Title:

Architectural changes of the biceps femoris after concentric or eccentric training.

Authors:

Ryan G Timmins[1], Joshua D Ruddy[1], Joel Presland[1], Nirav Maniar[1], Anthony J Shield[2], Morgan D Williams[3], David A Opar[1]

[1]School of Exercise Science, Australian Catholic University, Melbourne, Australia

[2]School of Exercise and Nutrition Sciences and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Australia

[3]School of Health, Sport and Professional Practice, University of South Wales, Pontypridd, Wales, UK

Corresponding author:

Ryan G. Timmins

School of Exercise Science, Australian Catholic University, 115 Victoria Parade, Fitzroy, 3065, Melbourne, Victoria, Australia

ryan.timmins@myacu.edu.au

Telephone: +61 3 9953 3742

Fax: +61 3 9953 3095

Running title:

Adaptability of biceps femoris architecture

Disclosure of funding:

N/A

ABSTRACT

Purpose: To determine i) the architectural adaptations of the biceps femoris long head (BFlf) following concentric or eccentric strength training interventions; ii) the time course of adaptation during training and detraining. **Methods:** Participants in this randomized controlled trial (control [n=28], concentric training group [n=14], eccentric training group [n=14], males) completed a 4-week control period, followed by 6 weeks of either concentric- or eccentric-only knee flexor training on an isokinetic dynamometer and finished with 28 days of detraining. Architectural characteristics of BFlf were assessed at rest and during graded isometric contractions utilizing two-dimensional ultrasonography at 28 days pre-baseline, baseline, days 14, 21 and 42 of the intervention and then again following 28 days of detraining. **Results:** BFlf fascicle length was significantly longer in the eccentric training group ($p<0.05$, *d* range: 2.65 to 2.98) and shorter in the concentric training group ($p<0.05$, *d* range: -1.62 to -0.96) after 42 days of training compared to baseline at all isometric contraction intensities. Following the 28-day detraining period, BFlf fascicle length was significantly reduced in the eccentric training group at all contraction intensities compared to 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 following the detraining period. **Conclusions:** These results provide evidence that short term resistance training can lead to architectural alterations in the BFlf. In addition, the eccentric training-induced lengthening of BFlf fascicle length was reversed and returned to baseline values following 28 days 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

INTRODUCTION

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 (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 (BFlf) 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 BFlf (16, 24). Interestingly, a previously strain injured BFlf possesses shorter fascicle lengths and greater pennation angles when compared to the contralateral uninjured BFlf (36). Furthermore differences in fascicle length can alter function, with muscles that possess longer fascicles having a greater maximal shortening velocity when compared to those with shorter fascicles (6, 17). Therefore it is important to develop an understanding of how muscle architecture can be altered by physical training in order to influence function, as well as guide hamstring strain injury prevention and rehabilitation practices.

Despite the large amount of research showing a range of architectural adaptations following eccentric training interventions (2, 3, 31), investigations which outline the time course for adaptation, including a period of detraining, are limited. Furthermore, the previous research into the adaptability of the BFlf following a training intervention only compared eccentric training to a non-training control group (28). It is therefore it is unclear how BFlf architectural adaptations might differ after eccentric and concentric strength training.

Given the high incidence of hamstring injury in the BFlf (16, 24), it is of interest to see how its architecture is altered following either concentric or eccentric strength training. Therefore the purposes of this study were to: 1) determine the architectural adaptations of the BFlf following either a concentric or eccentric strength training intervention and; 2) determine the time course of BFlf architectural adaptations during a 6-week training intervention, and following a 28 day period of detraining.

METHODS

Participants

Twenty-eight recreationally active males (age 22.3±4.2 y; 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 prior to 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 days prior to having their BFlf architecture assessed. The familiarization session and architectural assessment was completed on both limbs. Following this initial testing session (*28 days pre-baseline*), the participants were paired according to passive BFlf 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 weeks later (*baseline*) and had the maximal knee flexor strength and BFlf architectural characteristics assessed on both limbs. Following this the participants underwent 6 weeks of either a concentric- or eccentric–strength training intervention in a randomly selected limb (the contralateral limb served as a within-participant control). BFlf architecture of both limbs was re-assessed at days 14, 21 and 42 of the intervention, as well as 28 days after the completion of the strength training intervention. Knee flexor strength of both limbs was re-tested at the end of the training intervention (*day 42*) and 28 days 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, U.S.A), 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 minimise compensatory movements. All seating variables (e.g. seat height, pad position, etc.) 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 were dependent on training group, with the concentric training group starting from 0° of knee extension and the eccentric group beginning from 90°. Prior to 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°/s. The intensity of these contractions increased each set (1st set ~75% and 2nd set ~90% of the participants perceived maximum) until the final set at this velocity was performed at a maximal level. The test protocol began one minute following 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°/s and 180°/s (30s inter-set 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 computer at 1 kHz and stored for later analysis where it was fourth-order low pass Butterworth filtered (5 Hz). Peak torques at 240, 180 and 60°/s for concentric and 180 and 60°/s for eccentric knee flexion were defined as the mean of the six highest torque values for each contraction mode at each velocity.

BFlf architectural assessment

Muscle thickness and pennation angle of the BFlf were determined from ultrasound images taken along the longitudinal axis (Figure 1) of the muscle belly utilizing a two dimensional, B-mode ultrasound (frequency, 12 Mhz; depth, 8 cm; field of view, 14 x 47 mm) (GE Healthcare Vivid-*i*, Wauwatosa, U.S.A). The same images were utilized to estimate BFlf fascicle length. The scanning site was determined as the halfway point between the ischial tuberosity and the popliteal crease, along the line of the BFlf. 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 mid-point 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 following at least 5 min of inactivity. Assessments at rest were always performed first followed by the graded isometric contraction protocol. Assessment of BFlf architecture at rest was performed with the knee at 0º of knee flexion. Assessment of BFlf architecture during isometric contractions was always performed with the knee at 0º 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 (RGT) if the superficial and intermediate aponeuroses were not parallel.

Analysis was completed off-line (MicroDicom, Version 0.7.8, Bulgaria). For each image, six points were digitized as described by Blazevich and colleagues (5). Following the digitizing process, muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of BFlf. 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 (Figure 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):

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

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 (RGT) conducted and analysed all scans and was blinded to participant identifiers during the analysis. The methodology utilized in this study to assess the BFlf architectural characteristics has been previously reported by our laboratory (36).

Intervention

The participants performed 6 weeks of either maximal eccentric- or concentric-knee flexion strength training, with two sessions in the intervention’s first week and 3 sessions a week thereafter on an isokinetic dynamometer (Humac Norm, CSMI, Massachusetts, U.S.A) 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 (days/week) = 2
    - Sets = 4
    - Repetitions = 6

    - Total repetitions = 48

- Week 2:
    - Frequency (days/week) = 3
    - Sets = 4
    - Repetitions = 6
    - Total repetitions = 72
- Week 3:
    - Frequency (days/week) = 3
    - Sets = 5
    - Repetitions = 6
    - Total repetitions = 90
- Week 4:
    - Frequency (days/week) = 3
    - Sets = 5
    - Repetitions = 8
    - Total repetitions = 120
- Week 5:
    - Frequency (days/week) = 3
    - Sets = 6
    - Repetitions = 6
    - Total repetitions = 108
- Week 6:
    - Frequency (days/week) = 3
    - Sets = 6
    - Repetitions = 8
    - Total repetitions = 144

Each training session was separated by at least 48 hours. Contractions were distributed evenly across 60°/s and 180°/s. All participants started with two sets of three warm up efforts at 60°/s, in the contraction mode utilized 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 inter-set 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 inter-set 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 pre-control (*28 days pre-baseline to baseline*), intervention (*baseline to intervention day 42*) and detraining periods (*intervention day 42 to post-intervention 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 hours 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 days pre-baseline, baseline, intervention day 14, intervention day 21, intervention day 42, post-intervention day 28*) and the between-subject variable being group (eccentric or concentric), was used to compare changes in BFlf architecture throughout the training study. Architectural changes across the 28 day control period (*28 days pre-baseline to* baseline) were not significant ($p>0.05$). Therefore when determining the alterations in BFlf architectural characteristics following a 6-week 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 post-intervention day 28*). Where significant limb x time x group interactions for architecture and limb x 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 following the strength training intervention. The effect size was estimated based on the only intervention study to date that has reported changes in the BFlf architecture (28). That study reported a 33% increase in fascicle length following 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 BFlf 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 y, height 1.81±0.06 m, body mass 77.9±9.3 kg; concentric training group: age 23.4±5.1 y; 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%), with no differences when comparing the two groups (eccentric training group: 91%±2; concentric training group: 93%±1).

BFlf architectural comparisons

Control period, control limb changes and baseline comparisons

A significant limb x time x 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 BFlf architectural variables changed during the 4-week pre-intervention control period ($p>0.05$, *d* range = 0.03 to 0.17). Similarly, there were no significant differences at any time point, in the non-training control limbs for any BFlf architectural variables ($p>0.05$, *d* range = 0.03 to 0.27). Comparisons of all the BFlf 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 to 0.43).

Fascicle length and fascicle length relative to muscle thickness changes

A significant limb x time x 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 to 2.98, Table 1, Figure 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, Figure 2) after 42 days of the intervention compared to baseline, at all contraction intensities. Additionally there was a significant limb x time x 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.

Following the 28 day 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, Figure 2). Post-hoc analysis showed that fascicle length in the concentric training group following 28 days of detraining was no different to that observed end of the intervention, at any contraction intensity ($p>0.05$, *d* range: 0.15 to 0.67, Table 1, Figure 2). All other post-hoc comparisons of fascicle length and fascicle length relative to muscle thickness, 28 days following the intervention period, in the training limbs of both groups are presented in Table 1 and Figures 1 to 4.

Muscle thickness and pennation angle changes

No significant limb x time x group interaction effect was found for muscle thickness at any contraction intensity ($p>0.162$). However, a significant limb x time x 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, Figure 2) and significantly increased in the training limb of the concentric training group ($p<0.05$, *d* range: 1.60 to 2.50, Table 1, Figure 1 to 4) after 14 days of the intervention compared to 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 following the 28 day detraining period ($p>0.05$, *d* range: -0.55 to 0.02, Table 1, Figure 2). Post-hoc analysis showed that following the 28 days 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, Figure 2). All other comparisons of pennation angle changes following the 28 day detraining period are presented in Table 1.

Strength changes

A significant limb x 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 group ($p>0.05$). 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 to 0.78, Table 2) and the concentric training group ($p<0.05$, *d* range: 0.53 to 0.72, Table 2) after 42 days 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 days of the intervention when compared to baseline, at any contraction velocity ($p>0.05$, *d* range = 0.11 to 0.27).

There were no significant differences in knee flexor peak torque at any contraction velocity, in either group when comparing their strength following the 28 day 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 following the 28-day detraining period were significantly greater in the training limb of both training groups when compared to baseline ($p>0.05$, *d* range: 0.34 to 0.75, Table 2).

DISCUSSION

To the authors' knowledge, this is the first study reporting divergent BFlf architectural adaptations in response to concentric- or eccentric-strength training. Moreover, it is the first to provide evidence that eccentric training-induced increases in BFlf fascicle length are reversed following 28 days of detraining. The main findings were that eccentric strength training resulted in an increase in estimated BFlf 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 BFlf fascicle length and a non-significant increase in pennation angle were found following a 28 day detraining period when compared to the end of the strength training intervention. In contrast, the concentrically trained group maintained their BFlf architectural characteristics following 28 days 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 BFlf fascicle length and a reduction in pennation angle (measured at rest) following eccentric strength training in the current study (Figure 1) aligns somewhat with previous literature (28). Potier and colleagues (2009) found a 33% increase in resting BFlf fascicle length with a non-significant 3.1% reduction in resting pennation angle following 8 weeks of eccentric strength training. In comparison, the current study saw a significant 16% increase in resting BFlf fascicle length (the majority of which occurred within 14 days), with a non-significant 7.5% reduction in resting pennation angle. Differences in the training modalities employed (leg curl vs isokinetic dynamometry), intervention length (8 weeks vs 6 weeks) and the site of assessment may explain the different magnitudes of change reported in these studies. Additionally, no previous literature has examined BFlf architectural alterations during graded isometric contractions, following an intervention. In the present study, increases in BFlf fascicle length were observed at the end of the intervention when assessed 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 five days of downhill and presumably eccentric running exercise (18). However, the architectural alterations seen in this study may not be uniform along the BFlf 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 BFlf 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 BFlf 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 BFlf, following concentric and eccentric training. However, interventions which have employed 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) whilst 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) as well as 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 BFlf adaptive responses to these and many other variables.

The increases in BFlf fascicle length and reductions in pennation angle found in the current study following an eccentric strength training may have implications for hamstring strain injury prevention and rehabilitation. Elite athletes with a unilateral history of BFlf strain injury have shorter fascicles and greater pennation angles on their previously injured limb when compared to 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 re-injury, then understanding the most effective methods for altering these architectural characteristics will be of great value. The current data indicates that the continual application of high-intensity, eccentric-only strength training should be considered in hamstring rehabilitation and prevention programs in order to increase BFlf fascicle length and reduce pennation angle. Additionally the current study results 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 BFlf architecture.

The very rapid response of BFlf architectural adaptations supports previous literature which has found significant increases in fascicle length and pennation angle in the vastus lateralis within 14 days 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 days of training, with non-significant changes for the rest of the intervention (Figure 1 to 4). A similar, but inverse response was found in the concentric training group after 14 days of training, with non-significant 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 following 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 regards to the detraining responses following high-intensity eccentric- or concentric-strength training, only one study has investigated this, 3-months after a 10 week intervention in the vastus lateralis (3). Blazevich and colleagues (2007) found no significant alterations in knee extensor strength or vastus lateralis architectural characteristics following 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 BFlf fascicle length and an increase in pennation angle following 28 days of detraining. In comparison, the concentric group displayed similar findings to Blazevich and colleagues (2007), with architectural variables remaining unchanged following 28 days 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 BFlf architecture following 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 following 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 following an eccentric strength training intervention have been previously reported in the knee flexors, as well as within other muscle groups (27, 34). There is still some contradictory evidence as to whether a contraction mode-specific strength adaptation occurs following 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. Firstly, there are methodological limitations with the use of two-dimensional ultrasound for the estimation of BFlf fascicle length. As the field of view utilised in this study does not capture the entire BFlf fascicle, estimation is required. The equation utilised 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 BFlf fascicle length. Future studies should consider extended field of view ultrasound methods (23) to reduce the level of error when estimating muscle fascicle length. Secondly, the assessment of muscle architecture was only performed on the BFlf and did not include the other knee flexors. Therefore it is unknown what adaptations these other muscles displayed following the intervention and detraining period. However, as the BFlf is the most commonly strain injured hamstring muscle (16), the alterations following 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 utilised. The aim of this study was to investigate the effect of contraction mode, not velocity, on BFlf 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 following a concentric- or eccentric-strength training intervention.

In conclusion, the current study reports rapid, contraction-mode specific alterations in BFlf architecture following 6 weeks of either eccentric or concentric strength training interventions. Further, 28 days of detraining resulted in BFlf architectural characteristics returning to baseline levels in individuals who had completed eccentric training, whilst detraining had no influence on the BFlf architectural characteristics in those who completed concentric strength training. The findings of the current study provide insight into BFlf architectural alterations following 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.

ACKNOWLEDGMENTS

N/A

CONFLICT OF INTEREST

The authors report that this study was not funded at that no conflict of interest exists. Results of this study do not constitute endorsement of the American College of Sports Medicine.

REFERENCES

1. Abe T, Kawakami Y, Suzuki Y, Gunji A, Fukunaga T. Effects of 20 days bed rest on muscle morphology. *J Gravit Physiol*. 1997;4(1):S10-4.
2. Blazevich AJ. Effects of physical training and detraining, immobilisation, growth and aging on human fascicle geometry. *Sports Med*. 2006;36(12):1003-17.
3. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985)*. 2007;103(5):1565-75.
4. Blazevich AJ, Gill ND, Bronks R, Newton RU. Training-specific muscle architecture adaptation after 5-wk training in athletes. *Med Sci Sports Exerc*. 2003;35(12):2013-22. Epub 2003/12/04. doi: 10.1249/01.MSS.0000099092.83611.20.
5. Blazevich AJ, Gill ND, Zhou S. Intra- and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anat*. 2006;209(3):289-310.
6. Bodine SC, Roy RR, Meadows DA, et al. Architectural, histochemical, and contractile characteristics of a unique biarticular muscle: the cat semitendinosus. *J Neurophysiol*. 1982;48(1):192-201.

7. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc*. 2004;36(3):379-87.

8. Cohen D. *Statistical power analysis for the behavioral sciences*. Hillsdale (NJ): Erlbaum; 1988. p 75.

9. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175-91.

10. Franchi MV, Atherton PJ, Reeves ND, et al. Architectural, functional and molecular responses to concentric and eccentric loading in human skeletal muscle. *Acta Physiol (Oxf)*. 2014;210(3):642-54.

11. Fyfe JJ, Opar DA, Williams MD, Shield AJ. The role of neuromuscular inhibition in hamstring strain injury recurrence. *J Electromyogr Kinesiol*. 2013;23(3):523-30.

12. Guex K, Millet GP. Conceptual framework for strengthening exercises to prevent hamstring strains. *Sports Med*. 2013;43(12):1207-15.

13. Kaminski TW, Wabbersen CV, Murphy RM. Concentric versus enhanced eccentric hamstring strength training: clinical implications. *J Athl Train*. 1998;33(3):216-21.

14. Kellis E, Galanis N, Natsis K, Kapetanos G. Validity of architectural properties of the hamstring muscles: correlation of ultrasound findings with cadaveric dissection. *J Biomech*. 2009;42(15):2549-54.

15. Klimstra M, Dowling J, Durkin JL, MacDonald M. The effect of ultrasound probe orientation on muscle architecture measurement. *J Electromyogr Kinesiol*. 2007;17(4):504-14.

16. Koulouris G, Connell DA, Brukner P, Schneider-Kolsky M. Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. *Am J Sports Med*. 2007;35(9):1500-6.

17. Lieber RL, Ward SR. Skeletal muscle design to meet functional demands. *Philos Trans R Soc Lond B Biol Sci*. 2011;366(1570):1466-76.

18. Lynn R, Morgan DL. Decline running produces more sarcomeres in rat vastus intermedius muscle fibers than does incline running. *J Appl Physiol (1985)*. 1994;77(3):1439-44.

19. Morgan DL. New insights into the behavior of muscle during active lengthening. *Biophys J*. 1990;57(2):209-21.

20. Narici M, Cerretelli P. Changes in human muscle architecture in disuse-atrophy evaluated by ultrasound imaging. *J Gravit Physiol*. 1998;5(1):P73-4.

21. Narici MV, Flueck M, Koesters A, et al. Skeletal muscle remodeling in response to alpine skiing training in older individuals. *Scand J Med Sci Sports*. 2011;21 Suppl 1:23-8.

22. Noorkoiv M, Nosaka K, Blazevich AJ. Neuromuscular adaptations associated with knee joint angle-specific force change. *Med Sci Sports Exerc*. 2014;46(8):1525-37.

23. Noorkoiv M, Stavnsbo A, Aagaard P, Blazevich AJ. In vivo assessment of muscle fascicle length by extended field-of-view ultrasonography. *J Appl Physiol (1985)*. 2010;109(6):1974-9.

24. Opar D, Williams M, Timmins R, Hickey J, Duhig S, Shield A. Eccentric hamstring strength and hamstring injury risk in Australian Footballers. *Med Sci Sports Exerc*. 2015;47(4):857-65.

25. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther*. 2013;43(9):636-40.

26. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med*. 2013;41(4):734-41.

27. Paddon-Jones D, Leveritt M, Lonergan A, Abernethy P. Adaptation to chronic eccentric exercise in humans: the influence of contraction velocity. *Eur J Appl Physiol*. 2001;85(5):466-71.

28. Potier TG, Alexander CM, Seynnes OR. Effects of eccentric strength training on biceps femoris muscle architecture and knee joint range of movement. *Eur J Appl Physiol*. 2009;105(6):939-44.

29. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol*. 2009;94(7):825-33.

30. Selvanayagam VS, Riek S, Carroll TJ. Early neural responses to strength training. *J Appl Physiol (1985)*. 2011;111(2):367-75.

31. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol (1985)*. 2007;102(1):368-73.

32. Seynnes OR, Maganaris CN, de Boer MD, di Prampero PE, Narici MV. Early structural adaptations to unloading in the human calf muscles. *Acta Physiol (Oxf)*. 2008;193(3):265-74.

33. Sharifnezhad A, Marzilger R, Arampatzis A. Effects of load magnitude, muscle length and velocity during eccentric chronic loading on the longitudinal growth of the vastus lateralis muscle. *J Exp Biol*. 2014;217(Pt 15):2726-33.

34. Shepstone TN, Tang JE, Dallaire S, Schuenke MD, Staron RS, Phillips SM. Short-term high- vs. low-velocity isokinetic lengthening training results in greater hypertrophy of the elbow flexors in young men. *J Appl Physiol (1985).* 2005;98(5):1768-76.

35. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. *Med Sci Sports Exerc*. 2005;37(1):108-14.

36. Timmins R, Shield A, Williams M, Lorenzen C, Opar D. Biceps femoris long head architecture: a reliability and retrospective injury study. *Med Sci Sports Exerc.* 2015;47(5):905-13.

37. Timmins RG, Opar DA, Williams MD, Schache AG, Dear NM, Shield AJ. Reduced biceps femoris myoelectrical activity influences eccentric knee flexor weakness after repeat sprint running. *Scand J Med Sci Sports.* 2014;24(4):e299-e305.

38. Yu B, Queen RM, Abbey AN, Liu Y, Moorman CT, Garrett WE. Hamstring muscle kinematics and activation during overground sprinting. *J Biomech.* 2008;41(15):3121-6.

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, 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.

Figure 2: Changes in the architectural characteristics of the BFlf when assessed at rest in the trained limb and the contralateral untrained limb of both groups following 14, 21 and 42 days of the training intervention and following the detraining period (*day 70*). A) fascicle length B) pennation angle C) muscle thickness 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.

Table 1: Changes in the BFlf architectural characteristics in the training limb of each group at the start (day 0), after 14, 21 and 42 days of the training intervention as well as following the detraining period (day 70). All data represented as mean±SD unless otherwise stated. SD = standard deviation, MT = muscle thickness, cm = centimetres, 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.

Table 2: Changes in concentric and eccentric knee flexor peak torque at various contraction velocities in the training limb of each group before (day 0) and after the training intervention (day 42) as well as following the detraining period (day 70). All data represented as mean±SD unless otherwise stated. SD = standard deviation, °/s = degrees per second. *=$p<0.05$ vs Day 0, ** = $p<0.001$ vs Day 0.