Effect of an Isometric or Eccentric Hip Extension Exercise Intervention on Hamstring Strength, Architecture, and Morphology

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ABSTRACT

CARMICHAEL, D. S., J. T. HICKEY, P. J. TOFARI, M. N. BOURNE, M. R. WARD, and R. G. TIMMINS. Effect of an Isometric or Eccentric Hip Extension Exercise Intervention on Hamstring Strength, Architecture, and Morphology. *Med. Sci. Sports Exerc.*, Vol. 54, No. 12, pp. 2196–2207, 2022. **Purpose:** This study aimed to investigate hamstring architectural, strength, and morphological adaptations after an eccentric or isometric hip extension exercise intervention. **Methods:** Twenty-four recreationally active males performed either an eccentric ($n = 12$) or an isometric hip extension ($n = 12$) exercise intervention, twice per week for 6 wk, followed by a 4-wk detraining period. Biceps femoris long head (BFlh) architecture was assessed pre-intervention, mid-intervention, post-intervention, and post-detraining via two-dimensional ultrasound. Strength was assessed pre-intervention, post-intervention, and post-detraining during an isokinetic knee flexion, an isometric hip extension, a Nordic hamstring exercise, and a single-leg hamstring bridge repetition to fatigue test. Hamstring muscle morphology was assessed via magnetic resonance imaging before strength testing sessions. **Results:** The eccentric hip extension exercise intervention significantly lengthened BFlh fascicles (+19.7%, $P < 0.001$, $d = 1.57$), increased eccentric knee flexion torque (ECC $60^\circ\cdot s^{-1}$, +12%, $P < 0.005$, $d = 0.66$; ECC $180^\circ\cdot s^{-1}$, +8.3%, $P < 0.05$, $d = 0.41$), and increased BFlh (+13.3%, $P < 0.001$, $d = 1.96$) and semimembranosus (SM) muscle volume (+12.5%, $P < 0.001$, $d = 2.25$). After 4 wk of detraining, BFlh fascicles were significantly shortened in the eccentric group (−14.8%, $P < 0.005$, $d = -1.25$), whereas eccentric knee flexion torque and BFlh and SM volumes were unchanged. The isometric hip extension exercise intervention significantly increased isometric knee flexion torque (+10.4%, $P < 0.05$, $d = 0.54$), isometric hip extension force (+12.4%, $P < 0.05$, $d = 0.41$), and semitendinosus volume (+15%, $P = 0.054$, $d = 1.57$). All other outcome measures saw no significant changes. After 4 wk of detraining, no significant changes to any variables were observed in the isometric group. **Conclusions:** The eccentric but not isometric hip extension exercise intervention significantly increased BFlh fascicle length. Both exercise interventions demonstrated contraction mode–specific increases in strength. However, the eccentric hip extension exercise intervention resulted in preferential hypertrophy of BFlh and SM, and the isometric hip extension exercise intervention led to selective hypertrophy of semitendinosus. **Key Words:** HAMSTRING INJURY, RESISTANCE TRAINING, FASCICLE LENGTH, MUSCLE VOLUME

Hamstring strain injury (HSI) is the most common cause of time lost from competition in running-based sports (1–3), which can negatively affect team performance (4) and finances (5). Prospective injury research has found that elite athletes with shorter muscle fascicles in the commonly injured biceps femoris long head (BFlh) were at an increased risk of HSI, in comparison with those with longer fascicles (6). Eccentric knee flexor strength (7–11) and performance on the single-leg hamstring bridge (SLHB) to fatigue test (12) have also been associated with future HSI in soccer and Australian football athletes, respectively. Importantly for practitioners, research has shown that BFlh fascicle length, eccentric knee flexor strength, and performance on the SLHB to fatigue test are all modifiable through exercise interventions.

Exercise interventions emphasizing hamstring loading during eccentric knee flexion, such as the Nordic hamstring exercise (NHE), reduce HSI rates (11) and increase BFlh fascicle length (13–17) and eccentric knee flexor strength (7–11). Changes to BFlh fascicle length appear to be contraction mode specific, with divergent adaptations observed between contraction modes (17). Additionally, exercise range of motion and intensity of training have also been shown to influence fascicle length adaptations and behaviour (15,18). Despite contraction mode during

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training influencing adaptation, the combination of concentric and eccentric contraction phases to load the hamstrings at longer lengths during a conventional 45° hip extension exercise significantly increases BFlh fascicle length (19). Single-leg deadlifts, which place the hamstrings in a similar position to the 45° hip extension, demonstrate a greater end range of motion and lengthening of the hamstring musculotendinous unit (MTU) when compared with the NHE (18). The longer MTU lengths during the conventional 45° hip extension may contribute to the similarities observed in BFlh fascicle adaptation after NHE interventions, despite the differences in contraction mode. However, it is unknown if an eccentric-only version of the hip extension exercise could further increase BFlh fascicle length.

A potential barrier to eccentric-only hamstring exercises is the general perception that these interventions cause significant muscle soreness. This perception may contribute to poor compliance with the NHE intervention (20) and may explain why isometric exercises have been proposed as an alternative way to load the hamstrings without exacerbating muscle soreness (21–25). However, the effect of isometric exercise interventions on HSI incidence and associated risk factors, such as BFlh fascicle length or eccentric knee flexor strength, is unknown. Isometric exercises such as a Roman chair hold place the hamstring MTU at similar lengths to the 45° hip extension; however, no significant changes to the MTU length are observed throughout the exercise (19). Therefore, the extent to which the length of the fascicle adapts in response to an isometric hamstring exercise may differ.

Although shorter BFlh fascicles and lower levels of eccentric knee flexor strength have been associated with increased risk of HSI, between-leg deficits in BFlh muscle volume have been observed in athletes for up to 2 yr after the completion of HSI rehabilitation (26). These findings suggest an inability to increase BFlh muscle volume during rehabilitation, which is correlated to hamstring strength (27,28). Recent research has also shown that hamstring volume might partly mediate the susceptibility to muscle damage after eccentric exercise (29). As such, investigating exercises that increase hamstring muscle volume would be of interest to researchers and practitioners alike.

The primary aim of this study was to investigate changes in BFlh fascicle length after 6 wk of either an eccentric or an isometric hip extension exercise intervention. Secondary aims were to determine the effect that 6 wk of an eccentric or isometric hip extension exercise intervention has on hamstring strength and muscle volume.

We hypothesized that the eccentric hip extension exercise intervention would lead to 1) greater increases in BFlh fascicle length compared with the isometric intervention and 2) greater increases in hamstring strength and muscle volume compared with the isometric intervention, and 3) that any increases observed in either intervention group would revert to pre-intervention values after a 28-d period of detraining.

METHODS

Participants and study design. Twenty-seven apparently healthy males, who were considered recreationally active (i.e., undertaking at least 1 h of moderate intensity physical activity, 3 to 4 d·wk^{-1} (30)), were recruited to participate in this study. Potential participants were excluded if they had a history of lower limb, spinal, or wrist injury in the last 36 months or any history of knee or hip surgery. Ethical approval was granted by the Australian Catholic University Human Research Ethics Committee (approval no. 2017-97H), and all participants provided informed written consent before their participation in the study.

This randomized intervention trial was conducted between February and October 2021 and was registered with the Australian New Zealand Clinical Trials Registry (trial identifier: ACTRN12621000813886) in June 2021. All exercise sessions and assessments of muscle architecture and strength were completed in the Exercise Science research laboratory at the Australian Catholic University, Melbourne, Australia, and magnetic resonance imaging (MRI) data were collected at Imaging @ Olympic Park, Melbourne, Australia.

During their initial visit to the research laboratory, participants had their baseline BFlh architecture assessed via two-dimensional ultrasound and were familiarized with strength testing protocols and both hip extension exercise interventions. Data collected during this baseline BFlh architecture assessment were subsequently analyzed to rank order participants based on their fascicle length for stratified randomization. The first participant (with the longest fascicles) was then randomly allocated to one of the two intervention groups, and then the second was allocated to the remaining intervention group using a 1:1 allocation ratio. This process was repeated for each pairing of participants. This stratified approach to randomization was implemented to minimize differences between the two groups in baseline BFlh fascicle length, which was our primary outcome measure.

Follow-up assessments of BFlh architecture were completed immediately before the first session of the fourth week of exercise intervention (mid-intervention), approximately 1 wk after the 6-wk intervention (median [range], 6 [2–15] d) (post-intervention) and after a detraining period (median [range], 31 [26–40] d) (post-detraining). Strength assessments were conducted at these same post-intervention and post-detraining time points, whereas pre-intervention strength assessments were conducted approximately a week before the first training session (median [range], 6 [2–21] d).

Approximately 7 d after the initial familiarization session (median [range], 8 [5–23] d), participants had their baseline hamstring muscle volume assessed via MRI, on both lower limbs before their 6-wk training intervention. These same morphology assessments were repeated after the 6-wk intervention (median [range], 6 [3–12] d) and again after the detraining period (median [range], 31 [26–40] d).

Exercise interventions. The consensus on exercise reporting template was used to ensure completeness and quality of exercise intervention reporting in this study (31). Participants were prescribed a progressive 6-wk unilateral hip extension exercise intervention to be performed with either an eccentric or an isometric contraction mode, based on their random allocation. Before commencing their exercise intervention, participants had

TABLE 1. Sets and repetitions, time under tension, and inter-set rest periods, prescribed during each session in the eccentric and isometric hip extension exercise interventions, completed twice per week over a 6-wk period.

	Eccentric Hip Extension			Isometric Hip Extension		
Week	Sets and Reps	TUT	Rest	Sets and Reps	TUT	Rest
1	2 sets of 4 (5 s rep)	40 s	90 s	4 sets of 1 (10 s rep)	40 s	60 s
2	2 sets of 4 (5 s rep)	40 s	90 s	4 sets of 1 (10 s rep)	40 s	60 s
3	2 sets of 4 (5 s rep)	40 s	90 s	4 sets of 1 (10 s rep)	40 s	60 s
4	3 sets of 4 (5 s rep)	60 s	90 s	6 sets of 1 (10 s rep)	60 s	60 s
5	4 sets of 4 (5 s rep)	80 s	90 s	8 sets of 1 (10 s rep)	80 s	60 s
6	5 sets of 4 (5 s rep)	100 s	90 s	10 sets of 1 (10 s rep)	100 s	60 s

rep, repetition; TUT, target time under tension.

their training limb (left or right) determined by flipping a coin, with their contralateral limb acting as a within-participant control. For the duration of their participation in the study, participants were advised to continue with their habitual levels of physical activity but were requested to avoid performing any additional exercises that specifically involved the hamstrings of either their trained or control leg.

Both exercise interventions were completed twice per week under the full supervision of an appropriately qualified investigator (i.e., completed a minimum 3-yr undergraduate exercise science degree) in the ACU Exercise Science research laboratory with a 1:1 participant-to-supervisor ratio. Each exercise session was separated by at least 48 h, and participants were contacted by the lead investigator ~24 h after each session to rate their perceived posterior thigh soreness using a visual analogue scale (0 = no soreness whatsoever, 10 = unbearable soreness) (32).

Sets and repetitions were prescribed to match time under tension during every session between the two groups across the 6-wk intervention period (Table 1). Participants in both groups were encouraged by the supervising investigator to aim for a relative intensity target of ≥8 out of 10 on a 0 to 10 RPE scale (33) during each set of exercise. If participants reported an RPE < 8 out of 10 and their technique was determined to be safe and appropriate, external load was added in 5-kg increments for the subsequent set, by holding a weight plate to the xiphoid process. After a standardized warm-up of minimum one bodyweight and one lower intensity set of their exercise, participants commenced each session with the highest external load they had successfully held during their previous session, or familiarization in the case of their first session.

Adherence to the prescribed exercise intervention was monitored by the supervising investigator who recorded session attendance, external load, and RPE values into a spreadsheet during each exercise session. Immediately after the completion of the 6-wk exercise intervention, participants underwent a 28-d detraining period. During this period, participants were advised to continue their habitual levels of physical activity but were requested to avoid any exercises that specifically loaded the hamstrings of either their trained leg or their control leg (as per previous instructions throughout their study involvement).

Participants in the eccentric hip extension group performed this exercise using an adjustable Roman chair (Powertec Fitness Inc., Paramount, CA) set up at ~30° relative to the floor. Participants commenced this exercise with their trunk straight, hip and knee as close to 0° flexion as possible, anterior superior iliac spine palpable above the level of the support pad, training limb ankle held in place under an ankle pad, and contralateral limb allowed to rest above the opposite ankle pad (Fig. 1A). Participants were instructed to eccentrically contract their hamstrings and "slowly lower" their trunk toward a bench placed in front of them, while maintaining a neutral spine (Fig. 1B). To control for repetition time, participants were counted in to the beat of a metronome (60 bpm) and were instructed to lower their trunk over a 5-s period until they reached a finishing position of ~90° hip flexion (see Video S1, Supplemental Digital Content 1, Video of the eccentric hip extension exercise http://links.lww.com/MSS/C687). Participants then dropped any weight that was held onto a bench placed in front of them and used their upper body to push themselves up with the handles of the Roman chair. The supervising investigator then handed the participant the weight before them commencing the subsequent repetition, which ensured that the hamstrings were only loaded during the eccentric phase of the exercise.

Participants in the isometric hip extension group performed this exercise in a glute-ham raise bench (Barbarian Line, Wassenberg, Germany). Participants positioned themselves with their hip and knee as close to 0° flexion as possible, their back straight, anterior superior iliac spine palpable in front of the level of the support pad, and ankle of the training limb held in place under an ankle pad, with the contralateral limb allowed to rest or remain above the ankle pad (Fig. 2). The

FIGURE 1—Start (A) and end (B) positions of the eccentric hip extension exercise performed on a Roman chair set 30° relative to the floor. Participants were instructed to slowly lower the weight toward the bench in front of them over a 5-s duration, before using their upper body to return to the starting position.

FIGURE 2—The isometric hip extension exercise performed on a glute-ham raise bench set so that the participants hip and knee were both flexed to ~0° flexion.

knee of the training limb remained in a position of ~0° knee flexion. To complete an isometric hip extension repetition, participants were instructed to "take their weight" and maintain a prone position in the bench for 10 s (see Video S2, Supplemental Digital Content 2, Video of the isometric hip extension exercise http://links.lww.com/MSS/C688). Once the repetition was completed, the investigator took the weight from the participants, and the participant then relaxed and held onto the handles of the glute-ham raise bench, removing the load placed on the training limb, ensuring the hamstrings were only loaded isometrically.

BFlh architecture. At each of the above time points, ultrasound images (see Fig. S1, Supplemental Digital Content 3, Figure of two-dimensional ultrasound analysis http://links.lww.com/MSS/C689) were collected along the longitudinal axis of the BFlh muscle belly using a two-dimensional, extended field of view (EFOV) ultrasound (Versana Active; GE Healthcare, Wauwatosa, WI) with a 5-cm linear probe. Participants were positioned prone on a massage plinth, after 5 min of inactivity. The ultrasound probe, with a layer of conductive gel, was placed on the skin over the BFlh. Using the EFOV function, the probe was moved slowly and without interruptions along the length of the BFlh from the distal to the proximal musculotendinous junctions. The probe orientation was manipulated slightly by the investigator (R.G.T.) to ensure the fascicle plane was kept visible in the field of view of the probe throughout the scan. The investigator's reliability with the EFOV method was determined before the study commencement. This involved 20 individual limbs being imaged on 2 d, separated by 24 h. The images from each day were analyzed and compared to determine the day-to-day repeatability of the assessment. The investigator demonstrated high levels of reliability with intraclass correlation (ICC) values ranging between 0.82 and 0.91 and typical error as a coefficient of variation (%TE) between 4.5% and 5.9% across fascicle length, pentation angle, and muscle thickness measures of BFlh architecture.

Once the images were collected, analysis was undertaken offline (MicroDicom software, version 0.7.8; MicroDicom, Sofia, Bulgaria). Analysis was completed on fascicles at 50% of muscle length, which was identified before the assessment. This site was cross referenced with measures of muscle thickness and tendinous structures from the biceps femoris short head (BFsh) and the distal BFlh to ensure the same site was used across all assessments. Fascicle length (cm) was determined from the average of two fascicles running between the intermediate and the superficial aponeuroses. Pennation angle (°) was determined as the average of the angle between the drawn fascicles and the intermediate aponeuroses, with muscle thickness (cm) determined as the distance between the superficial and the intermediate aponeuroses at the midpoint of the image. The same investigator (R.G.T.) collected and analyzed all scans and was blinded to participant identity, training group, and time point (for mid-intervention, post-intervention, and post-detraining analyses).

Strength. Maximal unilateral knee flexor strength was assessed with participants seated on an isokinetic dynamometer (Biodex, Shirley, NY) with their hips flexed to ~85°. Participants were restrained by straps around the testing limb thigh, waist, and chest to mitigate any compensatory movements during maximal exertion. All isokinetic dynamometer setup variables (e.g., chair, backrest, motor, and ankle position) were recorded on both limbs during the participant's familiarization session and were maintained throughout the study to ensure the replication of the testing position during all assessments. Range of motion for all concentric and eccentric contractions was set between 5° and 90° of knee flexion. Gravity correction for limb weight was conducted for each participant at a position of 30° knee flexion (34). Both legs were assessed with the participant's preferred kicking leg tested first. Each dynamometer testing protocol began with participants completing a warm-up of three sets of three concentric knee extension and flexion contractions at an angular velocity of $240°\cdot s^{-1}$. Participants were instructed to complete each set at 50%, 75%, and 95% of their perceived maximal effort, respectively.

Isometric knee flexor torque was then assessed at 30° of knee flexion (0° = full knee extension), approximately 1 min after the warm-up. This consisted of three, 5-s maximal contractions, with 30 s rest in between efforts. For all three isometric efforts, participants were instructed to "squeeze" against the lever "as hard and fast as possible" and "hold" this effort for 5 s. After all isometric efforts, concentric torque was assessed at angular velocities of $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$ (30-s interset rest). For all concentric efforts, participants were instructed to initially "kick up" against the lever (knee extension) "as hard and fast as possible" until reaching the end range of motion, before "pulling down" against the lever (knee flexion) as hard and fast as possible. After the completion of all concentric efforts, three sets of three maximal eccentric knee flexion contractions were completed at angular velocities of $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$, respectively, with 30-s rest in between sets. For all eccentric efforts, participants were instructed to "resist" the lever arm (eccentric knee flexion) from extending their knee as forcefully as they can. The starting position of the lever arm for all testing contractions was 90° of knee flexion. The testing order was randomized by velocity within each contraction mode to limit any bias as an effect of testing order. Throughout the testing session, all participants were provided visual feedback of their maximal torque output to provide motivation. Participants were also provided verbal encouragement by the investigators to ensure maximal exertion for all contractions. Dynamometer torque and lever position data were transferred to a computer at 1 kHz and subsequently analyzed offline using custom written code in R version 4.1.1 (35). Average peak torque (N·m) for isometric contractions at 30° knee flexion was defined as the mean of the peak torque value from the three efforts. Average peak torque (N·m) at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$ for concentric and eccentric knee flexion was defined as the mean of the three highest torque values for each contraction mode at each velocity.

Maximal isometric hip extension strength was assessed unilaterally for both legs using an externally fixed load cell device, known commercially as the ForceFrame (Vald Performance, Queensland, Australia). Participants were positioned prone, with the hip and knee of the testing limb both in a neutral position (i.e., 0° of flexion) resting below an adjustable frame containing uniaxial load cells positioned superior to their popliteal crease (see Fig. S2, Supplemental Digital Content 4, Figure of isometric prone hip extension test http://links.lww.com/MSS/C690). The bar height was recorded for both limbs during the participant's familiarization session and was maintained throughout the study to ensure the replication of the testing position. From this position, participants were instructed to extend their hip and "push as hard and fast as possible" against the load cell for 3 to 5 s. Before their maximal testing effort, participants completed a standardized warm-up protocol consisting of one repetition at each of 50%, 75%, and 95% of their perceived maximal effort. After this, and a subsequent 1-min rest period, participants were asked to perform one maximal isometric effort. Throughout each testing effort, participants were asked to keep both of their feet slightly off the ground, to mitigate any compensatory effect from the contralateral limb or surrounding muscle groups of the testing limb. Participants were also instructed to keep their head resting on their arms folded flat in front of them and to not move the trunk during the efforts (see Fig. S2, Supplemental Digital Content 4, Figure of isometric prone hip extension test http://links.lww.com/MSS/C690). The investigators provided verbal encouragement to ensure maximal exertion for all efforts. The peak force value in newtons (N) for both limbs was recorded for use in all analyses. The investigators determined the day-to-day reliability for this test as part of this study. This investigation involved 10 individual limbs being assessed on 2 d, separated by 24 h, and showed that the test has high levels of reliability with ICC >0.97 and %TE of <6.2%.

Maximal bilateral eccentric knee flexor strength during the NHE was assessed using a NordBord (Vald Performance, Queensland, Australia). Participants were positioned kneeling on the NordBord while the investigator secured ankle braces containing uniaxial load cells superior to the lateral malleolus. The ankle braces were secured in a vertical position to ensure that force was always measured through the long axis of the load cell. From this position, participants either crossed their arms over their chest or held a weight to their chest (centered to the xiphoid process) while maintaining a neutral hip joint position (~0° flexion), ensuring only knee joint angles were altered during the movement. Participants were instructed to lower their torso to a prone position. Once in this position, they were verbally encouraged to continue slowly resisting the fall until they touched the ground below with either their hands or the weight held. The investigator assessed the quality of each repetition and deemed whether a maximal force output was achieved. Only the eccentric lowering phase of the NHE was completed. Participants completed a standardized warm-up protocol consisting of one repetition at each of 50%, 75%, and 95% of their perceived maximal NHE effort with no external resistance. After this, and a subsequent 2-min rest period, participants were asked to perform one maximal NHE repetition with bodyweight only. Additional external load was held at the chest by the participant in 5 kg increments if lowering movement was deemed to be controlled by investigators and "peak" force values plateaued during the NHE. The peak force value (N) for both limbs was recorded for use in all analyses.

Hip extension strength endurance was assessed via the SLHB repetitions to fatigue test, on both legs (12). From a supine position, participants were instructed to place their heel of the testing limb on a stable 60-cm box with a knee position of ~20° flexion and a hip position of ~60° flexion (see Video S3, Supplemental Digital Content 5, Video of single leg hamstring bridge test http://links.lww.com/MSS/C691). Participants were required to cross their arms over their chest, then they were encouraged to push through their heel to lift their pelvis off the ground into a position of 0° hip flexion and then lower themselves back to the ground in a controlled manner before starting the next repetition. The thigh of the non-testing limb was held in a stationary position of ~90° hip and knee flexion to mitigate any compensatory movements contributing to the testing repetitions (see Video S3, Supplemental Digital Content 5, Video of single leg hamstring bridge test http://links.lww.com/MSS/C691). The testing order for each limb was randomized for every participant. Participants performed each repetition to the beat of a metronome (60 bpm), using 2 s to lift and lower throughout the test, respectively. There was a brief resultant "hold" at the top of the lifting position, in between the final lifting and the first lowering beats. Testing technique and tempo was strictly enforced by the investigator. Participants were verbally encouraged to complete as many repetitions as possible. If correct testing technique or lifting tempo was not achieved, one warning was given. The test was ceased at the next fault in technique, and the resulting maximum number of repetitions was recorded.

Magnetic resonance imaging. All MRI was completed using a 3-T imaging system (Phillips Ingenia, Koninklijke Phillips N.V., Amsterdam, Netherlands). A 32-channel spinal coil was placed over the anterior thighs, and straps were positioned around both limbs to prevent any undesired movement. The participant was positioned supine in the magnet bore, with the hip and knee fully extended. Contiguous T1-weighted axial MRIs (transverse relaxation time = 2640 ms, echo time = 25 ms, field of view = 220 × 390 mm, slice thickness = 5 mm, interslice distance = 0 mm) were taken of both limbs, beginning at T12/L1 and finishing distal to the tibial condyles. To prevent any acute exercise-induced muscle swelling (25), participants were seated for a minimum of 15 min before data collection, and scans were performed before the completion of maximal strength assessments and >72 h after the final exercise intervention session.

Muscle volumes (cm^3) of the BFlh, BFsh, semitendinosus (ST), and semimembranosus (SM) were determined for both limbs, at all time points, using manual segmentation. Percentages of individual muscle length (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90%) were calculated. Using image analysis software (version 1.8.0, ImageJ, Bethesda, MD) (36), the anatomical cross-sectional area (cm^2) was determined at each muscle length site by identifying and manually tracing the boundaries of each muscle on each relevant axial slice (see Fig. S3, Supplemental Digital Content 6, Figure of magnetic resonance imaging segmentation http://links.lww.com/MSS/C692).

All segmentations and analyses were completed by the same investigator (D.S.C.) who was blinded to participant identity, training group, and time point. Muscle volume calculations were based on the assumption that each muscle is the ideal cylinder, whereby the sum of the anatomical cross-sectional area of the total number of traced slices was multiplied by the known distance between each traced slice ($V = T(A_1 + A_2 + \ldots + A_9)$, where V is the muscle volume, T is the known distance between slices, and A_x is the area of the numbered slice) (37). This methodology (i.e., analyzing a lesser number of slices) has demonstrated a highly accurate representation of total muscle volume when compared with muscle volume calculations using all visible muscle slices (i.e., differences of <0.005%) (37). The same investigator (D.S.C.) completed all morphology analysis and has excellent reliability (ICC >0.98 and %TE of <3.6%) for repeat analyses of all MRI segmentations and analyses.

Statistical analysis. All statistical analyses were performed using JMP V.11.01 Pro Statistical Discovery Software (SAS Inc., Cary, NC). Where appropriate, data were screened for normality using the Shapiro–Wilk test. Homoscedasticity was also assessed using Levene's test. Greenhouse–Geisser adjustment was applied when the assumption of sphericity was violated. A one-way ANOVA was used to assess if there were any differences between groups in baseline participant characteristic (i.e., age [yr], height [cm], weight [kg]) and their average weekly training variables (i.e., external load [kg], RPE, and posterior thigh muscle soreness), using the variables of time (weeks 1, 2, 3, 4, 5, and 6) and participant ID as the random factor. Repeated-measures linear mixed models fitted with the restricted maximum likelihood method were used to assess between- and within-group differences in BFlh architecture, strength, and muscle morphology.

For measures of BFlh architecture, the within-group variables were limb (training or control) and time (pre-intervention, mid-intervention, post-intervention, and post-detraining) with participant ID as the random factor. The between-group comparisons were made at each time point (pre-intervention, mid-intervention, post-intervention, and post-detraining). Similar analyses were used to determine changes in all strength and morphological measures, with the within-group variables for these analyses being limb (training or control) and time (pre-intervention, post-intervention, and post-detraining) and participant ID as the random factor. Similarly, the between-group comparisons were made at each time point (pre-intervention, post-intervention, and post-detraining).

Where significant main or interaction effects were detected, *post hoc t* tests with Tukey's HSD were applied to determine where any differences occurred. Mean differences of all measurements were reported with 95% confidence intervals (CI). Significance for all analyses was set at $P < 0.05$. Cohen's d effect sizes were reported where appropriate using the following classifications of small ($d = 0.20$ to 0.49), medium ($d = 0.50$ to 0.79), and large ($d > 0.80$) effects (38).

Sample size calculation. Based on estimated fascicle length adaptations after the 6-wk intervention, G*Power version 3.1.9.2 was used *a priori* to calculate sample size (39). The effect size was derived from the most conservative effect size after a 6-wk training intervention in the hamstrings (40). In this study, there was a ~14% increase in BFlh fascicle length after 6 wk of eccentrically biased training on a YoYo flywheel device ($d = 1.4$). Therefore, a sample size of 12 per group was determined as sufficient using the following inputs: power ($1 - \beta$ err probability) = 0.80, $\alpha = 0.05$, effect size = 1.2, and an anticipated dropout rate of 10%.

Comparably as a cross reference to confirm these estimates, similar studies have used ~12 participants per group (15,21,40).

RESULTS

Participants. Twenty-seven healthy, recreationally active males (age = 22.2 ± 4.5 yr, height = 179.1 ± 6.2 cm, weight = 76.3 ± 10.3 kg) provided informed written consent to participate in this study. Three participants dropped out after one, three, and seven exercise sessions, respectively (two from the eccentric group and one from the isometric group). The reasons for participant dropout were unavailability (two participants) and major knee injury external to study participation (one participant). Data collected from these three participants were excluded from results of this study. The remaining 24 healthy males (age = 21.8 ± 4.3 yr, height = 179.5 ± 6.1 cm, weight = 75.4 ± 10.5 kg) completed the study. No major adverse events occurred during the exercise intervention in either group.

There were no significant differences in participant age ($P = 0.857$), weight ($P = 0.279$), and height ($P = 0.059$) between the eccentric ($n = 12$) (age = 21.7 ± 4.9 yr, weight = 73.0 ± 9.4 kg, height = 177.1 ± 5.0 cm) and the isometric ($n = 12$) (age = 22.0 ± 3.6 yr, weight = 77.8 ± 11.1 kg, height = 181.9 ± 6.2 cm) training groups. All 12 participants in the eccentric intervention group completed all 12 prescribed training sessions (100% compliance). In the isometric intervention group, 10 participants completed all 12 prescribed training sessions and two participants completed 11 of the 12 prescribed sessions (98.6% compliance). There were no significant ($P > 0.05$)

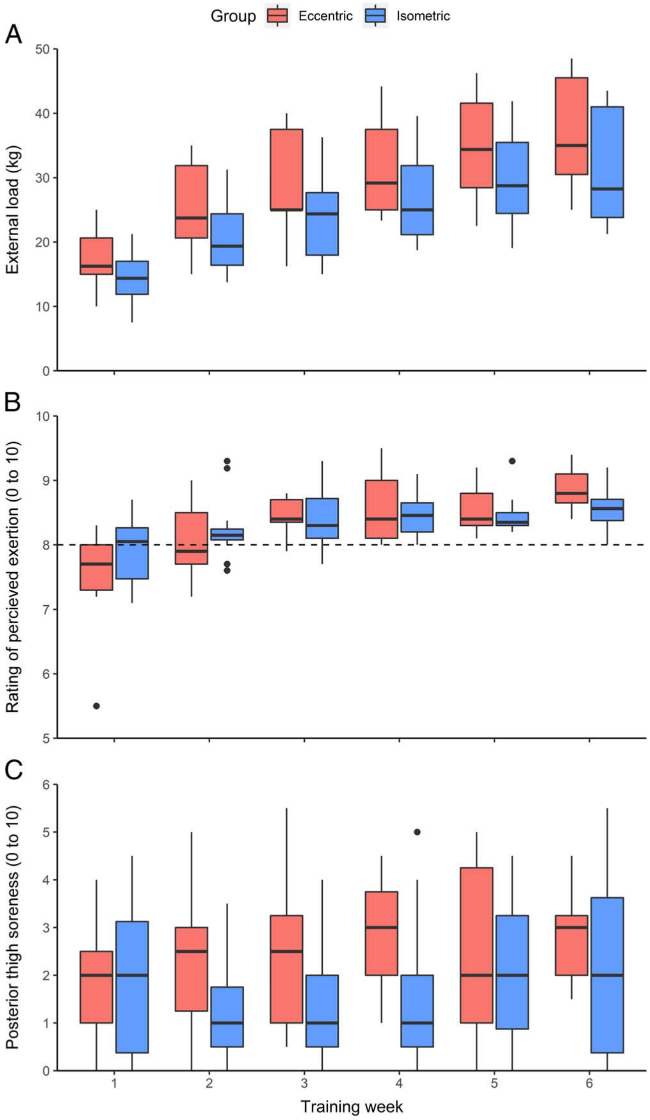

FIGURE 3—Interquartile ranges of weekly average external load held (A), RPE (B), and posterior thigh soreness (C) across every training week in the eccentric (*red*) and isometric (*blue*) intervention groups. The *horizontal dashed line* in panel B represents the target training intensity as a perceived exertion rating of 8 out of 10.

differences between the two groups in terms of weekly average external load, RPE, or posterior thigh soreness across the 6-wk training period (Fig. 3).

BFlh architecture changes. A significant time–limb interaction was found for BFlh fascicle length in the eccentric intervention group ($P < 0.001$). Immediately after the intervention, when comparing between the two groups (interaction effect of group–time = 0.061), the eccentric training limb had significantly longer fascicles than the isometric training limb (mean difference = 1.6 cm, 95% CI = 0.35 to 2.8 cm, $P = 0.004$, $d = 1.61$). *Post hoc* analyses showed that BFlh fascicles were significantly longer after the 6-wk intervention in the training limb of the eccentric group (mean difference = 1.5 cm, 95% CI = 0.53 to 2.5 cm, $P < 0.001$, $d = 1.57$) (Fig. 4).

After the detraining period, the training limb of the eccentric group possessed shorter fascicles when compared with the end of the intervention (mean difference = −1.4 cm, 95% CI = 0.37 to 2.4 cm, $P = 0.001$, $d = 1.25$). When comparing the fascicle length measures after detraining to those at pre-intervention, no difference was observed, suggesting the changes as a result of the of eccentric training had returned to baseline (mean difference = 0.2 cm, 95% = CI −0.84 to 1.15 cm, $P = 0.999$, $d = 0.16$).

There were no other significant within- or between-group differences in fascicle length at any time point (Table 2).

A significant main effect for limb was detected for BFlh muscle thickness in the eccentric intervention group ($P < 0.001$). However, *post hoc* analyses revealed no significant within- or between-group differences at any time point (Table 2).

A significant main effect for time was detected for pennation angle in the eccentric intervention group ($P < 0.05$). However, *post hoc* analyses revealed no significant within- or between-group differences at any time point (Table 2).

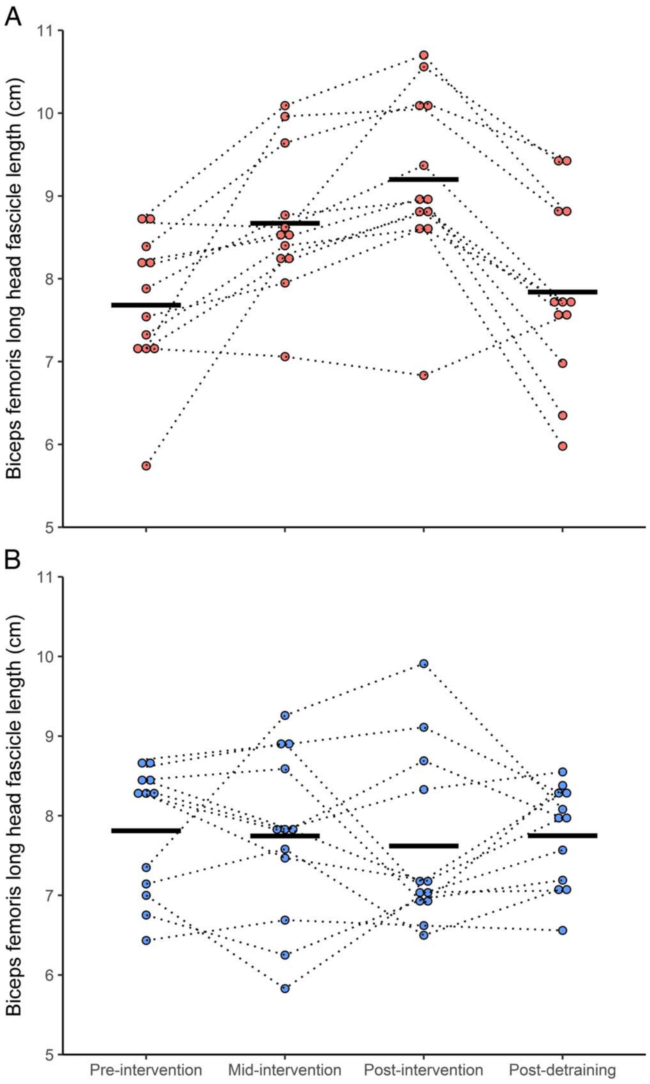

FIGURE 4—BFlh fascicle lengths across all time points in the eccentric (A) and isometric (B) intervention groups. Each *colored circle* represents an individual participant data point, with *dotted lines* representing individual change across time points. Group means are represented by a *solid black bar*.

TABLE 2. The effect of eccentric or isometric hip extension training interventions on BFlh architectural measures.

		Eccentric (n = 12)		Isometric (n = 12)	
Outcome Measure	**Time**	**Trained Limb**	**Control Limb**	**Trained Limb**	**Control Limb**
Fascicle length (cm)	Pre-intervention	7.7 ± 0.9	8.1 ± 1.3	7.8 ± 0.8	8.1 ± 1.4
	Mid-intervention	8.7 ± 0.9	7.5 ± 1.3	7.7 ± 1.1	7.2 ± 1.0
	Post-intervention	**9.2 ± 1.1****	7.7 ± 1.1	7.6 ± 1.1	7.6 ± 0.9
	Post-detraining	**7.8 ± 1.1***	7.4 ± 1.0	7.7 ± 0.6	7.5 ± 0.9
Muscle thickness (cm)	Pre-intervention	2.0 ± 0.2	1.9 ± 0.3	2.0 ± 0.3	2.0 ± 0.3
	Mid-intervention	2.1 ± 0.3	1.9 ± 0.3	2.1 ± 0.2	2.1 ± 0.3
	Post-intervention	2.2 ± 0.3	1.9 ± 0.2	2.0 ± 0.3	2.1 ± 0.3
	Post-detraining	2.0 ± 0.3	1.9 ± 0.2	1.9 ± 0.2	2.0 ± 0.2
Pennation angle (°)	Pre-intervention	15.4 ± 1.5	15.1 ± 2.3	15.5 ± 1.7	14.9 ± 1.8
	Mid-intervention	14.0 ± 1.9	15.0 ± 1.9	16.1 ± 2.0	15.7 ± 2.0
	Post-intervention	13.6 ± 2.0	14.9 ± 0.7	15.0 ± 1.2	15.6 ± 1.3
	Post-detraining	15.4 ± 2.3	15.3 ± 1.3	15.8 ± 1.7	14.9 ± 1.7

All data are presented as mean ± SD of absolute values. Data in bold highlight statistical significance.

*P < 0.05 vs post-intervention of same limb.

**P < 0.001 vs pre-intervention of same limb.

Isokinetic knee flexor strength changes. A significant main effect for time was found for average peak eccentric torque at 60°·s^{-1} (P < 0.001). *Post hoc* analyses detected a significant 12% increase in the training limb of the eccentric group after the intervention (mean difference = 17.4 N·m, 95% CI = 4.3 to 30.4 N·m, P = 0.003, d = 0.66). After the detraining period, the eccentric torque at 60°·s^{-1} of the training limb in the eccentric group was not significantly different when compared with post-intervention measures (mean difference = 1.2 N·m. 95% CI = −11.9 to 14.2 N·m, P = 0.998, d = 0.05). However, these measures at the end of detraining remained significantly higher than the pre-intervention measures (mean difference = 18.5 N·m, 95% CI = 5.5 to 31.6 N·m, P = 0.001, d = 0.71).

A significant main effect for time was found for average peak eccentric torque at 60°·s^{-1} (P < 0.05) in the isometric group. *Post hoc* analyses detected a significant 12% increase in peak eccentric torque at 60°·s^{-1} in the training limb of the isometric group after the detraining period, when compared with pre-intervention measures (mean difference = 19.1 N·m, 95% CI = 2.0 to 36.3 N·m, P = 0.020, d = 0.71).

There were no other significant within- or between-group differences in average peak eccentric torque at 60°·s^{-1} at any time point (Table 3).

A significant main effect for limb was found for average peak eccentric torque at 180°·s^{-1} (P < 0.05). *Post hoc* analyses detected a significant 8% increase in the training limb of the eccentric group after the intervention (mean difference = 12.5 N·m, 95% CI = 1.7 to 23.2 N·m, P = 0.024, d = 0.41). Similar to the eccentric torque results seen during 60°·s^{-1}, there were no changes after the detraining period in the eccentric group at 180°·s^{-1} when compared with post-intervention measures (mean difference = 8.1 N·m, 95% CI = −7.7 to 23.9 N·m, P = 0.658, d = 0.27). However, these measures at the end of detraining were still significantly higher than pre-intervention measures (mean difference = 20.6 N·m, 95% CI = 4.7 to 36.4 N·m, P = 0.004, d = 0.66).

TABLE 3. The effect of eccentric or isometric hip extension training interventions on various lower limb strength measures.

		Eccentric (n = 12)		Isometric (n = 12)	
Outcome Measure	**Time Point**	**Trained Limb**	**Control Limb**	**Trained Limb**	**Control Limb**
Eccentric knee flexion (60°·s^{-1}) (N·m)	Pre-intervention	144.9 ± 27.9	139.1 ± 18.9	155.5 ± 23.2	154.5 ± 31.2
	Post-intervention	**162.3 ± 24.9***	147.1 ± 27.5	168.9 ± 30.6	158.9 ± 30.4
	Post-detraining	**163.5 ± 24.0***	146.0 ± 21.0	**174.6 ± 30.6***	161.1 ± 29.2
Eccentric knee flexion (180°·s^{-1}) (N·m)	Pre-intervention	149.6 ± 31.6	147.7 ± 20.3	162.8 ± 25.4	159.0 ± 28.0
	Post-intervention	**162.1 ± 29.0***	152.2 ± 28.1	164.3 ± 29.7	162.2 ± 29.8
	Post-detraining	**170.1 ± 30.5***	152.1 ± 24.2	170.6 ± 28.6	163.9 ± 29.5
Isometric knee flexion (N·m)	Pre-intervention	122.6 ± 26.9	120.1 ± 12.0	134.4 ± 24.1	129.1 ± 25.5
	Post-intervention	135.0 ± 19.3	123.2 ± 20.0	**148.3 ± 27.6***	130.3 ± 28.1
	Post-detraining	134.8 ± 25.2	122.4 ± 20.3	**147.9 ± 25.4***	132.8 ± 21.9
Concentric knee flexion (60°·s^{-1}) (N·m)	Pre-intervention	119.9 ± 23.1	117.3 ± 12.9	131.6 ± 17.1	123.9 ± 18.3
	Post-intervention	123.2 ± 21.1	115.2 ± 17.6	139.1 ± 17.3	129.6 ± 21.5
	Post-detraining	125.1 ± 22.1	111.0 ± 18.6	140.8 ± 16.7	130.3 ± 16.5
Concentric knee flexion (180°·s^{-1}) (N·m)	Pre-intervention	99.5 ± 16.5	95.4 ± 8.7	109.0 ± 14.2	100.9 ± 12.8
	Post-intervention	105.0 ± 16.9	95.5 ± 13.0	114.9 ± 13.6	106.3 ± 14.4
	Post-detraining	104.7 ± 18.8	96.4 ± 11.9	112.8 ± 15.3	105.3 ± 13.8
Isometric hip extension (N)	Pre-intervention	427.4 ± 103.8	436.9 ± 137.6	493.1 ± 156.7	484.0 ± 136.8
	Post-intervention	505.4 ± 160.1	426.0 ± 123.4	**554.5 ± 144.0***	504.5 ± 139.5
	Post-detraining	475.2 ± 138.9	415.5 ± 86.7	**570.5 ± 187.1***	471.3 ± 125.8
NHE (N)	Pre-intervention	381.7 ± 66.8	380.9 ± 37.4	386.0 ± 67.0	384.2 ± 58.3
	Post-intervention	390.9 ± 66.5	393.9 ± 50.6	405.5 ± 61.5	398.6 ± 58.1
	Post-detraining	390.1 ± 68.0	399.1 ± 58.9	411.7 ± 66.6	407.4 ± 52.8
SLHB (repetitions)	Pre-intervention	14.8 ± 5.6	15.3 ± 4.6	13.8 ± 4.4	13.2 ± 3.5
	Post-intervention	15.4 ± 3.8	12.9 ± 3.5	16.5 ± 7.1	14.7 ± 5.7
	Post-detraining	14.9 ± 3.7	13.8 ± 2.6	14.8 ± 6.8	13.8 ± 4.8

All data are presented as mean ± SD of training and control limb. Data in bold highlight statistical significance.

*P < 0.05 vs pre-intervention of same limb.

NHE, Nordic hamstring exercise; SLHB, single leg hamstring bridge.

There were no other significant within- or between-group differences in average peak eccentric torque at $180^{\circ}\cdot s^{-1}$ at any time point (Table 3).

A significant main effect for limb was found for average peak isometric torque ($P < 0.001$) (Table 3). *Post hoc* analyses found a significant 10% increase in the training limb of the isometric group after the intervention (mean difference = 13.9 N·m, 95% CI = 1.3 to 26.6 N·m, $P = 0.023$, $d = 0.54$). After the detraining period, there were no significant changes in average peak isometric torque when compared with post-intervention measures in the isometric group (mean difference = −0.4 N·m, 95% CI = −12.3 to 13.0 N·m, $P = 0.999$, $d = 0.01$). However, these measures at the end of detraining were still significantly higher than pre-intervention measures (mean difference = 13.5 N·m, 95% CI = 0.9 to 26.2 N·m, $P = 0.029$, $d = 0.55$).

There were no other significant within- or between-group differences in average peak isometric torque at any time point (Table 3).

There were no significant within- or between-group differences for any average peak concentric measures of torque at any time point (Table 3). As such, no *post hoc* analyses were undertaken.

Isometric hip extension strength changes. A significant main effect for limb was detected for isometric hip extension strength ($P = 0.003$). *Post hoc* analyses detected a significant 12% increase in the training limb after the intervention in the isometric training group (mean difference = 61.3 N, 95% CI = 2.5 to 120.1 N, $P = 0.041$, $d = 0.41$).

NHE strength changes. There were no significant within- or between-group effects for measures of eccentric strength during the NHE at any time point (Table 3). As such, no *post hoc* analyses were undertaken.

SLHB changes. There were no significant within- or between-group effects for measures of hip extension strength endurance assessed using the SLHB at any time point (Table 3). As such, no *post hoc* analyses were undertaken.

Muscle volume changes. A significant main effect for limb was detected for BFlh volume in the eccentric training group ($P < 0.001$). *Post hoc* analyses showed that BFlh volume was significantly greater in the training limb after the intervention (mean difference = 13.4%, 95% CI = 4.7 to 22.4%, $P < 0.001$, $d = 1.96$) and remained unchanged after the detraining period (mean difference = 0.6%, 95% CI = −8.5 to 9.2%, $P = 0.999$, $d = -0.05$). *Post hoc* analyses showed no changes to BFlh volume across all time points in the isometric training group.

There were no other significant within- or between-group differences for BFlh muscle volume at any time point (Table 4).

A significant main effect for limb was found for SM volume in the eccentric group ($P < 0.001$). *Post hoc* analyses showed significant training-induced increases in SM volume after the intervention (mean difference = 12.5%, 95% CI = 6.0 to 19.1%, $P < 0.001$, $d = 2.25$), which did not change between the end of the intervention and after detraining (mean difference = −4.3%, 95% CI = −2.2 to 10.9%, $P = 0.378$, $d = -0.55$). *Post hoc* analyses showed no changes to SM muscle volume across all time points in the isometric training group.

There were no other significant within- or between-group differences for SM volume at any time point (Table 4).

A significant main effect for limb was found for ST volume in both the eccentric ($P = 0.005$) and the isometric training groups ($P = 0.029$). *Post hoc* analyses revealed a significant increase in ST muscle volume in the isometric group immediately after the training intervention (mean difference = 15%, 95% CI = 4.6 to 25.3%, $P = 0.005$, $d = 1.57$). By contrast, no significant increase in ST volume was observed immediately after the eccentric training intervention (mean difference = 11.1%, 95% CI = −6.5 to 28.8%, $P = 0.437$, $d = 1.21$), but ST volume was significantly greater at the end of the detraining period compared with pre-intervention (mean difference = 18.5%, 95% CI = 1.3 to 35.7%, $P = 0.028$, $d = 0.92$).

There were no other significant within- or between-group differences for ST volume at any time point (Table 4).

There were no significant within- or between-group effects for BFsh muscle volume at any time point (Table 4).

DISCUSSION

This is the first study to investigate the architectural, strength, and morphological adaptations of the hamstrings after 6 wk of

TABLE 4. The effect of eccentric or isometric hip extension training interventions on percentage change to hamstring muscle volume measures.

			Eccentric ($n = 12$)		Isometric ($n = 12$)	
Outcome Measure	**Time Point 1**	**Time Point 2**	**Trained Limb**	**Control Limb**	**Trained Limb**	**Control Limb**
BFlh volume	Pre-intervention	Post-intervention	**13.3 ± 6.8****	8.4 ± 7.2	6.9 ± 8.0	9.3 ± 9.0
	Pre-intervention	Post-detraining	**13.9 ± 8.3****	11.9 ± 9.1	9.5 ± 9.5	8.7 ± 8.4
	Post-intervention	Post-detraining	0.6 ± 10.7	3.6 ± 11.6	2.6 ± 12.4	−0.6 ± 12.3
SM volume	Pre-intervention	Post-intervention	**12.5 ± 5.6****	7.0 ± 4.3	5.5 ± 3.9	4.3 ± 5.5
	Pre-intervention	Post-detraining	**8.2 ± 5.5***	6.2 ± 4.9	6.3 ± 6.2	4.9 ± 6.9
	Post-intervention	Post-detraining	−4.3 ± 7.6	−0.8 ± 6.5	0.8 ± 7.3	0.6 ± 8.8
ST volume	Pre-intervention	Post-intervention	11.1 ± 9.2	2.2 ± 6.5	**15.0 ± 9.5***	4.7 ± 10.6
	Pre-intervention	Post-detraining	**18.5 ± 20.1***	9.9 ± 16.4	10.1 ± 14.9	3.0 ± 9.4
	Post-intervention	Post-detraining	7.4 ± 22.1	7.7 ± 17.6	−4.9 ± 17.7	−1.8 ± 14.1
BFsh volume	Pre-intervention	Post-intervention	3.2 ± 4.8	1.3 ± 4.3	6.7 ± 5.3	4.8 ± 7.0
	Pre-intervention	Post-detraining	7.7 ± 13.6	11.5 ± 21.1	2.7 ± 11.2	1.9 ± 10.9
	Post-intervention	Post-detraining	4.5 ± 14.4	10.2 ± 21.6	−4.0 ± 12.4	−2.9 ± 13.0

All data are presented as mean ± SD of percentages of change from time point 1 to time point 2. All data are positive unless specified otherwise. Data in bold indicate statistical significance.

*$P < 0.05$.

**$P < 0.001$.

BFlh, biceps femoris long head; BFsh, biceps femoris short head; SM, semimembranosus; ST, semitendinosus.

either an eccentric or an isometric hip extension exercise intervention and subsequent 4-wk detraining period. The main findings of this study are as follows: 1) the eccentric hip extension exercise intervention stimulated significant BFlh fascicle lengthening, whereas the isometric hip extension exercise intervention did not; 2) both eccentric and isometric hip extension exercise interventions resulted in contraction mode–specific increases in hamstring strength, while also stimulating significant hypertrophy in different hamstring muscles; and 3) BFlh fascicle length significantly shortened after 4 wk of detraining after an eccentric hip extension intervention, whereas knee flexor strength and muscle volumes were not significantly different between post-intervention and post-detraining.

The significant increases in BFlh fascicle length (mean difference = 1.5 ± 1.0 cm) observed after a 6-wk eccentric hip extension exercise intervention may have implications for practitioners aiming to reduce HSI risk. It has been previously reported that the risk of HSI in elite Australian soccer players reduced by ~74% for every 0.5 cm increase in BFlh fascicle length (6). Similar increases in BFlh fascicle length have been observed after NHE interventions (7–11), which are not often implemented in elite soccer (18), potentially contributing to persistent HSI incidence rates (41). Therefore, the eccentric hip extension exercise intervention implemented in this study presents a potentially viable alternative to effectively increase BFlh fascicle length.

Isometric hamstring exercises have been proposed as an alternative to eccentric training intervention to mitigate HSI risk (20,22–25) because of potentially causing less muscle soreness after implementation. However, our study showed no differences in posterior thigh soreness across the 6-wk training period between the isometric and the eccentric intervention groups, with BFlh fascicle length increases confined to the eccentric group only. This might indicate that eccentric hip extension exercise interventions could be implemented as part of in-season training or rehabilitation. It should be noted that isometric exercises completed at different hamstring MTU lengths may have differing adaptations on BFlh fascicle lengths (42,43). Although the isometric hip extension group loaded the hamstring muscle group at a relatively short MTU length, the roman chair exercise is commonly used as an alternative to eccentric hamstring exercises (25) and as such warranted investigation. It is possible that isometric exercises performed at longer MTU lengths might have different adaptations and should be investigated as part of future research. It should be noted that previous research comparing the NHE with a conventional 45° hip extension exercise intervention demonstrated similarities in BFlh fascicle length adaptation (21), despite the latter involving greater MTU lengths and excursions. Additionally, concentric isokinetic training has demonstrated BFlh fascicle shortening, despite training occurring at long muscle lengths (17). When coupled with the results of the current study, these data suggest the possibility that muscle training length might be a less important factor than once believed. As this study was the first to use an eccentric-only variation of the hip extension exercise, further research is required to investigate potential implementation within sporting organizations and in prospective studies to evaluate its effect on HSI risk. Additionally, when compared with previous eccentric exercise interventions, the training volume (i.e., sets, repetitions, and training frequency) of the current study was much lower (8,14,15,17,21). Considering the minimal soreness observed across both intervention groups, the high-intensity, low-volume prescription (Table 1) within the eccentric hip extension group in the current study might encourage greater compliance in HSI prevention approaches aiming to increase BFlh fascicle length.

The eccentric hip extension exercise intervention significantly increased unilateral isokinetic eccentric knee flexor strength, and these increases were maintained after 4 wk of detraining. Increasing knee flexor strength as part of an HSI risk mitigation strategy is based on the theory that stronger muscles are more resistant to muscle damage (29,44) and strain injury (45). Evidence from animal models shows that weaker muscles absorb less energy before induced injury when compared with stronger muscles (46). In humans, the implementation of eccentric hamstring exercises, where the muscle lengthens under tension, has been shown to reduce HSI rates (8). It is assumed that this may be associated with increases in eccentric strength and subsequently the ability to absorb more energy before strain-induced failure (46). However, the prospective evidence is mixed when measuring eccentric strength itself as an HSI risk factor (47). Therefore, the potential HSI risk mitigation benefits of eccentric resistance training may not necessarily be related to strength but changes to muscle structure and architecture induced by eccentric training, such as increased fascicle length.

The significant increases observed in unilateral isokinetic eccentric knee flexor strength in the eccentric group were not carried over to the NHE, which may be due to the bilateral nature of this test. Contraction mode–specific adaptations were also observed after the isometric hip extension exercise intervention in our study, with significant increases in isometric knee flexor and hip extensor strength, which were maintained after 4 wk of detraining. Isometric hip extension interventions have previously been shown to significantly improve SLHB performance (24), which has some limited association with HSI risk (12). However, the current study found that neither an eccentric nor an isometric hip extension training intervention can significantly improve SLHB performance, which may require a more low-intensity/high-volume prescription, compared with our high-intensity/low-volume approach.

Muscle volumes of the BFlh and SM were both significantly increased after the eccentric hip extension exercise intervention. The percentage change of muscle volume adaptations observed after eccentric hip extension training appears to mostly align with those associated with the conventional variation of the exercise (21,48), despite the significantly lower volume of training performed in the current study. Significant increases in ST volume were also observed immediately after the isometric training intervention, whereas the statistically significant improvements in ST muscle volume in the eccentric group were only observed after detraining. Deficits in ST muscle volume have been observed after anterior cruciate ligament reconstructions using tendon grafts from this muscle (49), meaning the isometric hip extension exercise might be a useful rehabilitation intervention in these cohorts. Although alterations to muscle volume have not been identified as an HSI risk factor, significant interlimb deficits have been observed in BFlh muscle volume in previously injured athletes for up to 2 yr after the completion of rehabilitation (26). Therefore, the findings of this study suggest that eccentric hip extension exercises may be capable of addressing deficits in BFlh muscle volume during HSI rehabilitation, whereas isometric hip extension might have applications after tendon grafts in anterior cruciate ligament reconstruction. Further research is required to explore the effect of hip extension exercise interventions in rehabilitative environments, and whether it can be successfully prescribed within sporting organizations to mitigate injury risk.

There are limitations associated with this study that should be acknowledged. All participants were uninjured recreationally active males, which may limit application of these findings to other populations, such as elite athletes and those recovering from injury. Future research should examine the effect of a similar intervention on higher-level athletes as well as those recovering from injury. There was no assessment of fascicle dynamics during the prescribed exercises. Although videos S1 and S2 (see Supplemental Digital Content 1, Video of the eccentric hip extension exercise, http://links.lww.com/MSS/C687, and Supplemental Digital Content 2, Video of the isometric hip extension exercise http://links.lww.com/MSS/C688) show that hip flexion angles increase while knee flexion angle remains relatively fixed during the exercises, which in theory would result in the lengthening of the hamstring MTU as a whole, we cannot say if these actions involved fascicle lengthening without directly measuring this outcome. Understanding the fascicle dynamics during such an intervention is important to advance the field in this area, and future research is needed to investigate these phenomena. Because of government-mandated lockdowns in Melbourne, Australia, in response to the SARS-CoV-2 (COVID-19) pandemic, five post-detraining assessments had to be postponed. Consequently, these participants underwent an extended detraining period, resulting in a slightly elevated range of detraining days (range = 26–40 d), but the mean (31.2 d) and median (31 d) still approximately met the desired 4-wk detraining period.

CONCLUSIONS

This study provides novel evidence that an eccentric but not isometric hip extension exercise intervention significantly increases BFlh fascicle length, without inducing any more muscle soreness 24 h after exercise than the isometric training group. These adaptations in BFlh fascicle length returned to pre-intervention measures after a 4-wk detraining period, whereas any strength increases were maintained after detraining. Eccentric hip extension training increased muscle volume of BFlh and SM, whereas isometric training demonstrated increases in only ST muscle volume. These results may have implications for hamstring injury prevention and rehabilitation practices, and future research is required to understand whether these interventions have a direct effect on HSI incidence.

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The authors report that no conflicts of interest exist. Results of this study do not constitute endorsement of the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

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