Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training

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ABSTRACT

TIMMINS, R. G., J. D. RUDDY, J. PRESLAND, N. MANIAR, A. J. SHIELD, M. D. WILLIAMS, and D. A. OPAR. Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training. *Med. Sci. Sports Exerc.*, Vol. 48, No. 3, pp. 499–508, 2016. **Purpose**: To determine the architectural adaptations of the biceps femoris long head (BFlh) after concentric or eccentric strength training interventions and the time course of adaptation during training and detraining. **Methods**: Participants in this intervention (concentric training group [$n = 14$], eccentric training group [$n = 14$], male subjects) completed a 4-wk control period, followed by 6 wk of either concentric- or eccentric-only knee flexor training on an isokinetic dynamometer and finished with 28 d of detraining. Architectural characteristics of BFlh were assessed at rest and during graded isometric contractions using two-dimensional ultrasonography at 28 d prebaseline; baseline; and days 14, 21, and 42 of the intervention and then again after 28 d of detraining. **Results**: BFlh fascicle length was significantly longer in the eccentric training group ($P < 0.05$; d range, 2.65–2.98) and shorter in the concentric training group ($P < 0.05$; d range, -1.62 to -0.96) after 42 d of training compared with baseline at all isometric contraction intensities. After the 28-d detraining period, BFlh fascicle length was significantly reduced in the eccentric training group at all contraction intensities compared with the end of the intervention ($P < 0.05$; d range, -1.73 to -1.55). There was no significant change in fascicle length of the concentric training group after the detraining period. **Conclusions**: These results provide evidence that short-term resistance training can lead to architectural alterations in the BFlh. In addition, the eccentric training-induced lengthening of BFlh fascicle length was reversed and returned to baseline values after 28 d of detraining. The contraction mode specific adaptations in this study may have implications for injury prevention and rehabilitation. **Key Words:** FASCICLE, MUSCLE ADAPTATION, HAMSTRING, ULTRASOUND, RANDOMIZED CONTROLLED TRIAL

The ability of a muscle to produce force is partly governed by its architectural characteristics, such as muscle thickness, pennation angle, and fascicle length (17). Architectural characteristics have been shown, in many different muscles, to change when exposed to mechanical stimuli, such as resistance training interventions (2,3,21,28,32). Understanding the changes to muscle architecture in response to a given stimulus is important when aiming to alter muscle function and the risk of injury (2,3,7,36).

During the terminal swing phase of the gait cycle, the hamstrings are required to actively lengthen to decelerate the extending knee and flexing hip (38). It is during this phase of the gait cycle where the hamstrings are at their longest, with the biceps femoris long head (BFlh) reaching approximately 110% of its length during upright stance (35). These high force, lengthening actions of the hamstrings may contribute to the high rate of strain injuries during running (26), the majority of which occur in the BFlh (16,24). Interestingly, a previously strain injured BFlh possesses shorter fascicle lengths and greater pennation angles when compared with the contralateral uninjured BFlh (36). Differences in fascicle length can alter function, with muscles that possess longer fascicles having a greater maximal shortening velocity when compared with those with shorter fascicles (6,17). Therefore, it is important to develop an understanding of how muscle architecture can be altered by physical training to influence function and guide hamstring strain injury prevention and rehabilitation practices.

Despite the large amount of research showing a range of architectural adaptations after eccentric training interventions (2,3,31), investigations that outline the time course for adaptation, including a period of detraining, are limited. Furthermore, the previous research into the adaptability of the BFlh after a training intervention only compared eccentric training

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with a nontraining control group (28). Therefore, it is unclear how BFlh architectural adaptations might differ after eccentric and concentric strength training.

Given the high incidence of hamstring strain injury in the BFlh (16,24), it is of interest to see how its architecture is altered after either concentric or eccentric strength training. Therefore, the purposes of this study were to determine the architectural adaptations of the BFlh after either a concentric or eccentric strength training intervention and determine the time course of BFlh architectural adaptations during a 6-wk training intervention and after a 28-d period of detraining.

METHODS

Participants

Twenty-eight recreationally active male subjects (age, 22.3 ± 4.2 yr; height, 1.81 ± 0.07 m; body mass, 76.9 ± 8.2 kg) with no history of lower limb injury in the past 12 months were recruited to participate in this study. All participants provided written informed consent before testing and training, which was undertaken at the Australian Catholic University, Fitzroy, Victoria, Australia. Ethical approval for the study was granted by the Australian Catholic University Human Research Ethics Committee.

Study Design

Participants undertook a maximal isokinetic dynamometry familiarization session no less than 7 d before having their BFlh architecture assessed. The familiarization session and architectural assessment was completed on both limbs. After this initial testing session (28 d prebaseline), the participants were paired according to passive BFlh fascicle length and randomly assigned to one of two training groups (allocation ratio, 1:1) to undertake either concentric- or eccentric-only knee flexor strength training. All participants ($n = 28$) returned to the lab 4 wk later (baseline) and had their maximal knee flexor strength and BFlh architectural characteristics assessed on both limbs. After this, the participants underwent 6 wk of either a concentric- or eccentric strength training intervention in a randomly selected limb (the contralateral limb served as a within-participant control). BFlh architecture of both limbs was reassessed at days 14, 21, and 42 of the intervention and 28 d after the completion of the strength training intervention. Knee flexor strength of both limbs was retested at the end of the training intervention (day 42) and 28 d after the completion of the intervention. All tests were performed at the same time of the day for each participant.

Outcome Measures

Isokinetic dynamometry. All knee flexor strength testing was completed on a Humac Norm isokinetic dynamometer (CSMI, Massachusetts), on both legs (left or right) in a randomized order. Participants were seated on the dynamometer with their hips flexed at approximately 85° from neutral and were restrained by straps around the tested/exercised thigh, waist, and chest to minimize compensatory movements. All seating variables (e.g., seat height, pad position) were recorded to ensure the replication of the participants' positions. Gravity correction for limb weight was also conducted, and range of motion was set between 0° and 90° of knee flexion (full extension = 0°) with the starting position for each contraction during strength testing being 90° of knee flexion. The starting position for all training contractions was dependent on training group, with the concentric training group starting from 0° of knee extension and the eccentric group beginning from 90°. Before all testing sessions, participants undertook a warm-up consisting of three sets of three concentric knee extension and flexion contractions at an angular velocity of $240°\cdot s^{-1}$. The intensity of these contractions increased each set (first set ~75% and second set ~90% of the participants perceived maximum) until the final set at this velocity was performed at a maximal level. The test protocol began 1 min after the final warm-up set and consisted of three sets of three repetitions of concentric and eccentric maximal voluntary contractions of knee flexion at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$ (30-s interset rest). For all concentric knee flexion efforts, the participants were instructed to "pull down" against the lever as fast as possible, whereas during eccentric contractions, they were told to "resist" the lever arm from extending their knee as hard as they could. All participants were provided visual feedback of their efforts as well as being verbally encouraged by the investigators to ensure maximal effort for all contractions. The testing order of contraction modes was randomized across the participant pool, and the testing protocol has been previously reported to not alter concentric or eccentric knee flexor strength (37). Dynamometer torque and lever position data were transferred to a computer at 1 kHz and stored for later analysis where it was fourth-order low pass Butterworth filtered (5 Hz). Peak torques at $240°\cdot s^{-1}$, $180°\cdot s^{-1}$, and $60°\cdot s^{-1}$ for concentric and $180°\cdot s^{-1}$ and $60°\cdot s^{-1}$ for eccentric knee flexion were defined as the mean of the six highest torque values for each contraction mode at each velocity.

BFlh architectural assessment. Muscle thickness and pennation angle of the BFlh were determined from ultrasound images taken along the longitudinal axis (Fig. 1) of the muscle belly using a two-dimensional, B-mode ultrasound (frequency, 12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-*i,* Wauwatosa). The same images were used to estimate BFlh fascicle length. The scanning site was determined as the halfway point between the ischial tuberosity and the popliteal crease, along the line of the BFlh. Once the scanning site was determined, the distances of the site from various anatomical landmarks were recorded to ensure its reproducibility for future testing sessions. These landmarks included the ischial tuberosity, fibula head, and the posterior knee joint fold at the midpoint between BF and semitendinosus tendon. On subsequent visits, the scanning site was determined and marked on the skin and then confirmed by replicated landmark distance measures. All architectural assessments were performed with participants in a prone position and the hip in a neutral position after at least 5 min of inactivity. Assessments at rest were always performed

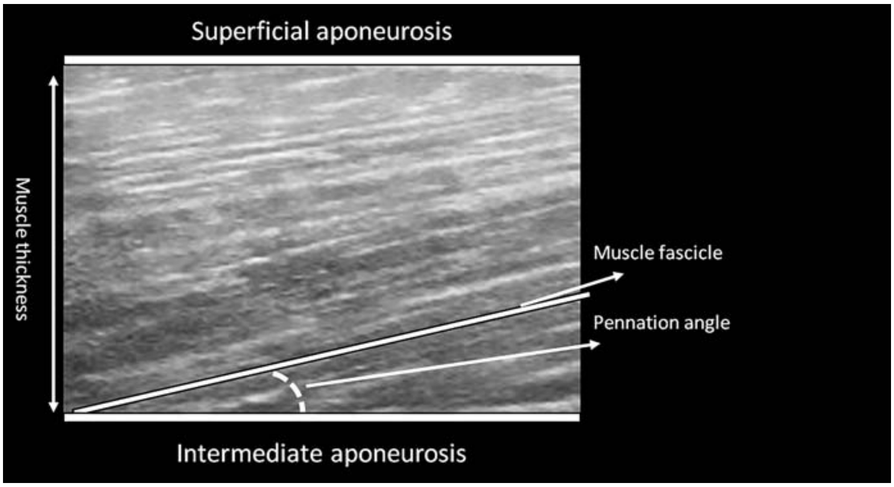

FIGURE 1—A two-dimensional ultrasound image of the biceps femoris long head. This image of the biceps femoris long head was taken along the longitudinal axis of the posterior thigh. From these images, it is possible to determine the superficial and intermediate aponeuroses, muscle thickness, and angle of the fascicle in relation to the aponeurosis. Estimates of fascicle length can then be made via trigonometry using muscle thickness and pennation angle.

first, followed by the graded isometric contraction protocol. Assessment of BFlh architecture at rest was performed with the knee at 0° of knee flexion. Assessment of BFlh architecture during isometric contractions was always performed with the knee at 0° flexion and preceded by a maximal voluntary isometric contraction, performed in a custom made device (25). The graded isometric contractions of the knee flexors were performed in the same device at 25%, 50%, and 75% of maximum voluntary isometric contraction (MVIC) with the participants shown the real-time visual feedback of the force produced to ensure that target contraction intensities were met. Assessment of the MVIC of the knee flexors was undertaken in a prone position, with both the hip and knee fully extended (0°). Participants were instructed to contract maximally over a 5-s period, from which the peak force was used to determine the MVIC.

To gather ultrasound images, the linear array ultrasound probe, with a layer of conductive gel was placed on the skin over the scanning site, aligned longitudinally and perpendicular to the posterior thigh. Care was taken to ensure minimal pressure was placed on the skin by the probe as this may influence measurement accuracy (15). Finally, the probe orientation was manipulated slightly by the sonographer (R.G.T.) if the superficial and intermediate aponeuroses were not parallel.

Analysis was completed offline (MicroDicom, Version 0.7.8, Bulgaria). For each image, six points were digitized as described by Blazevich and colleagues (5). After the digitizing process, muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of BFlh. A fascicle of interest was outlined and marked on the image. The angle between this fascicle and the intermediate aponeurosis was measured and given as the pennation angle (Fig. 1). The aponeurosis angle for both aponeuroses was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal line across the captured image (5,14). Fascicle length was estimated from an outlined fascicle between the aponeuroses. As the entire fascicle was not visible in the probe field of view, its length was estimated via the following validated equation from Blazevich and colleagues (5,14):

$$\mathrm{FL} = \sin(\mathrm{AA} + 90°) \times \mathrm{MT}/\sin(180° - (\mathrm{AA} + 180° - \mathrm{PA}))$$

where FL = fascicle length, AA = aponeurosis angle, MT = muscle thickness, AA = aponeurosis angle and PA = pennation angle.

Fascicle length was reported in absolute terms (cm) and also relative to muscle thickness (fascicle length/muscle thickness). The same assessor (R.G.T.) conducted and analyzed all scans and was blinded to participant identifiers during the analysis. The methodology used in this study to assess the BFlh architectural characteristics has been previously reported by our laboratory (36).

Intervention. The participants performed 6 wk of either maximal eccentric or concentric knee flexion strength training, with two sessions in the intervention's first week and three sessions a week thereafter on an isokinetic dynamometer (Humac Norm, CSMI, Massachusetts) using the same range of motion and seat positions configuration as dynamometry testing sessions. Only one limb received the strength training stimulus, with the contralateral limb acting as a within-participant control limb. Across the training period, the volume (number) of contractions was increased following the progression below:

- Week 1:
  - Frequency ($d \cdot wk^{-1}$) = 2
  - Sets = 4
  - Repetitions = 6
  - Total repetitions = 48
- Week 2:
  - Frequency ($d \cdot wk^{-1}$) = 3
  - Sets = 4

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- Repetitions = 6
- Total repetitions = 72

- Week 3:
  - Frequency ($d \cdot wk^{-1}$) = 3
  - Sets = 5
  - Repetitions = 6
  - Total repetitions = 90
- Week 4:
  - Frequency ($d \cdot wk^{-1}$) = 3
  - Sets = 5
  - Repetitions = 8
  - Total repetitions = 120
- Week 5:
  - Frequency ($d \cdot wk^{-1}$) = 3
  - Sets = 6
  - Repetitions = 6
  - Total repetitions = 108
- Week 6:
  - Frequency ($d \cdot wk^{-1}$) = 3
  - Sets = 6
  - Repetitions = 8
  - Total repetitions = 144

Each training session was separated by at least 48 h. Contractions were distributed evenly across $60° \cdot s^{-1}$ and $180° \cdot s^{-1}$. All participants started with two sets of three warm-up efforts at $60° \cdot s^{-1}$, in the contraction mode used for their training. For all training repetitions, the concentric training participants were moved to full knee extension (0°) by the investigator and were instructed to flex their knee as fast as possible through to 90° of knee flexion. The investigator then returned the lever arm to full knee extension, and the subsequent repetition was completed. This was undertaken until all repetitions were completed in their respective set, with a 30-s interset rest period. The eccentric training participants began with their knee at 90° of flexion. They were then instructed to maximally flex against the lever arm until full knee extension was reached (0°). The participant was then instructed to relax, the lever arm was repositioned to 90° of knee flexion by the investigators, and the subsequent contraction was performed. This was undertaken until all repetitions were completed in each set, with a 30-s interset rest period. All participants were provided visual and verbal feedback on the consistency of the torque produced during each repetition. These were compared against personal best performances, which were known by the participant, to aid motivation. During the control (28 d prebaseline to baseline), intervention (baseline to intervention day 42), and detraining periods (intervention day 42 to postintervention day 28), participants continued their habitual levels of physical activity. The only restriction was to not perform any other lower limb strength exercises. Finally, training compliance was determined as a percentage of sessions that were completed within 24 h of the intended time.

Statistical Analysis

All statistical analyses were performed using SPSS version 22.0.0.1 (IBM Corporation, Chicago, IL). Where appropriate, data were screened for normal distribution using the Shapiro–Wilk test and homoscedasticity using Levene's test. Greenhouse–Geisser adjustment was applied when the assumption of sphericity was violated ($P < 0.05$ for Mauchly's test of sphericity). At each contraction intensity, a split-plot design ANOVA, with the within-participant variables being limb (trained or untrained) and time point (28 d prebaseline, baseline, intervention day 14, intervention day 21, intervention day 42, and postintervention day 28) and the between-subject variable being group (eccentric or concentric), was used to compare changes in BFlh architecture throughout the training study. Architectural changes across the 28-d control period (28 d prebaseline to baseline) were not significant ($P > 0.05$). Therefore, when determining the alterations in BFlh architectural characteristics after a 6-wk intervention, all comparisons were made to baseline. Knee flexor peak torque comparisons, at each contraction velocity, used a similar split-plot design ANOVA, however, with different time point variables (baseline, intervention day 42, and postintervention day 28). Where significant limb–time–group interactions for architecture and limb × time for knee flexor peak torque were detected, *post hoc t* tests with Bonferroni adjustments were used to identify which comparisons differed. Significance was set at a $P < 0.05$, and appropriate Cohen's d (8) was reported for the comparison effect sizes, with the levels of effect being deemed small ($d = 0.20$), medium ($d = 0.50$), or large ($d = 0.80$) as recommended by Cohen (1988).

Sample Size

Sample size analysis was completed a priori using G-Power (9). The analysis was based on the anticipated differences in fascicle length after the strength training intervention. The effect size was estimated based on the only intervention study to date that has reported changes in the BFlh architecture (28). That study reported a 33% increase in fascicle length after the intervention with an approximate effect size of 1.9. Therefore, an effect size of 1.2 was deemed as a reasonable starting point. Power was set at 80% with an alpha level of 0.05 returning a calculated sample size of 12 per group. As a cross-reference to confirm the effect size, fascicle length differences in individuals with a unilateral BFlh strain injury displayed an effect size of 1.34 when comparing between the previously injured and contralateral uninjured limb (36).

RESULTS

Participants

The two training groups were similar with respect to age, height, and body mass (eccentric training group: age 21.2 ± 2.7 yr, height 1.81 ± 0.06 m, body mass 77.9 ± 9.3 kg; concentric training group: age 23.4 ± 5.1 yr; height 1.81 ± 0.07 m; body mass 76.2 ± 7.1 kg). Overall, compliance rates were acceptable for all participants (92% ± 2%; min = 85%; max = 100%),

TABLE 1. Changes in the biceps femoris long head architectural characteristics in the training limb of each group at the start (day 0), after 14, 21, and 42 d of the training intervention and after the detraining period (day 70).

	Concentric Group (*n* = 14)					Eccentric Group (*n* = 14)				
	Baseline (Day 0)	**Intervention (Day 14)**	**Intervention (Day 21)**	**End Intervention (Day 42)**	**Postintervention (Day 70)**	**Baseline (Day 0)**	**Intervention (Day 14)**	**Intervention (Day 21)**	**End Intervention (Day 42)**	**Postintervention (Day 70)**
0% MVIC										
FL (cm)	11.71 ± 0.9	10.74 ± 0.7*	10.45 ± 0.9*	10.33 ± 0.8**	10.45 ± 0.8*	11.53 ± 0.6	13.24 ± 0.9**	13.27 ± 0.9**	13.42 ± 0.8**	11.85 ± 1.0##
RFL	4.60 ± 0.2	4.01 ± 0.3**	3.90 ± 0.3**	3.86 ± 0.3**	3.97 ± 0.3**	4.31 ± 0.4	4.75 ± 0.4*	4.65 ± 0.4	4.64 ± 0.4	4.3 ± 0.2
PA (°)	12.57 ± 0.6	14.47 ± 0.9*	14.97 ± 1.4**	15.1 ± 1.3**	14.72 ± 1.5**	13.52 ± 1.2	12.21 ± 1.1*	12.40 ± 1.2*	12.50 ± 1.2*	13.50 ± 0.9
MT (cm)	2.54 ± 0.2	2.68 ± 0.2	2.70 ± 0.2	2.68 ± 0.2	2.64 ± 0.2	2.69 ± 0.2	2.80 ± 0.3	2.86 ± 0.2	2.91 ± 0.2	2.77 ± 0.3
25% MVIC										
FL (cm)	10.69 ± 0.6	10.01 ± 0.4*	9.83 ± 0.8*	9.63 ± 0.8*	10.03 ± 0.8	10.72 ± 0.5	11.92 ± 0.7*	12.35 ± 0.9**	12.33 ± 0.6**	11.13 ± 0.9#
RFL	4.15 ± 0.2	3.70 ± 0.2**	3.63 ± 0.2**	3.60 ± 0.2**	3.71 ± 0.3*	3.94 ± 0.3	4.2 ± 0.2	4.22 ± 0.3	4.20 ± 0.4	3.92 ± 0.2
PA (°)	13.95 ± 0.7	15.72 ± 0.9*	16.04 ± 1.2**	16.16 ± 1.2**	15.72 ± 1.3*	14.79 ± 1.2	13.89 ± 0.9	13.67 ± 1.2	13.87 ± 0.6*	14.81 ± 0.9
MT (cm)	2.58 ± 0.2	2.71 ± 0.2	2.71 ± 0.2	2.67 ± 0.2	2.70 ± 0.2	2.74 ± 0.2	2.87 ± 0.2	2.93 ± 0.2	2.95 ± 0.3	2.84 ± 0.2
50% MVIC										
FL (cm)	10.03 ± 0.7	9.60 ± 0.5	9.32 ± 0.6*	9.22 ± 0.5*	9.50 ± 0.6	10.15 ± 0.5	11.09 ± 0.7*	11.59 ± 0.7**	11.80 ± 0.6**	10.64 ± 0.8##
RFL	3.80 ± 0.2	3.50 ± 0.2*	3.41 ± 0.3*	3.37 ± 0.2**	3.46 ± 0.2*	3.64 ± 0.2	3.84 ± 0.2	3.92 ± 0.3	3.95 ± 0.3*	3.70 ± 0.2
PA (°)	15.30 ± 0.9	16.70 ± 1.2*	17.14 ± 1.4*	17.28 ± 1.2*	16.88 ± 1.3*	16.01 ± 1.2	15.10 ± 1.0	14.91 ± 0.9	14.74 ± 1.1*	15.72 ± 0.9
MT (cm)	2.65 ± 0.2	2.75 ± 0.2	2.74 ± 0.2	2.74 ± 0.2	2.75 ± 0.2	2.79 ± 0.2	2.89 ± 0.2	2.97 ± 0.2	3.00 ± 0.2	2.87 ± 0.2
75% MVIC										
FL (cm)	9.36 ± 0.6	9.21 ± 0.6	9.12 ± 0.6	8.78 ± 0.6*	9.15 ± 0.5	9.62 ± 0.6	10.51 ± 0.7*	11.03 ± 0.6**	11.21 ± 0.6**	10.20 ± 0.7#
RFL	3.53 ± 0.2	3.34 ± 0.2	3.28 ± 0.2*	3.18 ± 0.2*	3.31 ± 0.2	3.43 ± 0.2	3.64 ± 0.2	3.72 ± 0.2*	3.75 ± 0.3*	3.54 ± 0.2
PA (°)	16.50 ± 1.2	17.46 ± 1.2	17.86 ± 1.4	18.34 ± 1.1*	17.62 ± 1.2	17.03 ± 1.2	15.95 ± 1.1	15.70 ± 0.9*	15.54 ± 1.1*	16.44 ± 0.9
MT (cm)	2.65 ± 0.2	2.76 ± 0.2	2.79 ± 0.2	2.76 ± 0.2	2.77 ± 0.2	2.81 ± 0.2	2.89 ± 0.2	2.98 ± 0.2	2.99 ± 0.2	2.87 ± 0.2

All data represented as mean ± SD unless otherwise stated. SD = standard deviation, MT = muscle thickness, cm = centimeters, PA = pennation angle, RFL = fascicle length relative to muscle thickness, FL = fascicle length, MVIC = maximum voluntary isometric contraction.

**P* < 0.05 vs day 0.

***P* < 0.001 vs day 0.

#*P* < 0.05 vs day 42.

##*P* < 0.001 vs day 42.

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with no differences when comparing the two groups (eccentric training group: 91% ± 2%; concentric training group: 93% ± 1%).

BFlh Architectural Comparisons

Control period, control limb changes, and baseline comparisons. A significant limb–time–group interaction effect was found for fascicle length, fascicle length relative to muscle thickness and pennation angle ($P < 0.001$). *Post hoc* analyses showed no BFlh architectural variables changed during the 4-wk preintervention control period ($P > 0.05$; d range, 0.03–0.17). Similarly, there were no significant differences at any time point, in the nontraining control limbs for any BFlh architectural variables ($P > 0.05$; d range, 0.03–0.27). Comparisons of all the BFlh architectural variables at baseline displayed no significant differences between the concentric and eccentric training group in legs that were to be trained (i.e., the training leg) ($P > 0.05$; d range, 0.22–0.43).

Fascicle length and fascicle length relative to muscle thickness changes. A significant limb–time–group interaction effect was found for fascicle length at all contraction intensities ($P < 0.001$). *Post hoc* analysis showed that fascicle length was significantly longer in the training limb of the eccentric training group ($P < 0.05$; d range, 2.65–2.98; Table 1 and Fig. 2) and significantly shorter in the training limb of the concentric training group ($P < 0.05$; d range, −1.62 to −0.96; Table 1 and Fig. 2) after 42 d of the intervention compared with baseline at all contraction intensities. Additionally, there was a significant limb–time–group interaction effect for fascicle length relative to muscle thickness ($P < 0.001$). All *post hoc* comparisons for the training limbs of each group are presented in Table 1.

After the 28-d detraining period, fascicle length was significantly reduced in the training limb of the eccentric training group in comparison to the end of the intervention at all contraction intensities ($P < 0.05$; d range, −1.73 to −1.55; Table 1 and Fig. 2). *Post hoc* analysis showed that fascicle length in the concentric training group after 28 d of detraining was no different to that observed end of the intervention at any contraction intensity ($P > 0.05$; d range, 0.15–0.67; Table 1 and Fig. 2). All other *post hoc* comparisons of fascicle length and fascicle length relative to muscle thickness, 28 d after the intervention period, in the training limbs of both groups are presented in Table 1 and Figure 2.

Muscle thickness and pennation angle changes. No significant limb–time–group interaction effect was found for muscle thickness at any contraction intensity ($P > 0.162$). However, a significant limb–time–group interaction effect was detected for pennation angle at all contraction intensities ($P < 0.001$). *Post hoc* analysis showed that pennation angle was significantly reduced in the training limb of the eccentric training group ($P < 0.05$; d range, −1.30 to −0.85; Table 1 and Fig. 2) and significantly increased in the training limb of the concentric training group ($P < 0.05$; d range, 1.60–2.50; Table 1 and Figs. 1–2) after 14 d of the intervention compared with baseline at all contraction intensities. All other comparisons of pennation angle changes in the training limb of both groups are presented in Table 1.

Pennation angle was not significantly different in the training limb of the eccentric training group in comparison to the end of the intervention, at any contraction intensity after the 28-d detraining period ($P > 0.05$; d range, −0.55 to 0.02; Table 1 and Fig. 2). *Post hoc* analysis showed that after the 28 d of detraining, pennation angle of the concentric training group was no different compared to the end of the intervention, at any contraction intensity ($P > 0.05$; d range, −0.63 to −0.27; Table 1 and Fig. 2). All other comparisons of pennation angle changes after the 28-d detraining period are presented in Table 1.

Strength changes. A significant limb–time interaction effect for knee flexor peak torque was found at all contraction velocities for each group ($P < 0.001$). Comparisons at all contraction velocities, at baseline, displayed no significant differences between the concentric and eccentric training groups ($P > 0.05$). *Post hoc* analysis also revealed that knee flexor peak torque increased in both the training limb of the eccentric ($P < 0.05$; d range, 0.63–0.78; Table 2) and the concentric training group ($P < 0.05$; d range, 0.53–0.72; Table 2) after 42 d of the intervention, at all contraction velocities, when compared to baseline. There were no significant differences in knee flexor peak torque for the untrained limbs of either group after 42 d of the intervention when compared with baseline at any contraction velocity ($P > 0.05$; d range, 0.11–0.27).

There were no significant differences in knee flexor peak torque at any contraction velocity, in either group when comparing their strength after the 28-d detraining period to the values after 42 days of the intervention ($P > 0.05$; d range, −0.30 to −0.16; Table 2). Additionally, knee flexor peak torques at all contraction velocities after the 28-d detraining period were significantly greater in the training limb of both training groups when compared with baseline ($P > 0.05$; d range, 0.34–0.75; Table 2).

DISCUSSION

To the authors' knowledge, this is the first study reporting divergent BFlh architectural adaptations in response to concentric or eccentric strength training. Moreover, it is the first to provide evidence that eccentric training-induced increases in BFlh fascicle length are reversed after 28 d of detraining. The main findings were that eccentric strength training resulted in an increase in estimated BFlh fascicle length and a reduction in pennation angle, whereas concentric strength training caused reductions in estimated fascicle length and increases in pennation angle. Additionally, in those who trained eccentrically, a significant reduction in BFlh fascicle length and a nonsignificant increase in pennation angle were found after a 28-d detraining period when compared with the end of the strength training intervention. In contrast, the concentrically trained group maintained their BFlh architectural characteristics after 28 d of detraining. Finally, improvements in knee flexor strength were not specific to training contraction mode, with significant improvements in concentric and eccentric strength found in both training groups that persisted through the detraining period.

Observations of increases in BFlh fascicle length and a reduction in pennation angle (measured at rest) after eccentric strength training in the current study (Fig. 1) align somewhat with previous literature (28). Potier and colleagues (2009) found a 33% increase in resting BFlh fascicle length with a nonsignificant 3.1% reduction in resting pennation angle after 8 wk of eccentric strength training. In comparison, the current study saw a significant 16% increase in resting BFlh fascicle length (the majority of which occurred within 14 d), with a nonsignificant 7.5% reduction in resting pennation angle. Differences in the training modalities used (leg curl vs isokinetic dynamometry), intervention length (8 wk vs 6 wk), and the scanning site used to assess BFlh architecture may explain the different magnitudes of change reported in these studies. Additionally, no previous literature has examined BFlh architectural alterations during graded isometric contractions after an intervention. In the present study, increases in BFlh fascicle length were observed at the end of the intervention when assessed

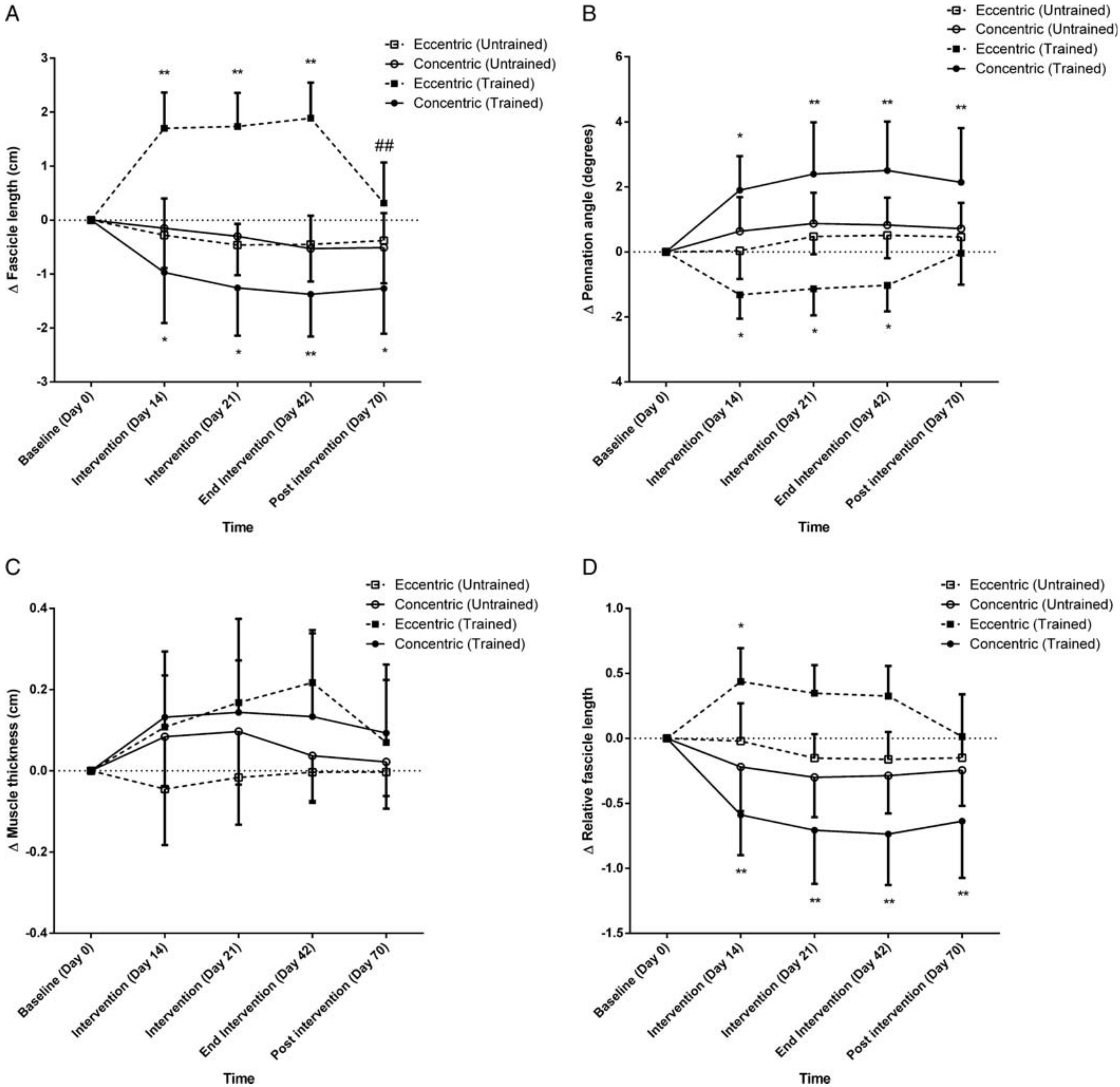

FIGURE 2—Changes in the architectural characteristics of the BFlh when assessed at rest in the trained limb and the contralateral untrained limb of both groups after 14, 21, and 42 d of the training intervention and after the detraining period (day 70). A, Fascicle length; B, pennation angle; C, muscle thickness; and D, fascicle length relative to muscle thickness. Error bars illustrate the standard deviation. *P < 0.05 vs day 0; **P < 0.001 vs day 0, ##P < 0.001 vs day 42.

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TABLE 2. Changes in concentric and eccentric knee flexor average peak torque at various contraction velocities in the training limb of each group before (day 0) and after the training intervention (day 42) and after the detraining period (day 70).

	Concentric Group (n = 14)					Eccentric Group (n = 14)				
Contraction Velocity	Baseline (Day 0)	End Intervention (Day 42)	Postintervention (Day 70)	%Change Following Intervention	%Change 28 Days Post Intervention	Baseline (Day 0)	End Intervention (Day 42)	Postintervention (Day 70)	%Change Following Intervention	%Change 28 Days Post Intervention
Concentric 240 (°·s^{-1})	89.3 ± 16.2	97.86* ±16.4	95.44 ± 13.3*	9.58	−2.47	97.2 ± 21.2	109.94* ±19.3	105.10* ±20.3	13.1	−4.40
Concentric 180 (°·s^{-1})	104.44 ± 19.1	116.2** ± 18.2	111.66 ± 17.8*	11.3	−3.95	111.3 ± 24.9	129.06** ± 24.3	122.57* ± 17.9	15.9	−5.01
Concentric 60 (°·s^{-1})	141.04 ± 28.3	159.5* ± 24.1	153.51 ± 25.9*	13.1	−3.75	134.15 ± 30.8	156.3** ± 25.2	152.8* ± 17.02	16.5	−2.23
Eccentric 60 (°·s^{-1})	186.53 ± 39.6	213.40* ± 35.1	203.74 ± 40.3*	14.4	−4.52	196.3 ± 44.4	228.8** ± 48.9	218.2* ± 36.7	16.6	−4.63
Eccentric 180 (°·s^{-1})	178.11 ± 44.7	200.62* ± 34.8	191.91 ± 35.7*	12.6	−4.34	185.9 ± 35.9	216.2** ± 43.01	209.02* ± 32.1	16.3	−3.32

All data represented as mean ± SD unless otherwise stated. SD = standard deviation.
*P < 0.05 vs day 0.
**P < 0.001 vs day 0.

during all graded isometric contractions in the eccentrically trained individuals. These increases in fascicle length may occur as a result of the addition of in-series sarcomeres, as has been shown in rat vastus intermedius muscles after 5 d of downhill and presumably eccentric running exercise (18). However, the architectural alterations seen in this study may not be uniform along the BFlh length. Changes in fascicle length (4), muscle thickness, and anatomical cross sectional area, after strength training interventions (3), are variable within a muscle. It is possible that the assessment of BFlh architecture in the current study may have occurred at a point on the muscle where the changes were less prominent in comparison to other studies (28). Alternatively, changes in tendon stiffness could theoretically result in altered fascicle lengths, with stiffer tendons causing an increased tension within the muscle, which could then result in the elongation of resting BFlh fascicle length. Further research is needed to clarify the mechanism responsible for fascicle length alterations in humans.

No previous studies have compared the architectural alterations in the BFlh, after concentric and eccentric training. However, interventions, which have used concentric or eccentric knee extensor training, have reported inconsistent architectural adaptations. Some have shown a contraction mode-specific adaptation similar to that observed in the current study (10,29), whereas others have not (3). Additionally, knee extensor isometric strength training at short and long muscle lengths has also been shown to increase fascicle length (22). A range of factors such as the relative maximum load (3,10), the participant's age and physical capacity (29), and the training stimulus velocity (33) might explain some of the variance between these results. However, it is not known why these alterations in the vastus lateralis differ to those reported in the current study. It is possible that differences in the structural and functional characteristics of the muscles may account for this variability. However, future research is needed to assist in determining the BFlh adaptive responses to these and many other variables.

The increases in BFlh fascicle length and reductions in pennation angle found in the current study after eccentric strength training may have implications for hamstring strain injury prevention and rehabilitation. Elite athletes with a unilateral history of BFlh strain injury have shorter fascicles and greater pennation angles on their previously injured limb when compared with the contralateral uninjured limb (36). Individuals with a history of hamstring strain injury are at an increased risk of future injury in comparison to those without a history (24,26). Therefore, if shorter fascicles and greater pennation angles in a previously injured athlete are partial contributors to the elevated risk of reinjury, then understanding the most effective methods for altering these architectural characteristics will be of great value. The current data indicate that the continual application of high-intensity, eccentric-only strength training should be considered in hamstring rehabilitation and prevention programs to increase BFlh fascicle length and reduce pennation angle. Additionally, the current findings suggest that muscle length in training is possibly not the major factor, as previously suggested (12), in determining fascicle length changes as long length, concentric exercise resulted in shortening of fascicle length. Further research is needed to determine how the combination of both concentric and eccentric contractions during conventional strength training methods may alter BFlh architecture.

The very rapid response of BFlh architectural adaptations supports previous literature, which has found significant increases in fascicle length and pennation angle in the vastus lateralis within 14 d of the commencement of an eccentrically biased strength training intervention (31). Furthermore, rat vastus intermedius in-series sarcomere numbers have been shown to increase within a week of commencing a downhill running protocol (18). In the current study, the majority of fascicle length and pennation angle changes in the eccentric strength training group occurred within the first 14 d of training, with nonsignificant changes for the rest of the intervention (Figs. 1 and 2). A similar but inverse response was found in the concentric training group after 14 d of training, with nonsignificant changes for the remainder of the strength training intervention. These results, along with those from other studies (3,31), suggest that early adaptations to strength training are not only from a neural mechanism (30) but may also be as a result of architectural adaptations.

The reported alterations in muscle architecture after periods of detraining are variable, with most conclusions being drawn from observations of prolonged periods of limb unloading, some of which show significant reductions in fascicle length, pennation angle and muscle volume (20,32), whereas some display no alterations (1). In regard to the detraining responses after high-intensity eccentric or concentric strength training, only one study has investigated this, 3-months after a 10-wk intervention in the vastus lateralis (3). Blazevich and colleagues (2007) found no significant alterations in knee extensor strength or vastus lateralis architectural characteristics after a 3-month detraining period. These results are inconsistent with the findings from the eccentric training group in the current study who displayed a significant reduction in BFlh fascicle length and an increase in pennation angle after 28 d of detraining. In comparison, the concentric group displayed similar findings to Blazevich and colleagues (2007), with architectural variables remaining unchanged after 28 d of detraining (3). The eccentric training group response to the intervention and then to detraining may be of interest for hamstring strain injury prevention and rehabilitation interventions as it has been argued that shorter fascicles (i.e., with fewer in-series sarcomeres) are more prone to muscle damage during high-intensity, eccentric contractions compared with longer fascicles (11,19,36). It remains to be seen what effect conventional strength training exercises, which possess both concentric and eccentric actions, have on hamstring muscle architecture. In addition, the apparent rapid decrease in fascicle lengths when the eccentric stimulus is removed would indicate that constant exposure to eccentric exercise may be important to maintain changes in BFlh architecture after an intervention period.

The strength training interventions in the current study induced significant increases in concentric and eccentric strength in the training limb of both the concentric and eccentric training groups (Table 2). Previous research investigating knee flexor strength alterations after eccentric or concentric strength training interventions are variable (13,28). To the authors' knowledge, this is the first study to show improvements in both isokinetically derived concentric and eccentric knee flexor strength independent of training modality. However, improvements in concentric strength after an eccentric strength training intervention have been previously reported in the knee flexors and within other muscle groups (27,34). There is still some contradictory evidence as to whether a contraction mode-specific strength adaptation occurs after either concentric or eccentric training (3,10,29). The current study shows that increases in eccentric strength can be achieved through long length, concentric strength training in the knee flexors. It is unclear if there might be a contraction mode specific adaptation in longer training programs. However, the current findings must be considered in line with the divergent architectural alterations seen between the two strength training interventions.

The authors acknowledge that there are limitations in the current study. First, there are methodological limitations with the use of two-dimensional ultrasound for the estimation of BFlh fascicle length. As the field of view used in this study does not capture the entire BFlh fascicle, estimation is required. The equation used in this study has been validated against cadaveric samples (14); however, it must be recognized that there is still a level of error associated with estimations of BFlh fascicle length. Future studies should consider extended field of view ultrasound methods (23) to reduce the level of error when estimating muscle fascicle length. Second, the assessment of muscle architecture was only performed on the BFlh and did not include the other knee flexors. Therefore, it is unknown what adaptations these other muscles displayed after the intervention and detraining period. However, as the BFlh is the most commonly strain injured hamstring muscle (16), the alterations after concentric and eccentric strength training interventions were of interest from a hamstring strain injury risk and rehabilitation perspective. Finally, the training stimulus was provided with an even distribution of the number of contractions across both slow and fast isokinetic velocities. As vastus lateralis architectural adaptations have been shown to be velocity dependent (33), it is not possible to determine if the changes in this cohort and muscle are due to the velocities used. The aim of this study was to investigate the effect of contraction mode, not velocity, on BFlh architectural changes as this may have greater implications for hamstring strain injury prevention and rehabilitation. Further research is needed to determine if there is a contraction velocity-specific adaptation in the knee flexors after a concentric or eccentric strength training intervention.

In conclusion, the current study reports rapid, contraction mode specific alterations in BFlh architecture after 6 wk of either eccentric or concentric strength training interventions. Furthermore, 28 d of detraining resulted in BFlh architectural characteristics returning to baseline levels in individuals who had completed eccentric training, whereas detraining had no influence on the BFlh architectural characteristics in those who completed concentric strength training. The findings of the current study provide insight into BFlh architectural alterations after concentric and eccentric strength training interventions. These results may have implications for hamstring injury prevention and rehabilitation programs, which might consider architectural alterations to training interventions as a factor that might mitigate risk of future injury.

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