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Hamstring Muscle-Tendon Geometric Adaptations to Resistance Training Using the Hip Extension and Nordic Hamstring Exercises

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ABSTRACT

Targeted resistance training stimulates hamstring muscle hypertrophy, but its effect on tendon-aponeurosis geometry is unknown. This study examined changes in hamstring muscle, free tendon, and aponeurosis geometry following a 10 week Nordic or hip extension exercise intervention. Thirty recreationally active males were randomly allocated ($n=10$ per group) to a Nordic, hip extension, or control group. Magnetic resonance imaging of both thighs was acquired pre- and post-intervention. Changes in free tendon and aponeurosis volume for each hamstring muscle, biceps femoris long head (BFlh) aponeurosis interface area and muscle volume-to-interface area ratio were compared between groups. Regional changes in muscle CSA were examined via statistical parametric mapping. The change in semimembranosus free tendon volume was greater for the Nordic than control group (mean difference = 0.06 cm^3, 95% CI = 0.02–0.11 cm^3). No significant between-group differences existed for other hamstring free tendons or aponeuroses. There were no between-group differences in change in BFlh interface area. Change in BFlh muscle volume-to-interface area ratio was greater in the hip extension than Nordic (mean difference = 0.10, 95% CI = 0.007–0.19, $p=0.03$) and control (mean difference = 0.12, 95% CI = 0.03–0.22, $p=0.009$) groups. Change in muscle CSA following training was greatest in the mid-portion of semitendinosus for both intervention groups, and the mid-portion of BFlh for the hip extension group. There was limited evidence for tendon-aponeurosis hypertrophy after 10 weeks of training with the Nordic or hip extension exercises. For the BFlh, neither intervention altered the interface area although hip extension training stimulated an increase in the muscle volume-to-interface area ratio, which may have implications for localized tissue strains. Alternative muscle-tendon loading strategies appear necessary to stimulate hamstring tendon adaptations.

1 | Introduction

Hamstring strain injuries are common in running-based sports [1, 2] and require prolonged recovery periods. Most hamstring strains affect the musculotendinous junction of the biceps femoris long head (BFlh) [3] and are typically sustained during forceful eccentric contractions. The hamstrings are also a key contributor to high-speed running performance, with muscle volume differentiating elite from sub-elite or untrained populations [4, 5]. Strength training is an important component of hamstring injury prevention and performance and there has been considerable interest in exploring the architectural [6], morphological [7, 8] and performance effects [9, 10] of training with different exercises. However, it is unclear whether corresponding geometric adaptations occur in the free tendon and/or aponeurosis.

Larger tendons tend to be stiffer [11] and play a role in both muscle-tendon injury prevention [12] and efficiency [13]. Additionally, tendon and aponeurosis geometry has a significant impact on the stresses and strains experienced by the adjoining muscle. For example, finite element modeling and dynamic MRI have revealed that a narrow proximal BFlh aponeurosis relative to a wide muscle increases the magnitude of muscle fiber strain at the proximal musculotendinous junction during active lengthening [14–16]. As a consequence, BFlh proximal aponeurosis size has been proposed as a risk factor for strain injury [17]. Recent data suggests that 12 weeks of lengthened state eccentric knee flexor training stimulates a greater increase in BFlh aponeurosis area than the Nordic hamstring exercise [18]; however, no study has examined the effect of hip extension training on this parameter, nor quantified the relative change in BFlh muscle to aponeurosis size. Conceivably, interventions that promote increases in BFlh aponeurosis interface area while having limited effect on muscle volume might be considered favorable for injury risk. To date, no study has examined the effect of resistance training on the geometry of all hamstring tendons and aponeuroses or the BFlh muscle volume-to-interface area ratio.

The choice of exercise and associated programming variables may have a significant impact on the muscle-tendon unit responses to training [19]. For example, hip-dominant exercises preferentially activate [20, 21] and load [22] the BFlh and semimembranosus while knee-dominant exercises selectively activate [20, 21] and load the semitendinosus and biceps femoris short head (BFsh) [22]. Such preferential loading elicits corresponding changes in muscle volume and CSA in healthy participants [7, 20]. We have previously demonstrated that 10 weeks of training with the 45° hip extension exercise promoted significantly more BFlh hypertrophy than the Nordic hamstring exercise (mean difference = 7%) [7], which preferentially developed the semitendinosus and biceps femoris short head (BFsh) [7]. Both exercises also increased BFlh fascicle length, which is associated with a reduced risk of hamstring injury [23]. Furthermore, as there is evidence of regional differences in hamstring muscle activation patterns [21, 24], it is also of interest to better understand regional geometric adaptation of the hamstrings to training with different exercises.

The primary aim of this study was to investigate the effect of 10 weeks of training with the Nordic or hip extension exercises on (1) hamstring tendon and aponeurosis volumes of all hamstring muscles, (2) regional changes in muscle CSA for all hamstrings, and (3) BFlh aponeurosis interface area. Given previously reported increases in tendon CSA following resistance training [25], we hypothesized that resistance training groups would induce increases in hamstring tendon and aponeurosis size relative to the control group. However, given that this is the first study to examine simultaneous hamstring muscle-tendon adaptations to resistance training, no specific hypotheses were set regarding expected differences between the resistance training groups.

2 | Materials and Methods

2.1 | Participants and Experimental Design

Thirty recreationally active men participated in the study. Participants were free from current trunk, pelvis, or lower limb injury, had no known history of hamstring or traumatic knee injury or other systemic health conditions, and were screened for MRI contraindications. Participants provided written informed consent. The study was approved by the Queensland University of Technology Human Research Ethics Committee and the University of Queensland Medical Research Ethics Committee [7].

This study is a secondary analysis of previously published magnetic resonance imaging (MRI) data, from a three-arm, randomized controlled trial [7]. Participants were stratified by baseline assessments of BFlh fascicle length and randomly allocated to control ($n = 10$; mean ± SD: 21.3 ± 3.7 years, 178.5 ± 5.4 cm, 75.9 ± 11.8 kg), Nordic exercise ($n = 10$; mean ± SD: 21.6 ± 3.2 years, 182.8 ± 8.7 cm, 85.0 ± 10.9 kg) or hip extension exercise ($n = 10$; mean ± SD: 23.1 ± 4.1 years, 179.8 ± 1.6 cm, 81.6 ± 9.8 kg) groups. Participants in resistance training groups undertook twice-weekly, supervised, and progressively overloaded training with their allocated exercise for 10 weeks (20 training sessions; Table 1), while control participants continued their regular activity. Participants were instructed to avoid any other lower limb resistance training. Exercise sessions were separated by a recovery period of at least 48 h. The Nordic exercise was performed with participants kneeling, the hips maintained in extension, and ankles secured superior to the lateral malleoli (Figure 1). The exercise was initially performed with bodyweight only and participants lowering as slowly as possible until prone. When participants were able to control the exercise (i.e., stop) in the final 10°–20° of the range of motion, load was held to the chest (centered to the xiphoid process) in increments of 2.5 kg (range = 2.5–20 kg) to ensure a supramaximal stimulus was maintained. Only the eccentric portion of the Nordic exercise was performed. For the hip extension, participants began with the spine and lower limb joints in the anatomical position and the exercised limb secured by a distal ankle pad. Participants lowered themselves through hip flexion until 90°

TABLE 1 | Intervention programming variables for the Nordic and hip extension exercise groups.

Week	Frequency	Sets	Repetitions
1	2	2	6
2	2	3	6
3	2	4	7
4	2	4	10
5–8	2	5	8–10
9	2	6	6
10	2	5	5

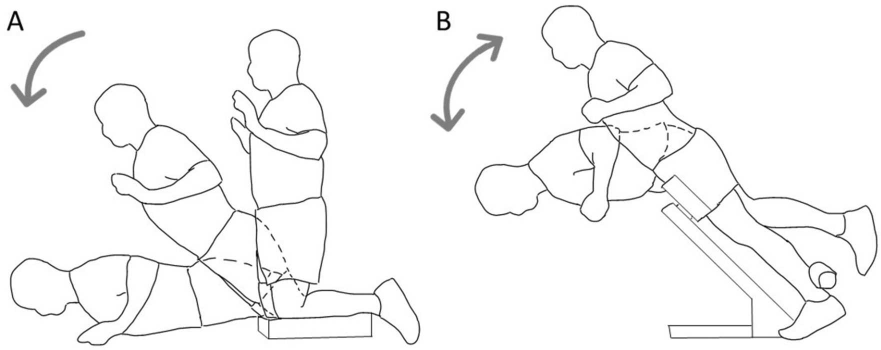

FIGURE 1 | Schematic representation of the Nordic (A) and hip extension (B) exercises.

was achieved, then returned to the start position. Spine and knee position was maintained throughout. Limbs were trained in an alternating pattern, with a 30s rest period to facilitate change over. In week 1, the hip extension group performed the exercise at an estimated 60%–70% of one repetition maximum (based on pre-training three repetition maximum testing), and in week two this increased to 70%–80% of one repetition maximum. In all subsequent weeks, hip extension participants completed training at maximal intensity of effort with external loads progressively increased based on their ability to complete the necessary repetitions and sets. The external load was applied to the hip extension exercise by holding weighted plates centered to the xiphoid process. Both groups progressively increased volume (see Table 1) with a reduction in repetitions to accommodate increased intensity in the final 2weeks. The inter-set rest period for both groups was 3min. MRI scans were acquired approximately 1 week pre- and post-intervention.

2.2 | Image Acquisition

MRIs were acquired of both thighs using a 3-Tesla scanner (Siemens TrioTim). Participants were positioned in supine, with knees and hips resting at neutral. Contiguous axial T1-weighted images were acquired from the iliac crest to the tibial plateau using a spinal coil (relaxation time = 750ms; echo time = 12 mx; field of view = 400mm; slice thickness = 10mm, post-processing = B1 filter).

2.3 | Image Processing

Two authors manually segmented the boundaries of muscle (MNB) and free tendons and aponeuroses of all hamstrings (SLL) for both limbs using either Sante DICOM Viewer and Editor (Cornell University; muscle only) or Materialise Interactive Medical Image Control System software (Mimics, v24.0, Materialise; tendon and aponeurosis only; Figure 2). Investigators were blinded to participant allocation. Tissues were segmented on all axial slices from the first to last slice in which they were clearly visible. Free tendons and aponeuroses were segmented as a continuous structure and subsequently subdivided based on the presence (aponeurosis) or absence (free tendon) of corresponding muscle tissue on each axial slice. CSA was extracted from each axial slice, for each tissue. Volume for each muscle, free tendon and aponeurosis was calculated as the product of summed axial CSAs and slice thickness. The 'spline' function in Mimics was used by one author (SLL) to manually trace the interface surface length (the contact border between the BFlh muscle and aponeurosis) on each axial slice in which it was visible [17, 26]. The BFlh interface area was calculated as the product of summed interface surface lengths and slice thickness [17]. The BFlh muscle volume-to-interface area ratio was calculated as the quotient of muscle volume and interface area.

To determine intra-rater reliability of manual hamstring tendon segmentations, all hamstring tendons and aponeuroses were segmented for a second time in five randomly selected participants and limbs. For the BFlh muscle-aponeurosis interface area, the interface visible on all axial slices was segmented for a second time on both limbs of five randomly selected participants. Intra-rater reliability was calculated using an absolute agreement of a single rater, two-way mixed effects model (Intraclass Correlation Coefficient$_{(3,1)}$, Table S1a) [27]. The standard error of the measurement (SEM) for hamstring free tendon volume ranged from 0.10 to 0.36 cm^3, and the minimal detectable change ranged from 0.28 to 1.00 cm^3. The standard error of the measurement for hamstring aponeurosis volume ranged from 0.26 to 0.92 cm^3, and the minimal detectable change ranged from 0.71 to 2.54 cm^3. The intra-rater reliability for BFlh interface area was excellent (Table S1b). The standard error of the measurement for interface area was 1.03 cm^2 and the minimal detectable change 2.86 cm^2.

2.4 | Statistical Analysis

Statistical analyses were performed using R programming language (version 4.3, in RStudio [28]). Linear mixed effects models (lme4 package) [29] were used to assess the effect of group (control, Nordic exercise, and hip extension exercise) and muscle (BFlh, BFsh, semitendinosus, semimembranosus) on changes in combined proximal and distal free tendon or aponeurosis volume. The effect of group on BFlh proximal aponeurosis interface area and muscle volume-to-interface area ratio was also investigated. For each outcome measure a linear mixed effects model was fitted using the following formula: absolute change ~ group * muscle + baseline measure + (1|ID). Group and muscle were included as an interacting fixed effect due to previous studies reporting variation in the recruitment of hamstring muscles during each exercise [20, 21]. Baseline measures of each outcome measure were also included as a fixed effect to account for any potential group

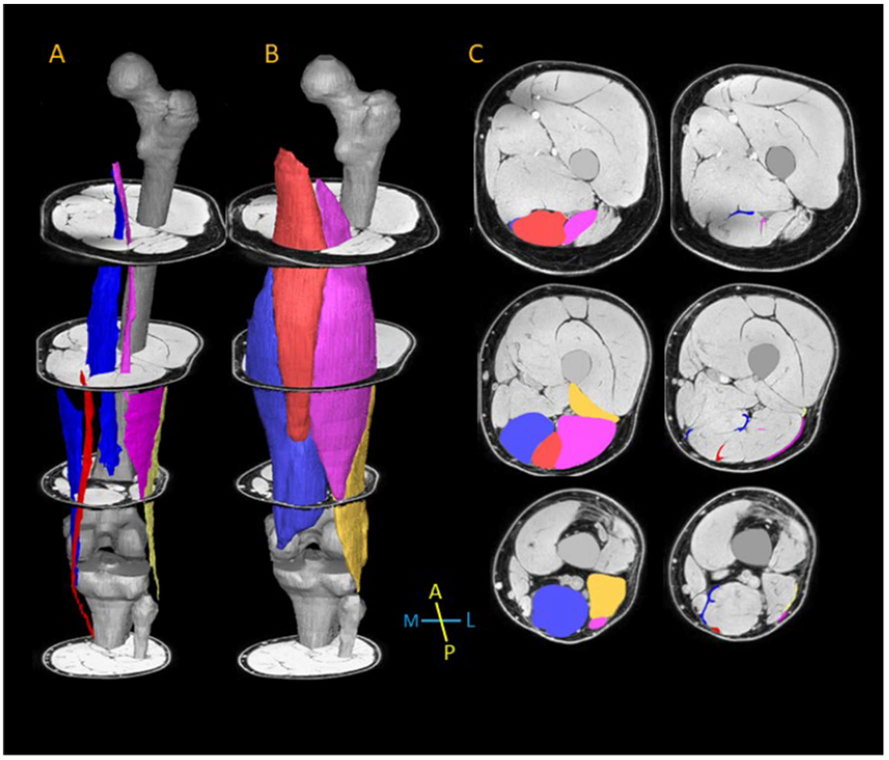

FIGURE 2 | Muscle and tendon segmentation from magnetic resonance imaging for a representative participant showing the posterior view of a right thigh. Shown are a 3D reconstruction of hamstring free tendons and aponeuroses (A) and color-matched muscle tissue (B) for the semimembranosus (blue), semitendinosus (red), biceps femoris long head (magenta), and biceps femoris short head (yellow), with corresponding axial slices shown (C).

variation in outcome measures. The participant was included as a random effect (random intercepts) to account for individual variation within the sample and enable multiple sample sites to be included per participant from the left and right legs, and the proximal and distal free tendons and aponeuroses. Additional models that included random effects for tissue type (aponeurosis and free tendon) and location (proximal and distal) were considered, with the final model selected based on the lowest Bayesian information criterion statistic. Post hoc analyses of the linear mixed effects models were performed using the 'emmeans' package [30]. Simple contrasts for the main effect of intervention group and muscle were performed separately using pairwise comparisons between all factor levels. *P* values for the absolute change in each outcome measure were calculated and considered statistically significant at $\alpha = 0.05$. *P* values were corrected for multiple comparisons using the multivariate *t* distribution ("mvt").

To assess regional differences in muscle geometry between groups, absolute and relative (percentage versus baseline) change in mean CSA along the length of muscle tissue was compared using one-dimensional statistical parametric mapping (SPM). Prior to conducting the SPM analysis, muscles, free tendons, and aponeuroses were normalized to 0%–100% of their length using linear interpolation, where the number of data points was based on the median number of slices across participants for each tissue. The 'spm1d' library in Python [31] was used to perform a continuous one-way ANOVA between intervention groups. Where a significant difference was identified ($\alpha = 0.05$), post hoc analysis was performed using a pairwise two-sample continuous *t*-test with Bonferroni corrections.

3 | Results

There were no significant differences in age, stature or mass between the control, hip extension, or Nordic exercise groups ($p > 0.05$). Compliance rates for intervention groups were excellent (Nordic exercise = 99.5%, hip extension exercise = 100% of planned sessions attended). No adverse events occurred as a result of the training interventions.

3.1 | Hamstring Aponeurosis and Free Tendon Volumes

There was a significant effect of group on semimembranosus free tendon volume with a larger training-induced increase in the Nordic exercise versus the hip extension group (mean difference: $0.06\,cm^3$, 95% CI = $0.02–0.11\,cm^3$, $p = 0.03$). There was no significant effect of group for the free tendons of any other hamstrings ($p = 0.33–1.00$; Figure S1). There was no significant effect of group on the change in aponeurosis volume for any hamstring ($p = 0.09–1.00$; Figure 3).

3.2 | BFlh Proximal Aponeurosis Interface Area and Muscle Volume-to-Interface Area Ratio

There was no significant effect of group on change in BFlh interface area ($p = 0.18–0.99$; Figure 4). There was a significantly greater increase in the BFlh muscle volume-to-interface area ratio in the hip extension group than the Nordic (mean

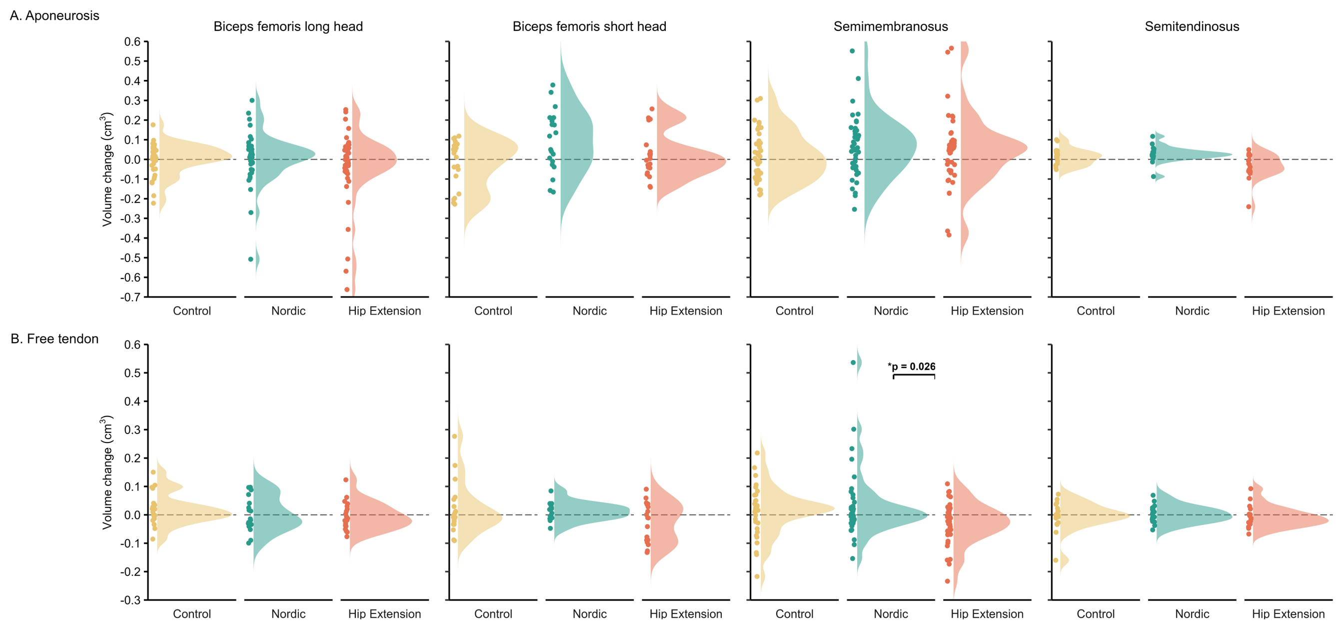

FIGURE 3 | Effect of group (Control, Nordic, Hip Extension) on change in aponeurosis (A) and free tendon (B) volumes by muscle. Curves represent density distribution functions fitted to individual participant data.

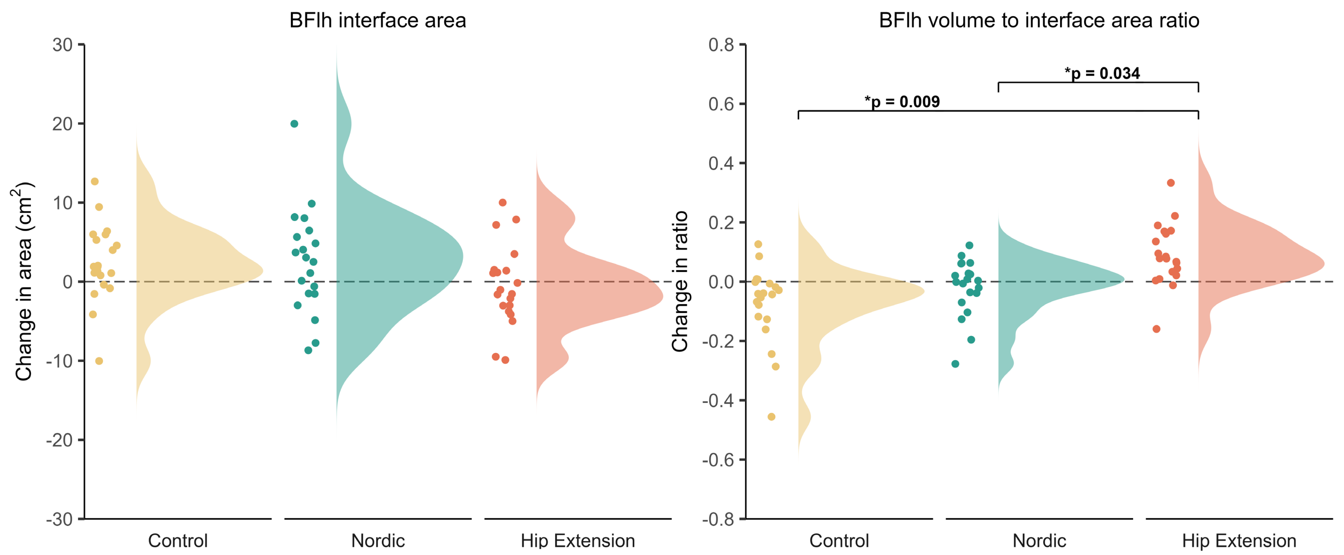

FIGURE 4 | Effect of group (Control, Nordic, Hip Extension) on change in biceps femoris long head proximal aponeurosis interface area and muscle volume-to-interface area. Curves represent density distribution functions fitted to individual participant data.

difference = 0.10, 95% CI = 0.01–0.19, $p = 0.03$) and control groups (mean difference = 0.12, 95% CI = 0.03–0.22, $p = 0.009$).

3.3 | Regional Changes in Muscle CSA

There was a main effect of group on the mean absolute increase in CSA for semitendinosus between 34% and 70% of its proximal-to-distal length ($p < 0.001$; Figure 5), and for BFlh between 47%–57% ($p < 0.009$) and 60%–67% ($p < 0.023$) of its proximal-to-distal length. Post hoc testing demonstrated a greater mean change in CSA of the semitendinosus for the Nordic group compared to the control group between 34% and 68% of muscle length ($p < 0.001$), and a greater mean change in semitendinosus CSA for the hip extension group compared to the control group between 39%–53% ($p < 0.001$) and 58%–66% ($p = 0.013$) of muscle length. The hip extension group displayed a greater mean change in BFlh CSA compared to the control group between 47%–51% ($p = 0.035$) and 61%–68% ($p = 0.015$) of muscle length. There was no main effect of group for either the BFsh or semimembranosus, and analyses did not surpass the critical F threshold.

There was a main effect of group on the mean relative (percentage change from pre- to post-intervention) change in CSA for semitendinosus between 33% and 71% of its proximal-to-distal length ($p < 0.001$; Figure 4), and for BFlh between 60% and 68% ($p = 0.007$) of its proximal-to-distal length. Post hoc testing demonstrated differences between semitendinosus regional change in the Nordic compared to the control group between 25%–27% and 34%–69% the normalized length of the muscle ($p < 0.001$ to 0.047), and the

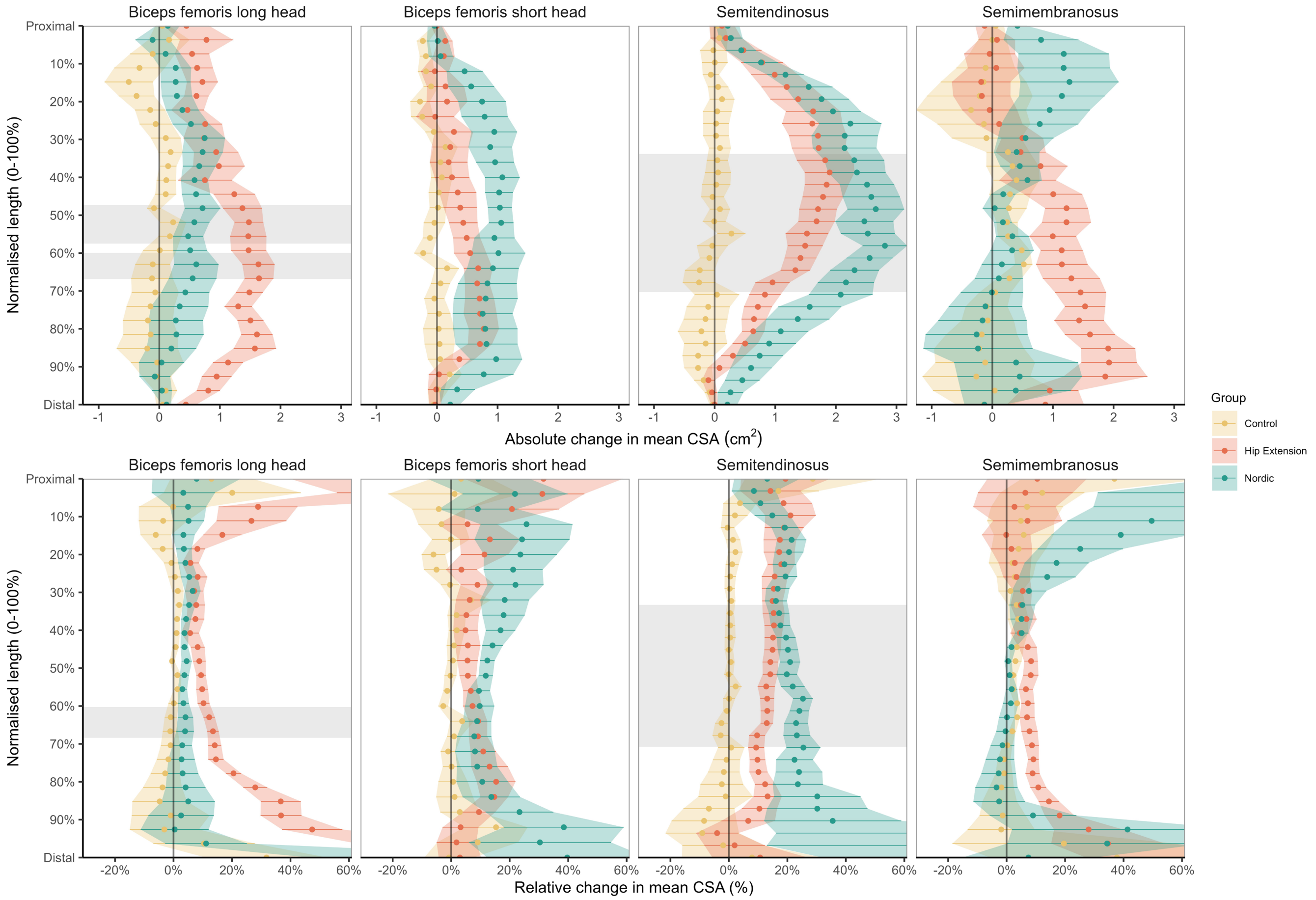

FIGURE 5 | Effect of group (Control, Nordic, Hip Extension) on regional change in absolute (top row) and relative (bottom row) cross-sectional area (CSA) for each muscle. Muscle length is expressed relative to resting length of the muscle tissue only (proximal to distal). Gray-shaded areas represent a main effect of group.

hip extension groups compared to the control group for the semitendinosus (38%–53% and 58%–66%, $p<0.001$ to 0.006) and BFlh (61%–69% and 77%–81%, $p=0.004$–0.033). There was no main effect of group for either the BFsh or semimembranosus, and analyses did not surpass the critical F threshold.

4 | Discussion

The main finding of this study was that despite the Nordic and hip extension exercises promoting significant increases in hamstring muscle size [7], there was limited evidence for corresponding increases in tendon or aponeurosis size [25]. These findings suggest that the 10week intervention period was of insufficient duration and/or training programming variables were not optimal to induce geometric change in hamstring free tendons and aponeuroses. Further, the hip extension exercise induced an increase in the size of the BFlh relative to the aponeurosis interface. Lastly, this study provided the first evidence of non-uniform regional increases in BFlh and semitendinosus muscle size in response to training. Taken together with findings from Bourne et al. [7] the main conclusion from this study is that hamstring muscle geometry appears to be more responsive to the training intervention than the free tendon/aponeurosis. Longer interventions, potentially involving greater mechanical strain, may be necessary to stimulate tendon or aponeurosis hypertrophy.

Group differences in free tendon volume due to training were restricted to small differences and in only one muscle. Although we observed a greater increase in semimembranosus free tendon volume in the Nordic group than the hip extension group, the magnitude of this difference was within the SEM, and caution should be applied when interpreting such changes. We also observed no evidence for training-induced increases in aponeurosis volume for any muscle. One recent study revealed that 12weeks of eccentrically biased knee flexor training performed on a seated leg curl stimulated significantly greater (+9%) increases in BFlh aponeurosis area than the Nordic hamstring exercise (+3%) [18]. Small increases in CSA of other healthy lower limb tendons and aponeuroses have been reported following resistance training studies of up to 14weeks [25]; however, this is the first study to examine training-induced adaptations of all individual hamstrings' free tendons and aponeuroses. It is possible that the 10week duration and programming of the present study was insufficient to induce tendon adaptation. For example, training performed at high compared to low strains is most effective for inducing positive tendon adaptation [25] and it is possible that the intensity of our intervention was suboptimal in this regard. Nevertheless, it should be acknowledged that both exercises were performed at maximal (hip extension) or supramaximal intensities of effort (Nordic) sufficient to promote significant increases in strength, muscle size and fascicle lengths [7].

No training-induced changes in BFlh aponeurosis interface area were found in the present study despite observations of increased BFlh muscle CSA and volume following hip extension training [7]. As a consequence, hip extension training stimulated a significant increase in the BFlh muscle volume to interface area ratio relative to the Nordic and control groups. Prior work suggests that possessing a narrower BFlh aponeurosis relative to muscle width increases the strain experienced adjacent to the muscle-tendon junction during active lengthening [14, 15, 32]. Training-induced increases in muscle size in the absence of corresponding aponeurosis adaptation might therefore increase the strain experienced at the musculotendinous junction during potentially injurious tasks (e.g., sprinting); however, future work is needed to confirm this hypothesis.

This is the first study to examine regional hamstring CSA adaptations in response to training. Hypertrophy was greatest in the mid portions of the semitendinosus and BFlh muscle bellies following hip extension and in the mid potions of BFlh after Nordic training, with no significant group differences observed in the most proximal or distal regions. Such alterations in MTU geometry may have consequences for function. For example, the lack of hypertrophy in distal regions may serve to minimize training-induced increases in the moment of inertia of the thigh, as has been shown for the quadriceps femoris [33], which might be considered favorable for sprint performance and running economy. Why such regional changes occur is somewhat unclear, however, regional differences in hamstring electromyographical activity [21, 24] and metabolic activity [24] have been observed previously, the latter of which has been associated with training-induced patterns of lower limb muscle hypertrophy [19, 34]. Further, non-uniform increases of key signaling molecules for skeletal muscle remodeling (i.e., focal adhesion kinase) have been reported in the vastus lateralis following knee-extension resistance training [35], which may be precursors to regional adaptation. However, whether the hamstrings exhibit regional change in signaling processes following hip- or knee-dominant exercises is unknown, as is the functional impact of regional CSA increases on localized fiber strains and athletic performance.

The main limitation of this study was that assessment of tendon adaptation was restricted to measurement of changes in tendon geometry and did not include measurement of tendon material properties (modulus), which can also influence localized tendon stresses and strains. Given the challenges associated with measuring modulus, future work is required to determine appropriate methods to accurately and reliably monitor this in the hamstrings. The MRI acquisition parameters were optimized for estimating muscle size, and therefore, some fine detail for tendon geometry was likely lost due to the thickness of slices. Consequently, we were unable to clearly visualize the semitendinosus proximal tendon which has a mean length of less than an individual axial slice (0.2 ± 0.7 cm) [36] and this may account for some variability in segmentation (Supporting information S1). Future studies investigating tendon geometry would benefit from thinner slices to provide complete detail. There is a paucity of information on the adaptation of lower limb tendons to interventions beyond 14 weeks [25], and identifying the effects of longitudinal loading on hamstring tendons may explain whether the lack of tendon mean CSA increases were due to the short-term loading intervention in the present study. Strain experienced during exercise itself is a key stimulus for tendon adaptation [25], but characterization of tendon strain experienced during common hamstring exercises (e.g., magnitude, duration) has yet to be reported and the intervention featured in the current study did not factor this. Future work is required to determine the effects of resistance training on other hamstring muscle and tendon properties, the time-course of any changes, and how these influence hamstring injury risk and athletic performance.

5 | Conclusion

A 10 week progressive intensity Nordic or hip extension intervention induced significant region-specific increases in hamstring muscle size but was insufficient to produce corresponding increases in tendon or aponeurosis size. The hip extension exercise increased the BFlh muscle volume-to-interface area ratio, which may increase force-generating capacity without modifying the force-transmitting structure. Novel and/or longer-term training interventions may be required to promote positive adaptations in hamstring tendons and aponeuroses.

6 | Perspective

This study provides the first evidence that short-term strength training stimulates limited change in hamstring free tendon or aponeurosis size despite promoting non-uniform muscle hypertrophy and significant increases in strength [7]. These findings might have implications for hamstring tendon function and injury given that tendon stress at a given load is more sensitive to its morphological than material properties [37]. Further, a disproportionately small proximal BFlh aponeurosis increases localized strains at the commonly injured musculotendinous junction during active lengthening [15, 16] and has been proposed as a risk factor for hamstring strain injury. In the current study, the hip extension intervention increased the size of the BFlh muscle relative to its aponeurosis while the Nordic exercise did not. Given the lack of adaptation in tendon geometry, practitioners may need to consider how exercise-programming choices affect the ratios between the size of the force-generating muscle and force-transmitting tendon/aponeurosis. Additionally, from a practical perspective, practitioners should consider the likely need for long-term loading to stimulate adaptations in hamstring free tendon and aponeurosis geometry.

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Ethics Statement

Ethical approval was provided by the Queensland University of Technology Human Research Ethics Committee and the University of Queensland Medical Research Ethics Committee [7].

Consent

Written informed consent was provided by all participants prior to data collection.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data is available via request to the corresponding author.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.