieber and Bodine-Fowler 1993; Brockett et al. 2001). Currently, the literature is inconsistent whether NH strength training induces a shift of peak torque towards more extended knee positions. After one NH training session, Brockett et al. (2001) showed an immediate shift (7.7°) in optimum knee flexion torque, which was sustained at 10-day post-exercise. Over a 4-week NH intervention, Clark et al. (2005) showed an approximate 6° shift in the angle of peak concentric torque towards knee extension. In contrast to these two reports, the knee angle of peak eccentric hamstring torque was unchanged following 4- and 6-week NH interventions (Iga et al. 2012; Delahunt et al. 2016). Only one study to date has directly evaluated hamstring length adaptations following an NH strength intervention, showing a 20.8% fascicle length increase after 10 weeks (Bourne et al. 2016). Although increases in hamstring muscle fascicle length would be a likely mechanism by which the NH exercise can be injury-protective, shifting of the torque curve is an indirect measure of sarcomerogenesis and evidence of the shift in optimum torque production towards longer lengths is controversial.

Another possible adaptation that could contribute to injury-resistance following NH exercise is increasing the stiffness of the muscle. Strain, rather than force, is responsible for injury (Lieber and Friden 1993) and stiffer muscles experience less strain for a given force. Increasing muscle stiffness can be accomplished by increasing muscle cross-sectional area. Given that muscle hypertrophy accompanies resistance training, gains in muscle size and, therefore, stiffness are plausible following NH training. Another mechanism for stiffness to be modifiable is to increase the stiffness of the tissue, or elastic modulus. This also seems a viable mechanism, as muscle modulus is known to be modifiable with exercise training (Kovanen et al. 1984). However, changes in neither muscle size nor stiffness after NH interventions have been determined. Therefore, both avenues for increasing tissue stiffness could contribute to injury-resistance following NH exercise.

Investigating the architectural and stiffness adaptations, the following NH strength training would add to the body of literature determining how NH training is effective in hamstring injury reduction. Therefore, the purpose of this study was to examine the effects of NH eccentric strength training on hamstring muscle architecture, stiffness, and strength (magnitude and knee angle of peak torque). Using an exercise that has been shown to reduce hamstring strains, comprehensively evaluating the biomechanical and architectural adaptations of hamstring muscles to the NH exercise could lead to better and more efficient methods of developing injury-resistant tissues. Ultimately, elucidating the mechanism(s) of hamstring injury reduction from the NH exercise would help to minimize hamstring injury risk by enabling clinicians to optimally implement this exercise into injury-prevention and strength and conditioning programs.

Methods

Participants

Twenty adults, aged 18–25, participated in this study (Table 1). All participants self-reported as being recreationally active (5+ h of physical activity per week). Exclusion criteria included a BMI greater or equal to 30 kg/m^2 and any history of hamstring injuries. In addition, after randomization into groups, we qualitatively assessed the

Table 1 Descriptive statistics for the NH training and control group (mean ± SD)

	Male/female ratio	Age	Height (m)	Mass (kg)	BMI
NH training	4/6	18.3 ± 0.5	1.7 ± 0.1	71.3 ± 15.9	25.4 ± 3.9
Control	2/8	19.9 ± 1.2	1.6 ± 0.1	64.1 ± 12.1	23.9 ± 2.7

experimental subjects' willingness and ability to initiate the exercise. Given that all our subjects were experienced in resistive training exercises, all subjects randomized into the experimental group were included and none were excluded based on these criteria. All participants were required to sign a consent form prior to participation in this study. All documentation and procedures used for this study were approved by the Institutional Review Board.

Testing protocol

Participants were prone (hip flexion = 0°, knee flexion = 0°, and ankle in relaxed position) on a standard treatment table. As a surrogate of the entire hamstring group to represent the changes in hamstring muscle function, panoramic ultrasound images of the long head of the biceps femoris (BFLH) were obtained (SuperSonic Imagine, Aixplorer, Bothell, WA). We chose to examine the BFLH muscle, as it is the most commonly injured hamstring muscle (De Smet and Best 2000; Ekstrand et al. 2012).

The right BFLH muscle was imaged cross-sectionally and longitudinally (Fig. 1) from its distal to proximal musculotendinous junction, where all hamstring muscles form one common tendon just inferior to the gluteal fold; this location was verified via ultrasound image. Cross-sectional images were acquired along the length of the muscle at 11 equidistant points from the most distal cross-sectional image of the muscle that could be traced and measured, which is just proximal to the musculotendinous junction, to the gluteal fold; encompassing 0–100% of the visualized muscle length. Two images for each of the 11 cross-sectional points were recorded. Two longitudinal images were then recorded to allow for the estimation of fascicle length and pennation angle. In addition, shear modulus of the BFLH muscle was measured using ultrasound elastography. Ultrasound elastography generates shear waves in a tissue of interest and images these waves with B-mode imaging to calculate propagation velocity within a muscle. As the stiffness of a muscle tissue is directly proportional to wave propagation velocity, this allows for the calculation of the tissue shear modulus. This elastography data provided a measure of passive muscle material stiffness. Previous research has found this to be a valid technique for assessing muscle material properties (Eby et al. 2013). From the muscle belly (50% of the muscle length), mean and standard deviations from the central region of interest (3 mm diameter) of two elastograms were recorded (Fig. 1).

All muscle contractions were performed on a HUMAC NORM Dynamometer (CSMI, model 502140, Stoughton, MA). Participants were seated with hips flexed to 90°.

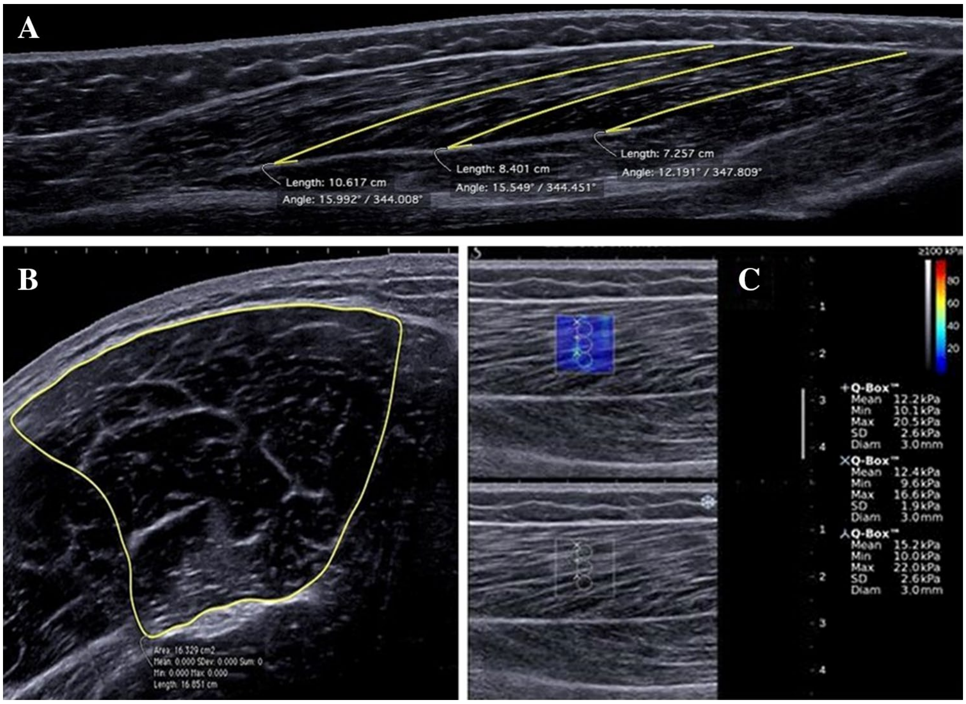

Fig. 1 **a** Fascicle lengths, pennation angles, **b** cross-sectional area, and **c** elastogram of the right biceps femoris long head with ROI (*circles*)

The lateral epicondyle of the knee was aligned to the axis of rotation of the dynamometer arm. The right lower leg was then secured to the dynamometer arm. The leg was not weighed for gravity through the software, as the weighting procedure removes the knee flexor torque due to both the weight of the leg and any passive torque produced by the hamstrings. Gravity correction was performed offline, based on an anthropometric model (Kellis and Baltzopoulos 1996). Subjects' lower leg length measurements were used to calculate the center of mass location of the lower leg and proportion of weight the lower leg and foot constitute relative to total body weight (Dempster 1955). Once the gravitational moment at 0° of knee flexion is known, the gravitational moment of the lower leg and foot can be calculated as a function of the cosine of knee flexion at any given angle (Kellis and Baltzopoulos 1996). Participants went through two protocols: four consecutive passive knee extension flexions (range of motion 0°–100°) at 5° per second to measure the passive knee flexor torque (primarily attributed to the passive elements of the hamstring muscles and thus representing the passive contributions of the hamstrings to resist knee extension) and three repetitions of maximal knee extensions (eccentric hamstring contractions) at 60° per second. All maximal isokinetic contractions began with a familiarization trial at 50% of the participant's expected maximum effort, with a 1 min rest each trail.

Post-training assessments were conducted on a separate day, no more than 5 days, after the conclusion of training and were performed identically to baseline assessments.

Training protocol

Intervention sessions began on a separate day after baseline measurements. Participants were randomly assigned into two groups: intervention (NH training) or control by a coin-toss generator. The NH exercise consists of the participant starting in a kneeling position, with their torso from the knees upwards held rigid and straight. A partner applies pressure to the heels/lower legs, while the participant attempts to resist gravity as they fall forward; eccentrically contracting their hamstring muscles to control descent into the prone position (Petersen et al. 2011). NH training corresponded to the injury-prevention protocol of Petersen et al. (2011), with a progressive eccentric overload over the course of 6 weeks (Delahunt et al. 2016). NH training sessions began with a warm-up for 5 min on a cycle ergometer at a brisk pace, followed by three sets of static hamstring stretches (standing, seated, and supine). The static stretches were performed by the participants three times on each leg, alternated, with a 30 s hold. Subjects, regardless of group assignment, were encouraged to reach for their toes until they felt an uncomfortable, but not painful, sensation on the hamstrings during the stretch. Following a 5-min break, participants completed the prescribed NH exercise according to the training schedule (Table 2). Consistent verbal encouragement was given by the examiner to motivate the subjects to lower themselves as far as they could in a controlled manner and for as many repetitions and sets as the training schedule allowed. After all sets were completed, participants closed the session with the same three sets of static stretches. To facilitate compliance with the strength training protocol, participants in the intervention group were counseled that the exercise would likely produce muscle soreness after each session, similar to soreness experienced following an intense resistance training workout in a gym. A subject was considered compliant if they had not missed any training sessions in weeks 1 and 2, no more than one session in weeks 3–6, and no more than three sessions total; a compliance of 80%, similar to Petersen et al. (2011).

The control group sessions began with a warm-up for 5 min on a cycle ergometer at a brisk pace, then three sets of static hamstring stretches. Following a 5 min break, participants closed the session with the same three sets of static stretches. The control group followed the same schedule of sessions as the training group.

Data reduction

Fascicle length, pennation angle, and muscle volume were assessed for the BFLH muscle using the Osirix software (Pixmeo, Bernex, Switzerland). Fascicle length was measured from the deep to superficial muscle aponeurosis. Pennation angle was measured as the angle between the deep aponeurosis and fascicle orientation. The average of three fascicle lengths (middle, distal, and proximal) and their corresponding pennation angles were recorded from two separate longitudinal images, and the average of both images was used for analysis. The average of two integrated cross-sectional area vs. muscle length curves was used to calculate muscle volume (Fig. 2). Volume was calculated using the trapezoid method, where the area of each trapezoid (the area between two successive cross-sectional areas) is equal to

Table 2 Nordic hamstring training protocol

Week	Session/week	Set × repetition
1	1	2×5
2	2	2×6
3	3	3×6–8
4	3	3×8–10
5	3	3×12–10–8
6	3	3×12–10–8

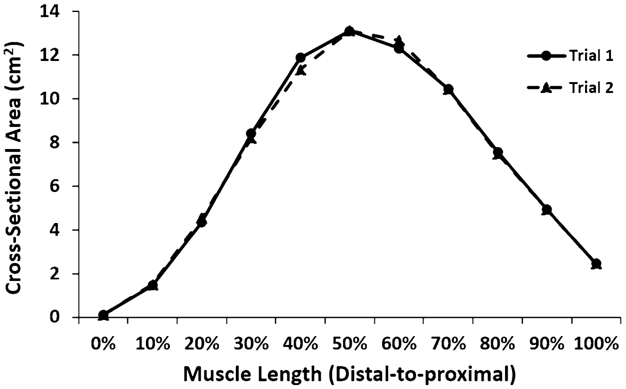

Fig. 2 Cross-sectional area vs. muscle length for a representative male subject. 0% located at distal musculotendinous junction and 100% located at gluteal fold. Volumes calculated: trial 1 = 196.32 cm^3, trial 2 = 195.83 cm^3

$$\frac{\text{CSAn} + \text{CSAn} + 1}{2} \times h$$

where h is the interval distance between the two cross-sectional area measurements, which is the same for all ten intervals. The ten areas were then summed to arrive at volume. Physiological cross-sectional area (PCSA), defined as the muscle volume divided by the fascicle length, was then calculated (Fukunaga et al. 1992; Ward et al. 2009). Muscle stiffness was analyzed on the ultrasound unit to measure shear modulus. From the muscle, the average value from the central region of interest (ROI) of two elastograms was recorded (Fig. 1).

Due to the longitudinal nature of the current study along with known operator dependency of ultrasound imaging a pilot study ($n = 11$) determined the day-to-day reliability (intraclass correlation coefficient, ICC 2,k) and precision (standard error of the measurement, SEM) for all ultrasound variables. The ultrasound protocol was repeated twice with 1 week between sessions: an appropriately small time window, where muscle architecture and stiffness are highly unlikely to change. ICC 2,k (SEMs) were all excellent: fascicle length, 0.99 (0.11 cm); pennation angle, 0.88 (1.1°); volume, 0.99 (2.07 cm^3), PCSA, 0.99 (0.42 cm^2); and shear modulus, 0.94 (0.69 kPA). Due to the high magnitude of between-subject variation for all measurements for our ICCs which may have contributed to the excellent results, we also performed a limits of agreement analysis which shows the presence of systematic error (difference between means of day 1 and day 2) and the overall magnitude of measurement error (±95% limits of agreement, LOA) irrespective of natural between-subject variation. The mean differences ± 95% LOAs were all considered good to excellent: fascicle length, 0.07 ± 0.44 cm; pennation angle, 0.2° ± 2.3°; volume, 1.23 ± 8.33 cm^3; PCSA, −0.01 ± 1.76 cm^2; and shear modulus, −0.50 ± 3.67 kPa. To put this analysis into context, the 95% LOAs expressed as a percentage of the day-to-day mean measurements of the reliability subject sample were: 5.6% fascicle length; 16.0% pennation angle; 4.8% volume; 7.2% PCSA; and 21.3% shear modulus and represent the absolute measurement error associated with these measurements.

Peak torque and knee angle at peak torque for the hamstring during the eccentric isokinetic torque curves at 60° per second was recorded. Passive torque across the full knee angle range was plotted over the course of four consecutive flexion–extension trials. Peak passive knee flexor torque was calculated as the average passive torque in the last 5° of terminal extension (0°–5°). All dynamometer data were normalized to body mass.

Statistical analysis

We calculated 2 (group: intervention and control) × 2 (conditions: pre and post) ANOVAs with repeated measures on condition to analyze the dependent variables of hamstring architecture (fascicle length, pennation angle, volume, and PCSA), stiffness, peak eccentric flexor torque, peak passive flexor torque, and knee angle at peak eccentric flexor torque. In the presence of significant group × condition interactions, Tukey's HSD post hoc analyses were performed using a custom spreadsheet to locate the significant mean differences. In the presence of significant condition group × condition interactions, Cohen's D_{rm} effect sizes were also calculated for the repeated measures and adjusted with Hedges g (D_{rmg}) to correct for potentially biased estimates; as sample sizes were <20 for each group (Lakens 2013). Because of the lack of published data to properly compute the effect sizes on our ultrasound variables (our most important variables of interest) as a result of the NH training specifically, proper a priori statistical power analysis was not feasible. However, a previously published 6-week NH intervention (Delahunt et al. 2016) produced a large effect size (partial eta squared of 0.23) for the group × condition interaction showing the intervention group increased strength (peak eccentric torque), but the control group did not. Based on this effect size, a total sample size of 14 subjects (7 in each group) would be needed to reach a statistical power of 0.96. Furthermore, a very large effect size (Cohen D_z > 6.0) for increasing fascicle length by 34% was shown in the hamstrings following an 8-week eccentric dynamometer-based protocol (Potier et al. 2009). A sample size estimate of ten experimental subjects experiencing a conservative 8% (~1/4 of the change reported) (Potier et al. 2009) increase in fascicle length would have yield a statistical power of 0.98. Power analysis was conducted with G × power v3.1 (Faul et al. 2007). Statistical analysis was performed using SPSS (version 22.0; SPSS Inc, Chicago, IL). The α level was set a priori at 0.05.

Results

Compliance

According to our a priori criteria, all subjects in both groups were considered compliant with the training schedule. No participant in the NH group missed any training days. Two participants in the control group missed 1 day of weeks 4 and 5, respectively.

Muscle architecture and stiffness

BFLH architecture and stiffness measurements are presented in Table 3. The group main effect, condition main effect, and group × condition interaction for fascicle length were all non-significant ($p = 0.093$, $p = 0.842$, $p = 0.377$, respectively, Table 3). In addition, there were no main effects for group ($p = 0.477$), condition ($p = 0.139$), or group × condition interactions ($p = 0.334$) for pennation angle. A significant main effect (condition) and interaction (group × condition) for muscle volume was observed ($F = 11.03$, $p = 0.004$; $F = 29.52$, $p < 0.001$ respectively) with no main effect for group ($p = 0.889$). Post hoc testing revealed that the NH group significantly increased volume by 10% (d_{rmg} = 1.63) as a result of the intervention with no change in volume for the control group (d_{rmg} = 0.47). A significant main effect (condition) and interaction (group × condition) for muscle physiological cross-sectional area (PCSA) was also observed ($F = 6.363$, $p = 0.021$; $F = 5.385$, $p = 0.032$, respectively) with no main effect for group ($p = 0.589$). Post hoc testing revealed that the NH group significantly increased PCSA by 12% ($d_{\mathrm{rmg}} = 0.84$) as a result of the intervention with no change for the control group ($d_{\mathrm{rmg}} = 0.05$). Muscle stiffness showed no significant condition main effect ($p = 0.443$) or group × condition interaction ($p = 0.184$). However, the NH training group's mean stiffness (12.9 kPa, 95% CI 11.28, 14.45) was significantly lower than the control group's mean stiffness (16.2 kPa, 95% CI 14.59, 17.76) regardless of condition assessed (group main effect, $F = 9.61$, $p = 0.006$).

Passive knee flexor torque and muscle strength

After the 6-week intervention, no significant changes in peak passive knee flexor torque or peak eccentric hamstring flexor torque were seen in the NH training or control group ($p = 0.092$ and $p = 0.563$, respectively; Table 3). In addition, no group main effects or group × condition interactions were observed for peak passive knee flexor torque ($p = 0.367$, $p = 0.839$, respectively) or peak eccentric flexor torque ($p = 0.808$, $p = 0.150$, respectively). A significant main effect for condition showed that knee angle at peak eccentric torque increased from 17.5° (95% CI 11.64, 23.76) to 25.7° (95% CI 19.24, 32.28) after the intervention ($F = 5.373$, $p = 0.032$), but the group main effect and group × condition interaction effect were not significant ($p = 0.521$, $p = 0.215$, respectively).

Discussion

Effects of Nordic hamstring strength training on muscle architecture and stiffness

There are limited data in the literature elucidating the mechanisms of hamstring muscle–tendon complex adaptations to the NH training stimulus, despite this exercise being the only one to date capable of reducing initial and recurrent hamstring injuries. Therefore, this study attempted to evaluate the biomechanical and architectural adaptations

Table 3 Hamstring measurements' pre- and post-intervention

	NH training		Control	
	Baseline, mean ± SD	Post, mean ± SD	Baseline, mean ± SD	Post, mean ± SD
BF fascicle length (cm)	8.96 ± 1.23	9.07 ± 1.73	8.19 ± 0.68	8.01 ± 0.94
BF pennation angle (°)	13.6 ± 3.2	14.9 ± 2.7	13.1 ± 3.4	13.4 ± 3.3
BF volume (cm^3)	131.46 ± 43.31	145.2 ± 46.42*	142.81 ± 45.74	139.49 ± 43.75
BF PCSA (cm^2)	16.08 ± 6.43	18.05 ± 7.33*	18.67 ± 6.68	18.75 ± 6.51
BF stiffness (kPa)†	13.13 ± 2.29	12.61 ± 3.18	15.22 ± 4.15	17.13 ± 2.38
Peak passive knee flexor torque (Nm/kg)	0.14 ± 0.08	0.15 ± 0.09	0.16 ± 0.05	0.18 ± 0.04
Peak eccentric hamstring torque (Nm/kg)	1.55 ± 0.57	1.73 ± 0.80	1.74 ± 0.38	1.66 ± 0.19
Knee angle at peak eccentric hamstring torque (°)	21.5 ± 17.6	25.1 ± 16.4*	13.9 ± 4.9	26.4 ± 10.8*

*Significant change from baseline ($p < 0.05$)

†Significant group main effect ($p < 0.05$)

of hamstring muscles to the NH exercise through a 6-week eccentric training intervention. Our primary findings show that in response to the 6-week NH intervention, muscle volume and not fascicle length increased. In addition, our experimental group did not significantly increase eccentric hamstring strength as expected. The following discussion will focus on these two main findings.

The architectural measurements of muscle size, volume, and PCSA, are strongly associated with muscle strength (Lieber and Fridén 1993). Eccentric training, specifically the NH curl, has been shown to improve hamstring muscle strength, even more so than the traditional concentric-focused training exercises (Mjølsnes et al. 2004). While previous studies found increased hamstring muscle strength and neuromuscular control after a 4- and 6-week NH training program, there were no changes to angle of eccentric peak torque (Iga et al. 2012; Delahunt et al. 2016). The present muscle volume increase (11%) and PCSA increase (12%) seen in the BFLH are comparable to eccentric training muscle volume gains in the literature (Alegre et al. 2006; Duclay et al. 2009; Baroni et al. 2013; Franchi et al. 2014). The eccentric NH curl does seem to be an effective stimulus for muscle growth; however, other architectural measurements were not equally affected by this intervention.

We expected eccentric NH strength training to increase hamstring muscle fascicle length, as shown previously with eccentric strength training (Alegre et al. 2006; Blazevich et al. 2007; Potier et al. 2009; Baroni et al. 2013; Bourne et al. 2016). However, fascicle length did not increase in the NH training group, possibly due to the joint positions assumed during training. Changes in BFLH fascicle length are more sensitive to changes in hip position than changes in knee position (Hawkins and 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 used dynamometry-based training interventions, with the hip at 90° and resistance through full knee range of motion (Blazevich et al. 2007; Potier et al. 2009). Bourne et al. (2016) were able to show hamstring fascicle length increases after NH training. However, from the exercise in Fig. 1 (Bourne et al. 2016), it appears that participants were provided with resistance through a large knee range of motion (more than 90°), enabled by the elevated training surface and additional torso weight. Comparatively, participants in this NH intervention were required to keep the hip at 0° and only provided resistance through a smaller knee range of motion (because of the non-elevated surface) resulting in training at shorter muscle lengths. Sharifnezhad et al. (2014) confirmed that fascicle length increases are dependent on the range of lengths used during the intervention; showing the vastus lateralis fascicle lengths increased in the leg that exercised at a longer muscle length (25°–100° knee flexion), with no change in fascicle length for the leg exercised at a shorter muscle length (25°–65° knee flexion) after training. Furthermore, Guex et al. (2016) confirmed that hamstring fascicle length increases after a dynamometer-based eccentric strength intervention are dependent on the muscle length during training; BFLH fascicle lengths increased more when trained at a longer muscle length (80° hip flexion), compared to shorter muscle length (0° hip flexion). Thus, the joint positions during the NH curl training may have contributed to the lack of fascicle length change (and the lack of shift in maximal eccentric torque towards longer lengths) seen after the intervention. In addition, when fascicle increases have been shown to occur, they increase fairly quickly; 3–5 weeks into eccentric training (Blazevich et al. 2007; Baroni et al. 2013; Guex et al. 2016; Bourne et al. 2016). The current NH intervention length of 6 weeks was similar to previous studies (Iga et al. 2012; Delahunt et al. 2016). Given these findings, it seems unlikely that an increase in muscle fascicle length is responsible for the injury protection provided by NH exercise.

Muscle stiffness adaptations also were not observed following the intervention. As an unfortunate effect of random assignment, the NH training group's mean stiffness was significantly lower than the control group's mean stiffness at baseline. Nonetheless, no changes to either group were apparent post-intervention. Material muscle properties can be affected by changes to the collagen content, collagen linking, or tissue fluid. Increases in muscle modulus due to exercise have been seen previously (Kovanen et al. 1984). Conversely, muscle modulus has been shown to decrease after stretching interventions (Akagi and 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 on muscle stiffness may have been negated by the addition of a stretching warm-up. However, the intervention was intended to be as clinically relevant as possible, and stretching is common practice with strengthening interventions. Given the lack of change in tissue stiffness seen within the scope of the 6-week intervention of this study, increased muscle modulus seems unlikely to contribute to the injury protection provided by the NH exercise.

Individualistic responses to strength training

Despite significant increases in muscle growth (volume and PCSA), our experimental group as a whole did not significantly increase peak eccentric hamstring strength. Although it is common for training intervention studies to present changes to experimental participants as a group, there is evidence of individualistic responses, positive or negative treatment effects, to the same training stimulus (Hubal et al. 2005; Erskine et al. 2010). Erskine et al. (2010) examined participant-specific responses in maximum knee joint torque, quadriceps femoris muscle force, and PCSA after 9 weeks of strength training. From the varied training adaptations to muscle force and PCSA, the authors concluded that this gave rise to the greater variability seen in maximum knee joint torque. Our results, along with those of Erskine et al. (2010), shed more light onto the true nature of strength training adaptations. The NH stimulus itself does not produce uniform outcomes (injury prevention) for all individuals; not every athlete trained was injury free (Brooks et al. 2006; Arnason et al. 2008; Petersen et al. 2011; van der Horst et al. 2015). Therefore, it is important to examine strength training outcome variables on the participant-specific level, as well as the group level.

Interpreting the individualized difference in responses to the NH strength training exercise could help determine the characteristics of individuals who may be considered positive or "high" responders from those who experience neutral, negative, or "low" responses. In the present study, it was clear that eccentric strength adaptations to NH training were variable and not uniform within the experimental group. Therefore, a supplemental analysis was performed on the experimental group to gain a better understanding of the characteristics of individuals who experienced strength gains (responders) vs. those individuals who did not experience strength gains (non-responders). Each subgroup was analyzed independently, where the dependent variables were subjected to paired samples *t* tests to determine if the experimental effect was real with alpha levels set to 0.10 (Curran-Everett and Benos 2004). Mean differences and 95% confidence intervals of the differences determined the level of certainty of the experimental effect and effect sizes (Cohen's D_{rm}) (Cohen 1988; Lakens 2013) determined the magnitude of the treatment effects for all variables with $p < 0.10$ (Curran-Everett and Benos 2004). The magnitude of effect sizes is categorized as: <0.20 (no effect), 0.20–0.49 (small), 0.50–0.79 (medium), 0.80–1.29 (large), and 1.30 and greater (very large) (Rosenthal 1996).

The experimental group's hamstring muscle function changes after the 6-week intervention is presented in Tables 4 and 5, partitioned into responders and non-responders. The responders had a large treatment effect for increasing strength, while the non-responders did not experience a change in strength, which merely confirms that our two groups were properly classified based on the primary outcome variable of strength. For the architectural measurements, the responders also had "very large" treatment effects for volume, pennation angle, and PCSA. Given the increases in strength and PCSA without changes to fascicle length seen in the responders, a change to fascicle pennation angle is necessary to maintain structure in a muscle. Passive knee flexor torque also increased in the responders, whereas the non-responders showed no change in passive knee flexor torque or eccentric hamstring torque after training. However, with no change to muscle modulus seen in the responders after training, this increase in passive torque is likely due to the concomitant increases in hamstring muscle size and strength.

In contrast to the responders, the non-responders showed an initial trend towards a significant increase in fascicle length ($p = 0.086$) with a very large treatment effect. However, due to the 95% confidence interval encapsulating zero, there is not 95% certainty that this treatment effect is relevant. Non-responders showed no change in volume, with a non-significant decrease to PCSA. While this finding makes intuitive sense in this same group who did not experience change in strength, it is unlikely meaningful considering it represents a ~2% decrease in PCSA, while the 95%

Table 4 Supplemental analysis: hamstring measurements of the experimental responders

	Baseline Mean ± SD	Post Mean ± SD	Paired differences Mean (95% CI)	*p* value	Effect size Cohen D_{rmg}
BF fascicle length (cm)	8.88 ± 1.18	8.59 ± 1.5	−0.29 (−0.93, 0.36)	0.319	–
BF pennation angle (°)	13.4 ± 3.8	15.1 ± 3.1*	1.7 (0.7, 2.8)	0.008	1.34
BF volume (cm^3)	127.49 ± 37.78	141.67 ± 37.75*	14.18 (7.56, 20.80)	0.002	1.79
BF PCSA (cm^2)	15.55 ± 5.01	18.50 ± 6.53*	2.97 (1.37, 4.54)	0.004	1.55
BF stiffness (kPa)	13.46 ± 2.42	12.07 ± 2.83	−1.39 (−4.36, 1.59)	0.297	–
Peak passive knee flexor torque (Nm/kg)	0.12 ± 0.08	0.16 ± 0.1*	0.04 (0.01, 0.06)	0.009	1.30
Peak eccentric hamstring torque (Nm/kg)	1.49 ± 0.68	1.87 ± 0.93*	0.38 (0.09, 0.67)	0.019	1.10
Knee angle at peak eccentric hamstring torque (°)	21.0 ± 17.5	18.5 ± 14.9	−2.6 (−16.6, 11.5)	0.673	–

$N = 7$

95% CI 95% confidence interval of the differences

*Significant change from baseline (see *p* value column for exact values)

Table 5 Supplemental analysis: hamstring measurements of the experimental non-responders

	Baseline Mean ± SD	Post Mean ± SD	Paired differences Mean (95% CI)	*p* value	Effect size Cohen D_{rmg}
BF fascicle length (cm)	9.15 ± 1.59	10.19 ± 2.01	1.05 (−0.37, 2.47)	0.086	1.65
BF pennation angle (°)	14.1 ± 1.9	14.3 ± 2.0	0.2 (−4.8, 5.3)	0.874	–
BF volume (cm^3)	140.73 ± 63.04	153.44 ± 72.63	12.71 (−12.21, 37.63)	0.159	–
BF PCSA (cm^2)	17.33 ± 10.37	17.00 ± 10.56	−0.33 (−0.81, −0.14)	0.096	−1.57
BF stiffness (kPa)	12.37 ± 2.15	13.85 ± 4.26	1.48 (−4.76, 7.73)	0.414	–
Peak passive knee flexor torque (Nm/kg)	0.18 ± 0.04	0.14 ± 0.03	−0.03 (−0.13, 0.06)	0.256	–
Peak eccentric hamstring torque (Nm/kg)	1.70 ± 0.14	1.42 ± 0.24	−0.28 (−0.73, 0.16)	0.112	–
Knee angle at peak eccentric hamstring torque (°)	22.7 ± 21.8	40.6 ± 5.5	17.9 (−42.3, 78.1)	0.329	–

No significant change from baseline (see *p* value column for exact values)

$N = 3$

95% CI 95% confidence interval of the differences

LOA analysis required a ~7% change for the change to be considered above and beyond measurement error. With only three individuals in this group, these results should not be extrapolated to represent generalized characteristics of “non-responders”. Future research is warranted to better characterize the NH adaptations in both responders and non-responders to ultimately better tailor strengthening exercise programs to the anticipated responses of the individual.

Limitations

We did not measure hamstring tendon tissue stiffness or assess its contribution to passive knee torque. Though the biceps femoris is the most commonly injured hamstring muscle (Ekstrand et al. 2012), it should be noted that we were not able to measure the other three hamstring muscles’ adaptations with the same comprehensive nature. Therefore, assumptions about hamstring muscle architecture can only be confidently made for the BFLH muscle. Muscle volume was likely underestimated slightly due to the lack of distal and proximal cones in the volume measurement. Given that our most distal and proximal cross-sectional areas were very small, with the proximal most cross-sectional areas ranging from 1.2 to 2.6 cm^2, it was estimated that not modeling the cones to calculate the volume of muscle not visualized with ultrasound underestimated the overall muscle volume from 1.2 to 2.7%. In addition, because the longitudinal nature of our study sought to determine the architectural responses to the NH training exercise, this small volume underestimation was likely to have negligible effect on the overall interpretation of our results. While previous research showed that stiffness can be assessed with ultrasound elastography (Eby et al. 2013), this particular study evaluated swine muscle stiffness with skin and subcutaneous fat stripped from the muscle. Therefore, it is feasible that skin and subcutaneous fat could have confounded our elastography results. Future research is needed to fully understand the effect of skin and subcutaneous fat on human muscle stiffness, as measured in the current study *in-vivo*.

Conclusions

The Nordic hamstring exercise was a good training exercise for muscle growth; muscle volume, not fascicle length, increased following the intervention. It can now be hypothesized that the mechanism behind the NH exercise reducing hamstring injury risk is its ability to increase muscle size, not increase muscle fiber length; as is commonly assumed, nor increase tissue stiffness. Future NH research may study the effects of knee ROM during training on fascicle length and strength adaptations. Continued exploration of the mechanics behind the NH strength training exercise, shown to reduce hamstring injury, is a necessary step in understanding muscular adaptations to resistance exercise and enhancing training effectiveness of mitigating hamstring muscle injury.

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