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The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation

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ABSTRACT

Purpose To determine the time course of architectural adaptations in the biceps femoris long head (BF_{LH}) following high or low volume eccentric training. **Methods:** Twenty recreationally active males completed a two week standardised period of eccentric Nordic hamstring exercise (NHE) training, followed by four weeks of high (n=10) or low volume (n=10) training. Eccentric strength was assessed pre and post intervention and following detraining. Architecture was assessed weekly during training and after two and four weeks of detraining **Results:** After six weeks of training, BF_{LH} fascicles increased significantly in the high (23 ± 7%, P<0.001, d=2.87) and low volume (24 ± 4%, P<0.001, d=3.46) groups, but reversed following two weeks of detraining (high volume, -17 ± 5%, P<0.001, d=-2.04; low volume, -15 ± 3%, P<0.001, d=-2.56) after completing the intervention. Both groups increased eccentric strength after six weeks of training (high volume, 28 ± 20%, P=0.009, d=1.55; low volume, 34 ± 14%, P<0.001, d=2.09) and saw no change in strength following a four week period of detraining (high volume, -7 ± 7%, P=0.97, d=-0.31; low volume, -2 ± 5%, P=0.99, d=-0.20). **Conclusions:** Both low and high volume NHE training stimulate increases in BF_{LH} fascicle length and eccentric knee flexor strength. Architectural adaptations reverted to baseline levels within two weeks after training, but eccentric strength is maintained for at least four weeks. These observations provide novel insight into the effects of training volume and detraining on BF_{LH} architecture, and may provide guidance for the implementation of NHE programmes.

Key words: fascicle length, eccentric training, muscle architecture, ultrasound.

INTRODUCTION

Hamstring strain injury (HSI) is the most common non-contact injury in many running based sports [1-3] and approximately 80% of all injuries involve the biceps femoris long head (BF_{LH}).[2, 4-6] Despite significant research efforts in the previous decade, HSI incidence has not declined [3, 7] and in some sports has increased.[8, 9] The financial burden associated with an average 14 day HSI in European football teams is estimated to be up to £250,000 (AUD $359,409).[10]

Recently, it has been reported that elite footballers with BF_{LH} fascicles shorter than 10.56cm were ~4 times more likely to suffer a HSI in the subsequent season than athletes with longer fascicles.[5] In this cohort, a 0.5cm increase in fascicle length was sufficient to reduce the risk of HSI by 74%.[5] Low levels of eccentric knee flexor strength have also been associated with an increased risk of HSI in elite football, and greater levels of eccentric strength have been associated with lesser risk.[5] These data suggest that interventions aimed at increasing BF_{LH} fascicle lengths and eccentric knee flexor strength should be prioritised in HSI prevention programmes.

Eccentric conditioning has proven extremely effective in the prevention of first time and recurrent HSI.[11-13] For example, a large-scale randomised controlled trial employing an eccentric Nordic hamstring exercise (NHE) intervention reported reductions in first time and recurrent HSIs of ~60 and 85% in Danish professional and amateur football players.[11] While the mechanism(s) by which the NHE confers injury preventive benefits may not be fully understood, four to ten weeks of training with this exercise has been shown to stimulate increases of 1.9 to 2.2cm in BF_{LH} fascicle length [14, 15] and improvements of 7 to 27% in eccentric knee flexor strength.[15-17] However, four to six weeks of NHE training have also resulted in no changes in fascicle length [18] or eccentric knee flexor strength.[18, 19] Increases in BF_{LH} fascicle length and improvements in eccentric knee flexor strength have also been observed after 6 to 10 weeks of eccentric training utilising isokinetic dynamometry [20] and eccentric prone leg curls [21] which suggests that eccentric conditioning is a robust stimulus for improving these parameters. However, all of the aforementioned investigations have employed high volumes (~100 weekly repetitions) of training, and it remains unclear as to whether BF_{LH} architecture and eccentric strength would respond similarly to lower volumes of the same exercise stimulus. Examining the adaptation in response to lower volume training protocols is warranted, as high training volumes are a proposed reason for a lack of compliance to the evidence based NHE.[22] There is also little available evidence on the time course of architectural and strength adaptations, particularly to NHE training, and whether these adaptations are maintained during periods of detraining.

The primary aim of this study was to determine the effect of either a high or low volume eccentric NHE training intervention on BF_{LH} architecture and eccentric knee flexor strength. In addition, we aimed to determine the time course of BF_{LH} architectural adaptations over the course of the six week intervention and throughout a 28 day detraining period. It was hypothesised that individuals in the high volume group would display greater increases in BF_{LH} fascicle length and eccentric strength after six weeks when compared to the low volume training group. It was further hypothesised that these adaptations would be maintained across the detraining period in the high volume training group, but not in the low volume training group.

METHODS

Study design

Twenty recreationally active males (age 22.3 ± 2.8 yrs; height 179.1 ± 7.7cm; body mass 75.1 ± 8.8kg) with no history of lower limb, hamstring, back, hand or wrist injury in the previous

36 months were recruited to participate in this longitudinal training study. All participants provided written informed consent prior to participation. The investigation was conducted at the Australian Catholic University, Fitzroy, Victoria, Australia and ethical approval was granted by the Australian Catholic University Human Research Ethics Committee (ethical approval number: 2016-20H)

On their first visit, participants were familiarised to the NHE during which their initial training load was determined. At least five days following the familiarisation session (median, 6 days; range, 5 to 21 days), participants underwent maximal eccentric knee flexor strength testing during the NHE and had their BF_{LH} architecture assessed. All participants then began a standardised two week period of NHE training (Table 1). Following this, participants were paired according to their baseline BF_{LH} fascicle length, and randomly assigned to either a high or low volume training group (allocation ratio, 1:1). Both groups then completed a further four weeks of training where the high volume group progressively increased volume, whereas the low volume group completed a maximum of eight repetitions per week (Table 1). Within 7 days (mean, 6.0 ± 1.2 days) of completing the intervention, all participants had their BF_{LH} architecture and maximal eccentric knee flexor strength reassessed. Participants then underwent a four week period of detraining, where BF_{LH} architecture was reassessed after 14 days (mid detraining) and 28 days (end detraining). Eccentric knee flexor strength was only assessed after 28 days of detraining to avoid influencing muscle architecture characteristics. For the duration of the study, participants were asked to maintain habitual levels of physical activity, but were specifically required to refrain from any resistance training exercise involving the hamstrings.

Nordic hamstring exercise intervention

All training was completed on a NHE field testing device.[23] Participants were required to kneel on a padded board with their ankles secured in braces located superior to the lateral malleolus. The ankle braces were attached to uniaxial load cells (Delphi Force Measurement, Gold Coast, Australia) with wireless data acquisition capabilities (Mantracourt, Devon, UK) which were secured to the board via a pivot which allows generated knee flexor force to be measured through the longitudinal axis of the load cells.[23] In this kneeling position, participants were instructed to either cross their arms over the chest (if performing the exercise without additional load) or to hold a weight centred to the xyphoid process and keep their hips fully extended throughout the movement. In this position, participants were instructed to lean forwards and slow their descent as much and as far as possible. Participants were instructed to continue resisting maximally until either their hands or the held weight touched the mat. Only the eccentric/lowering portion of the exercise was performed and participants were instructed to use their arms to push themselves back to the starting position. Where participants were observed to have sufficient strength to completely control the movement in the final 10-20^{o} of the NHE, they were then required to hold a weight plate (range, 5 to 25kg) to ensure supramaximal exercise intensity was maintained. Additional weight was added in increments of 2.5kg. During all testing and training sessions, strong verbal encouragement was provided to participants to ensure maximal effort in each repetition. All strength data was recorded during all training and testing sessions, and verbal feedback of peak eccentric strength values (N) was given to provide incentive for maximal efforts. Where possible, each participant completed training and testing at a similar time of day throughout the study. Only one participant missed more than two training sessions and they were removed from the study.

Following the conclusion of the two week standardised training period, participants were stratified into groups and completed a further four weeks of either high or low volume training (Table 1). During this period the low volume intervention group had no progression in volume, though additional training weight was added where necessary, as described above.

The high volume group (protocol derived from Bourne et al 2017) increased in volume progressively over the four week period, whilst also adding weight when satisfying the load progression criteria. The area under the force-time curve, reported as Impulse (N.s), was calculated for every repetition performed in the study as an additional marker of the difference in exercise exposure between groups. Impulse from each repetition was summed for each participant on a weekly basis and reported as group means.

Eccentric knee flexor strength testing

Eccentric strength was assessed pre intervention, end intervention and end detraining utilising the NHE field testing device (NordBord, Vald Performance, Queensland, Australia).[23] Prior to testing, participants completed a standard warm up protocol consisting of one repetition at each of 50, 75 and 95% of their perceived maximum effort. Following a rest period of two minutes, participants were then instructed to complete one set of three maximal NHE repetitions holding their initial load (identified during their familiarisation session). The largest eccentric strength value during each repetition of the NHE from each limb was measured, and the average of the three peak values was recorded. During end intervention and end detraining assessments, a set of three maximal NHE repetitions was also performed using the final weight the participant had progressed to by the end of the training period.

Biceps femoris long head architectural assessment

Architectural characteristics of the BF_{LH} were assessed utilising two-dimensional, B-mode ultrasonography (frequency,12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-i, Wauwatosa). Ultrasound images were taken along the longitudinal axis of the muscle belly at the halfway point between the popliteal crease and the ischial tuberosity. To ensure future reproducibility of the assessment site, the distances between this point and nearby anatomical landmarks (posterior knee joint fold at midpoint between biceps femoris and semitendinosus tendons, ischial tuberosity and fibular head) were recorded. All subsequent assessments utilized this same site. Participants underwent all ultrasound imaging in a prone position with a neutral hip and knee prior to any training or testing and after being inactive for at least 5 minutes beforehand.

All architectural assessments and analyses were completed by the same experienced assessor (R.G.T) with previously published reliability data [24] and was blinded to participant ID, group and time. Ultrasound imaging was completed by placing a layer of conductive gel on the skin overlying the pre-determined assessment site, where the linear array ultrasound probe was longitudinally aligned perpendicular to the posterior thigh. Minimal pressure was applied to the skin during ultrasound imaging to reduce potential impact on measurement accuracy.[25]

All analyses of ultrasound images were performed offline (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was defined as the distance between superficial and intermediate aponeuroses of the BF_{LH}. Pennation angle was determined by outlining and marking a fascicle of interest on the image and measuring the angle between this fascicle and the intermediate aponeuroses (Figure 1). Aponeurosis angle (superficial and intermediate) was defined as the angle between the marked aponeuroses and a line which intersected horizontally across the image. As entire fascicles were not visible in the linear array probe's field of view, fascicle length was estimated utilising a previously validated equation [26] and reported in absolute terms (cm):

$$FL = \sin(AA + 90°) \times MT \div \sin(180° - (AA + 180° - PA))$$

Where FL= fascicle length, AA= aponeuroses angle, MT= muscle thickness and PA= pennation angle

Statistical analyses

Statistical analyses were completed using JMP version 10.0.0 (SAS Institute Inc., Cary, NC, 1989-2007). Where appropriate, data were screened for homoscedasticity and normality using Levene's and Shapiro-Wilks tests, respectively. Greenhouse-geisser adjustments were performed where assumptions of sphericity were violated. A split-plot design analysis of variance (ANOVA) was used to compare BF_{LH} architectural variables between groups across the intervention period. For this analysis, the within-group variable was time (pre intervention [day 0], day 7, day 14, day 21, day 28, day 35, end intervention [day 42], mid detraining [day 56], end detraining [day 70]). As BF_{LH} architecture did not differ between limbs (dominant vs non-dominant) at any time point ($p>0.05$), an average of the two limbs was used throughout the study. To determine the effect of training on eccentric knee flexor strength, a split-plot design ANOVA was again used. For this analysis, the within-group variable was time (pre intervention [day 0], end intervention [day 42], end detraining [day 70]) and the between-group variable was group (high or low volume). As strength did not differ between limbs (dominant vs non-dominant) at any time point ($p>0.05$), a two-limb average was used. Where significant main or interaction effects of architecture and strength variables were detected, *post hoc* t tests with Tukey's corrections were applied to determine where any differences occurred. Significance was set at $p<0.05$ for all analysis. Where appropriate, Cohen's *d* was also reported for the comparison of effect sizes which were classified as small ($d = 0.20$), medium ($d = 0.50$) or large ($d = 0.80$) (Cohen, 1988).

Sample size calculations

Calculations of sample size were performed *a-priori* using G*Power, version 3.1.9.2.[27] These calculations were based on estimated differences in fascicle length following the six week intervention. The effect size was derived from the most conservative effect available in the relevant literature, where a 16% increase in BF_{LH} fascicle length was shown following 6 weeks of eccentric training (d = 2.5). The effect size utilised in the current study was conservatively set at half of the report effect from Timmins et al (2016). Therefore, a sample size of 10 participants per group was deemed sufficient with an effect size of 1.25, with power set at 80%, an alpha level of <0.05 and accounting for a 10% drop out rate.

RESULTS

Participants in the low volume (age 22.3 ± 3.2 years; height 176.3 ± 9cm; body mass 76.3 ± 10.3kg) and high volume (age 22.2 ± 2.6 years; height 181.9 ± 5.3cm; body mass 73.8 ± 7.2kg) groups were similar in age, body mass and height (*p*>0.05). The low volume group completed all training sessions (100% compliance), whereas the high volume group completed 99.2% of all available sessions (119 of 120 sessions).

The impulse recorded during the NHE from participants in the high volume group was 3.2 times greater across the duration of the study compared to the low volume group (see Supplementary table 1).

Biceps femoris long head architectural adaptations

A summary of the BF_{LH} architectural adaptations following the intervention and detraining periods can be found in Figures 2A, 2B and 2C and Tables 2 and 3.

Fascicle length

A significant main effect of time was found for fascicle length (*p*<0.001) however no significant interaction between group and time (*p*=0.982) was detected. *Post hoc* analyses showed an increase in fascicle length in both high and low volume groups at the end of the intervention in comparison to pre intervention fascicle length (high volume; mean difference, 2.4cm; 95% CI, 1.1 to 3.7cm; *p*<0.001, *d*=2.87; low volume; mean difference, 2.4cm; 95% CI, 1.1 to 3.7cm; *p*<0.001, *d*=3.46). Shortening of BF_{LH} fascicles was found in both training groups at mid detraining (high volume; mean difference,-2.2cm; 95% CI, -3.5 to -0.85cm; *p*<0.001, *d*=-2.04; low volume; mean difference, -1.9cm; 95% CI, -3.2 to -0.6cm; *p*<0.001, *d*=-2.56) and end of detraining (high volume; mean difference, -2.5cm; 95% CI, -3.9 to -1.1cm; *p*<0.001, *d*=-2.44; low volume; mean difference, -2.2cm; 95% CI, -3.5 to -0.9cm; *p*<0.001, *d*=-2.93) when compared to the end of the intervention period. No between group differences in fascicle length were found when comparing pre intervention to mid detraining (high volume; mean difference, 0.2cm; 95% CI, -1.1 to 1.5cm; *p*=1.00, *d*=0.21 ; low volume; mean difference, 0.5cm; 95% CI, -0.8 to 1.8cm; *p*=1.00, *d*=0.71) or end detraining (high volume; mean difference, 0.1cm; 95% CI, -1.2 to 1.5cm; *p*=1.00, *d*=-0.13; low volume; mean difference, 0.2cm; 95% CI, -1.1 to 1.5cm; *p*=1.00, *d*=0.24) time points.

Pennation angle

Significant main effects for time (*p*<0.001) and group (*p*<0.001) were found for BF_{LH} pennation angle. However, no significant group and time (*p*=0.940) interaction was found for either training group. *Post hoc* analyses showed a significant decrease in pennation angle after the intervention period in the low volume group (mean difference, -2.7°; 95% CI, -4.6 to -0.8°; *p*<0.001, *d*=-2.21) but not in the high volume group (mean difference, -1.8°; 95% CI, -3.6 to 0.1°; *p*=0.077, *d*=-1.56). There was no change in pennation angle from the end of the intervention to the mid detraining period (high volume; mean difference, 1.8°; 95% CI, -0.1 to 3.7°; *p*=0.060, *d*=1.75; low volume; mean difference, 1.7°; 95% CI, -0.1 to 3.6°; *p*=0.098, *d*=1.33) but these increases were significant after four weeks of detraining for both groups (high volume; mean difference, 2.1°; 95% CI, 0.2 to 4.0°; *p*=0.016, *d*=1.83; low volume; mean difference, 2.3°; 95% CI, 0.4 to 4.1°; *p*=0.003, *d*=1.99). No significant differences were found when pre intervention and mid detraining (high volume; mean difference, 0.1°; 95% CI, -1.8 to 1.9°; *p*=1.00, *d*=0.03; low volume; mean difference, 0.4°; 95% CI, -1.4 to 2.3°; *p*=1.00, *d*=0.68) or end detraining pennation angle were compared (high volume; mean difference, 0.32°; 95% CI, -1.6 to 2.2°; *p*=1.00, *d*=0.24; low volume; mean difference, 0.4°; 95% CI, -1.4 to 2.3°; *p*=1.00, *d*=0.32).

Muscle thickness

A significant main effect of group was detected when comparing BF_{LH} muscle thickness ($p<0.001$). No main effect of time was observed ($p=0.968$), nor was any significant interaction effect detected between group and time ($p=0.99$); therefore no post hoc tests were performed.

Eccentric knee flexor strength adaptations

A summary of the strength adaptations following the intervention and detraining periods can be found in Figures 2D and in Table 4.

Significant main effects of time ($p<0.001$) and group ($p=0.018$) were found for eccentric strength however no interaction effects were observed between group and time ($p=0.639$). *Post hoc* analyses identified that eccentric strength was significantly greater at the end of the intervention compared to pre intervention for both training groups (high volume; mean difference, 112N; 95% CI, 19 to 204N; $p=0.009$, $d=1.55$; low volume; mean difference; 142N; 95% CI, 49 to 235N; $p<0.001$, $d=2.09$). However, there were no significant differences in eccentric strength from end intervention compared to end detraining in either training group (high volume; mean difference, -24N; 95% CI, -119 to 71N; $p=0.97$, $d=-0.29$; low volume; mean difference, -14N; 95% CI, -106 to 79N; $p=0.99$, $d=-0.19$). Eccentric strength after four weeks of detraining was significantly higher than pre intervention strength in the low volume training group (mean difference, 129N; 95% CI, 36 to 222N; $p=0.002$, $d=2.07$) but not in the high volume training group (mean difference, 87N; 95% CI, -8 to 183N; $p=0.090$, $d=1.36$).

DISCUSSION

This study is the first to investigate the effects of high or low volume NHE training on BF_{LH} architecture and eccentric strength. We have provided novel data to suggest that (1) BF_{LH}

fascicle length and eccentric knee flexor strength adaptations respond similarly to both high and low volume NHE training following a standardised two week training period, (2) training-induced fascicle length changes reverse after a two week period of detraining and (3) both training groups preserved strength adaptations after a four week period of detraining.

Fascicle lengthening is one likely mechanism by which the NHE confers injury preventive benefits to HSI. For example, recent evidence suggests that elite Australian soccer players with short BF_{LH} fascicles at the start of pre-season (<10.56cm) are four times more likely to suffer a HSI in the subsequent season than those with longer fascicles.[5] Furthermore, for every 0.5cm increase in BF_{LH} fascicle length, the risk of future HSI was reduced by 74%.[5] In the current study, participants in both the high and low volume NHE training groups lengthened their BF_{LH} fascicles by ~1cm after 2 weeks and ~2.4cm after 6 weeks of training. These adaptations would be expected to result in reductions in hamstring strain injury risk.

The NHE has proven effective in reducing HSIs in a number of large-scale randomised controlled trials.[11, 12, 28] Despite these observations, compliance to evidence based protocols is poor with only 11% of surveyed UEFA teams claiming to implement these programmes.[22] One possible explanation is that the high volume protocols advocated in the literature [29] may not be practical in an elite sporting environment.[11] For example, the aforementioned RCTs have typically employed three sessions per week of ~30 repetitions, which may be effectively implemented at amateur levels of competition, but may not be feasible in elite sport where athletes are typically involved in a significant volume of other training and match play. However, prior to this work, it was unclear what effect low volume training interventions have on previously identified risk factors for HSI, such as BF_{LH} architecture and eccentric strength. Our data suggest, for the first time, after a standardised two week training period, four weeks of high volume NHE training is no more effective than a low volume protocol for lengthening BF_{LH} fascicles and increasing eccentric strength. In the current study, the low volume group saw BF_{LH} fascicle lengthening of 24% after six weeks of NHE training, or a further 5% after training with as little as eight repetitions for four weeks. This is in contrast with 23% for the high volume group who performed up to 100 repetitions per week and experienced a further 6% increase in fascicle length over four weeks, despite additional volume during this period. It would be of interest to reverse the order of the training periods and perform the low or high volume training periods first. With this reversed design, perhaps the low volume training group would experience a more gradual fascicle length adaptation across the first four weeks of training compared to the high volume group. Earlier work employing high volumes of NHE reported BF_{LH} fascicle length increases of 12 to 24% [14, 15, 30, 31] while others observed a 16% increase after six weeks of high volume eccentric training on an isokinetic dynamometer.[20] However, one study saw no change in BF_{LH} fascicle length following 6 weeks of NHE training. Collectively, these data highlight the effectiveness of eccentric conditioning for lengthening BF_{LH} fascicles.

Increases in fascicle length presumably result from the proliferation of in series sarcomeres, as has been reported after five days of downhill running in rats.[32] Lynn & Morgan (1998) proposed that this increase of serial sarcomeres would lead to a shift in force-length relationship, thereby increasing a muscles strength at longer lengths and reducing its susceptibility to damage during active lengthening.[33] However, fascicle lengthening due to increases in tendon stiffness is one possible alternative explanation.[34] Clearly, further research is needed to fully understand the mechanism(s) underpinning fascicle lengthening.

The time course of architectural adaptations resulting from training or detraining is important from the perspective of optimising hamstring injury prevention and rehabilitation programmes. The results of this study suggest that significant increases in BF_{LH} fascicle length can be achieved in as little as 14 days of NHE training (Figure 2A). These observations are in line with earlier work by our group demonstrating increases in fascicle length within 14 days of commencing eccentric training on an isokinetic dynamometer.[20] However, this is the first study to identify reductions in BF_{LH} fascicle length (-17 to -15%) after a detraining period of only two weeks. These results suggest the removal of an eccentric training stimulus can, within two weeks, result in a reversal of fascicle length adaptations gained from training, which may have implications for the application and frequency of eccentric exercise as a means to mitigate the risk of HSI.

Eccentric strengthening is an important component of HSI prevention programmes [35] on the basis that eccentric knee flexor weakness may predispose to future injury.[5, 36] For example, elite Australian footballers and professional soccer players with low levels of eccentric knee flexor strength in pre-season were four times more likely to suffer an HSI in the following season than stronger athletes. In the current study, both the high and low volume training groups significantly increased eccentric knee flexor strength by 28 and 33% (112 and 142N) respectively following the six week intervention (Figure 2D). This is in line with earlier observations by of a 27% increase in eccentric knee flexor strength following 10 weeks of high volume NHE training.[15] Further, training interventions employing an eccentric prone leg curl,[21] or eccentric-only knee flexion training using an isokinetic dynamometer,[20] observed increases in eccentric knee flexor strength of 34 and 17% respectively. It is also noteworthy that neither intervention group in the current study appeared to decrease strength after four weeks of detraining, which is in line with earlier observations.[20] However, it has been speculated that decreases in strength observed following an eight week period of detraining may have been caused by an observed reduction in neural activity.[37] This may indicate that eccentric knee flexor strength adaptations in the current study were the result of neural, not morphological or architectural adaptations and that a lengthier detraining period could possibly have achieved a detraining effect on strength. Both training groups saw increases in weekly impulse from the beginning to end of the low or high volume training periods (high volume, 57%; low volume, 5.8%) which aligns closely with the alterations in total weekly repetitions across this period (high volume, 56%; low volume, 0%). These data suggest that improvements in eccentric knee flexor strength can be achieved using very low volumes of training (expressed in terms of total repetitions or impulse) and that these adaptations can be maintained across short periods of detraining. These findings may also dictate that the intensity of contraction is of more relevance than training volume to the adaptive response of the hamstrings to eccentric exercise, however, further work would be required to confirm this premise.

There are some limitations associated with this study that should be acknowledged. During the NHE, participants were instructed to resist their descent maximally until contact was made with the ground. Even so, range of motion and velocity during the NHE may not have been uniform across participants. It is possible that range of motion and velocity may have influenced the extent of architectural adaptations. However, as this is how the NHE is prescribed in the field, the findings from this study have implications for practical implementation of the exercise. Intervention studies investigating muscle length of employed exercises during training have found little impact on muscle architecture adaptation.[38, 39] Finally, the use of two-dimensional ultrasound to estimate fascicle length has some associated methodological limitations. Entire BF_{LH} fascicles are too large for the field of view used in this study, thus an estimation of fascicle length was required. Although there is inherent error in using estimations of fascicle length, the equation used [26] has previously been validated against cadaveric measurements.[40] Future research should consider the use of extended field of view ultrasonography [41] to minimise potential error.

In conclusion, both high and low volume NHE training produces similar BF_{LH} fascicle length and eccentric knee flexor strength adaptations following training. Increases in BF_{LH} fascicle length were found within two weeks of training and similar magnitude decreases were observed after two weeks of detraining. However, neither training group experienced significant reductions in eccentric strength after a 28 day period of detraining. These results provide novel insight into the effect of training volume on muscle architecture and eccentric knee flexor strength which may have implications for hamstring injury prevention and rehabilitation programs. Further research is required to better clarify the dose-response relationship between eccentric exercise and minimising HSI risk.

PERSPECTIVE

The current study found that the prescription of either high or low volumes of the NHE across a 6 week period resulted in similar increases in eccentric knee flexor strength and BF_{LH} fascicle length. Given the association between eccentric strength and BF_{LH} fascicle length and future risk of HSI, the current data provides some support for the implementation of low volume exposures of the NHE for prophylactic purposes. Whether such low volume prescriptions of the NHE do result in actual reductions in HSI risk requires further investigation via a randomised control trial.

Competing interests: DAO is a listed co-inventor on an international patent application filled for the experimental device used to measure eccentric knee flexor strength during the Nordic hamstring exercise (PCT/AU2012/001041.2012). No other competing interests are declared.

Contributors: JDP was primarily responsible for recruitment, statistical analysis, data collection and manuscript writing. RGT performed all architecture data collection and analysis. DAO, MDW, MNB and RGT were responsible for study design. MDW, RGT, DAO were involved in statistical analysis. DAO, RGT, MNB and MDW assisted in manuscript writing.

Ethical approval: Ethical approval was granted by the Australian Catholic University Human Research Ethics Committee (ethical approval number: 2016-20H).

Data sharing statement: The authors are happy to provide data to other resarchers upon request.

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Figure legends

Figure 1. A two-dimensional ultrasound image of the biceps femoris long head with the architectural characteristics pennation angle, a partially visible fascicle, muscle thickness, and superficial and intermediate aponeuroses.

Figure 2. Absolute change in biceps femoris long head A) fascicle length, B) pennation angle, C) muscle thickness and D) eccentric strength across the six week training intervention and four week detraining periods. All data presented is a two-limb average of the dominant and non-dominant limb. All comparisons were within-group and compared to baseline. * $p<0.001$ vs baseline, # $p<0.05$ vs baseline. Error bars specify standard deviation from the mean.