Differences in lower limb strength and structure after 12 weeks of resistance, endurance, and concurrent training

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ABSTRACT

Purpose: Investigate strength & structural adaptations after 12-weeks of resistance, endurance cycling and concurrent training.

Methods: Thirty-two healthy males undertook 12-weeks of resistance-only (RT; n=10), endurance-only (END; n=10) or concurrent resistance and endurance training (CONC; n=12). Biceps femoris long head (BFlh) architecture, strength (three-lift 1RM) and body composition were assessed.

Results: Fascicle length of the BFlh reduced 15±6% (p<0.001) and 9±6% (p<0.001) in the END and CONC group post-intervention, with no change in the RT group (-4±11%, p=0.476). All groups increased BFlh pennation angle (CONC: 18±9%, RT: 14±8%, END: 18±10%). Thickness of the BFlh increased post-intervention by 7±6% (p=0.002) and 7±7% (p=0.003) in the CONC and RT groups, respectively, but not in the END group (0±3%, p=0.994). Both the CONC and RT group significantly increased by 27±11% (p<0.001) and 33±12% (p<0.001) in three-lift totals following the intervention, with no changes in the END cohort (6±6%, p=0.166). No significant differences were found for total body (CONC: 4±2%, RT: 4±2%, END: 3±2%) and leg (CONC: 5±3%, RT: 6±3%, END: 5±3%) fat free mass.

Conclusions: 12-weeks of resistance-only, endurance-only or concurrent resistance and endurance training significantly modified BFlh architecture. This study suggests that conventional resistance training may dampen BFlh fascicle shortening from cycling training whilst increasing strength simultaneously in concurrent training. Furthermore, the inclusion of a cycle endurance training stimulus may result in alterations to hamstring architecture that increase the risk of future injury. Therefore, the incorporation of endurance cycling training within concurrent training paradigms should be re-evaluated when trying to modulate injury risk.

Key words: fascicle length, cycling, muscle injury, hamstring.

INTRODUCTION

Hamstring strain injuries (HSIs) are the most prevalent, non-contact injury in sports which involve high speed running, with upwards of 80% of these occurring within the biceps femoris long head (BFlh)[1]. These injuries also present a significant financial burden for the athlete and their sporting organisation[2]. However, despite the significant research effort over the last decade, HSI incidence has not declined[3].

It has recently been shown that elite soccer players with short BFlh fascicles are four times more likely to suffer a HSI in a competitive season than those with longer fascicles[4]. It was identified that for every 0.5cm increase in fascicle length, there was a concomitant reduction in HSI risk of 74%[4]. Therefore, understanding fascicle length adaptations in response to various training interventions will have implications for HSI prevention programmes.

The architectural characteristics of the BFlh can be modified with various forms of resistance-training interventions[5]. However, the magnitude and direction of the adaptations are strongly influenced by the contraction mode utilised during the training period. For example, interventions utilising the Nordic hamstring exercise, a stimulus which only consists of an eccentric contraction of the knee flexors (and is non-isokinetic in nature), have been shown to significantly increase fascicle length of the BFlh by 30%[6,7]. Conversely, concentric only training on an isokinetic dynamometer significantly reduces BFlh fascicle length by ~14%[8]. However, conventional resistance-training programs undertaken in elite sporting environments consist of exercises that have both an eccentric and concentric phase[9]. Despite the prevalence of these exercises in practical settings, there is a limited amount of evidence showing the BFlh architectural adaptations following these interventions. Therefore, more research into the BFlh architectural adaptations following conventional resistance-training interventions is needed.

In team sports, athletes are typically exposed to a range of stimuli that compete to promote various adaptations in an attempt to balance performance improvement whilst minimising injury risk. With these athletes, the prescription of resistance-training interventions is rarely undertaken independent of aerobic conditioning[10]. For example, stationary cycling is used as part of an athlete’s combined concurrent training regime[9,10]. Moreover, many team-sports incorporate concurrent training programs to maximise adaptations to strength, power and/or endurance for optimal performance. Whilst the BFlh architectural adaptations following various resistance-training interventions have been investigated [6,8,11], it is unclear what effect undertaking concurrent resistance and endurance cycling training (which has a low level of hamstring activity[12] and in-series strain[13]) may have on these alterations.

The primary aim of this study was to investigate the BFlh architectural, strength and body composition adaptations after a 12-week intervention of either conventional resistance only, endurance only or concurrent resistance and endurance training in young recreationally active males. It was hypothesised that the existence of a conventional resistance-training stimulus (in the concurrent and resistance-only groups) would promote a lengthening of BFlh fascicle length with reductions in pennation angle and improvements in lower limb strength. Whereas, it was hypothesized that the endurance-only stimulus would result in a shortening of BFlh fascicles, increases in pennation angle and no changes in lower limb strength.

METHODS

Participants

Thirty-two recreationally active males (age 24.6±1.1 years; height 1.79±0.02 metres; body mass 77.1±2.10 kilograms) with no history of lower limb injury in the previous 12 months were recruited to participate in this study. All participants provided informed consent before testing and training, which was undertaken at the Australian Catholic University, Fitzroy, Victoria, Australia. Ethical approval was granted by the Australian Catholic University Human Research Ethics Committee. The trial was also registered with the Australian New Zealand Clinical Trials Registry (ACTRN12617001229369).

Study design

This study was part of a larger project from which separate data has already been published[14]. This training intervention was conducted between June 2016 and October 2017. The study utilised a parallel groups design with participants being stratified according to their total lean body mass (LBM). Participants were then allocated to either resistance only (RT; n=10), endurance only (END; n=10) or concurrent resistance and endurance training (CONC; n=12) for the 12-week intervention. For the duration of the study, participants consumed a high protein diet of 2g/kg/day, which was confirmed through weekly food logs submitted to the researchers[14]. Participants underwent pre-intervention BFlh architectural and body composition (by whole-body dual-energy X-ray absorptiometry (DXA)) assessments as well as $VO_{2\ peak}$, leg press, knee extension and bench press 1-repetition maximum (1RM) testing. Participants met with a dietitian fortnightly for consultation regarding protein and energy intakes for the duration of the study. Muscle architecture was re-assessed after weeks 2, 4 and 8 of training and at the end of the intervention. After week 6 of training, $VO_{2\ peak}$ (END and CONC only) and 1RM (RT and CONC only) testing was undertaken to adjust training prescription for subsequent weeks. At the end of the intervention participants had all their pre-measures reassessed within seven days of the final training session. All testing and training sessions were supervised by a member of the research team at the Australian Catholic University.

Methodology

BFlh architecture assessment

The methods used by the research group to assess BFlh architecture has been previously reported[15]. Briefly, muscle thickness, pennation angle and fascicle length of the BFlh was determined from ultrasound images taken along the longitudinal axis of the muscle belly (Figure 1) utilising a two-dimensional, B-mode ultrasound (frequency, 12Mhz; depth, 8cm; field of view, 14 x 47mm) (GE Healthcare Vivid-*i*, Wauwatosa, U.S.A). The scanning site was determined as the halfway point between the ischial tuberosity and the knee joint fold, along the line of the BFlh. All architectural assessments were performed with the participant prone on a massage plinth, after 5 min of inactivity. The orientation of the probe was manipulated by the assessor whose reliability has been previously reported[15]. The intraclass correlations for all variables ranged between 0.96 to 0.97. The typical error as a percentage of coefficient of variation for all variables is less than 3.4% (range 2.1 to 3.4%).

Once the images were collected (Figure 1), analysis was undertaken off-line (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of the BFlh. Pennation angle was defined as the angle between the inferior aponeurosis and a fascicle of interest. The aponeurosis angle for both aponeuroses was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image[16,17]. As the entire fascicle was not visible in the field of view of the probe, its length was estimated via the following equation[16,17]:

FL=sin (AA+90°) x MT/sin(180°-(AA+180°-PA)).

Where FL=fascicle length, AA=aponeurosis angle, MT=muscle thickness and PA=pennation angle. Fascicle length was reported in absolute terms (cm). The same assessor collected and analysed all scans and was blinded to participant identifiers during the analysis. The extrapolation technique and equation has been validated against cadaveric tissues and as such is considered a robust way of estimating fascicle lengths.[17,18]

VO_{2peak} Testing

The assessment of $VO_{2\ peak}$ was performed on a Lode cycle ergometer (Excalibur sport, Lode, The Netherlands) using an incremental test to volitional fatigue as previously described in detail[19]. Assessments of $VO_{2\ peak}$ were undertaken pre, after week 6 of training (END and CONC only) and at the completion of the intervention. The maximum aerobic power (MAP)[20] from the pre-training and week 6 tests were used to determine training loads for the endurance program for the END and CONC groups.

Strength Testing

Maximal strength assessment

Maximal strength was assessed by determining each participants 1RM plate-loaded 45^o incline leg press, seated knee extension and bench press, as previously described[14]. Briefly, following warm-ups of each exercise at submaximal intensities, participants undertook a progressive series of near-maximal single repetition efforts. The 1RM for each exercise was determined as the heaviest weight that was lifted through a full range of motion. Assessments were undertaken prior to the training study, after week 6 of training (CONC and RT only) and at the completion of the intervention. The 1RM's from the pre-training and week 6 assessments were used to determine training loads for the resistance program following these sessions for both the CONC and RT groups. For all analysis, a sum of the 3 lifts was used to determine training-induced changes.

Body composition

Total body and leg fat free mass were determined using DXA (GE Lunar iDXA Pro, GE Healthcare; software: Encore 2009, version 16). Assessments were undertaken prior to, after 4 and 8 weeks of training as well as following the training intervention using best practice guidelines (e.g., provided standardised meals the evening before)[21].

Training intervention

Participants in the RT and END groups performed training 3 d/wk, separated by at least 24 hours. The CONC group undertook the same training programs as the other two groups, however these were spread across 6 d/wk in an alternating pattern (e.g. Resistance training: Monday, Wednesday, Friday; Endurance training: Tuesday, Thursday and Saturday). This was done with the intent to maximise the likelihood for lower body strength improvements[22] and to lengthen the time between sessions to minimize any potential inference between the RT and END programs[23].

The resistance training intervention utilised a range of exercises with the intent of improving hip and knee extensor strength (45° leg press, Romanian deadlift, seated knee extensions, barbell step back lunge, barbell hip thruster and stiff legged deadlift). Training volume was modified by manipulating the number of sets, repetitions and relative intensity of each exercise to provide progressive overload throughout the 12-week intervention. All training efforts of leg press or knee extension were performed at a relative intensity between 60 to 97.5% of 1RM. For example, leg press was progressed from participants doing 5 sets of 10-15 repetitions at 70% of 1RM in the first week of training, to 2 sets of 2 repetitions at 97.5% of 1RM in the final week. Additional exercises focussing on the hip and knee extensors (Romanian deadlift, barbell step back lunge, barbell hip thruster and stiff legged deadlift) were performed at an intensity eliciting an RPE of ~9-10 by the last set. The progression was similar to the leg press, with participants undertaking 4 sets of 10 repetitions in the first week of training to doing 3 sets of 5 repetitions in the final week. All exercises consisted of a 3-minute between-set rest period and were completed using conventional training methods, where the weight lifted in the concentric phase is then lowered in the eccentric without any additional overload. Finally, all coaching cues were provided with the intent to control the velocity of the weight/barbell throughout the range of motion as best as possible.

The endurance training intervention was undertaken on a Lode cycle ergometer and was made up of a range of simulations including undulating hill efforts (25-110% MAP), moderate-intensity continuous training (50% MAP), moderate-intensity (70% MAP) and high-intensity interval training (100% MAP). The moderate and high-intensity intervals were separated by recovery periods ranging between 20-60 seconds at 40% MAP. Training volume was modified by manipulating the number of intervals as well as the relative intensity to provide progressive overload across the 12-week intervention.

Training volume and intensity were periodised throughout the 12-weeks to provide progressive overload with the intent to improve lower body strength. Financial incentives were provided to encourage participant compliance and effort during training with those having the largest pre- to post-intervention increases in 1RM (CONC and RT) and $VO_{2\ peak}$ (CONC and END) receiving these. All training programs have previously been published and are available online[14] and from the supplementary documents 1 and 2.

Statistical analyses

All statistical analyses were performed using JMP version 11.0.0 (SAS Institute Inc., Cary, NC, USA). Where appropriate, data were screened for normal distribution using the Shapiro-Wilk test and homoscedasticity using Levene's test. Repeated measures linear mixed models fitted with the restricted maximum likelihood (REML) method were used to assess changes in BFlh architecture, total body and leg fat free mass, as well as the three-lift total across the duration of the study. For each measure, factors were group (CONC, END or RT) and time (Pre, Weeks 2, 8, 12), with participant as the random factor. For BFlh architecture and leg fat free mass, the left and right limbs were averaged, as they did not differ at any time point. Additionally, all between group comparisons for all measures at baseline showed no differences. Where significant main or interaction effects were detected, *post hoc* t tests with Tukey's HSD were applied to determine where any differences occurred. Significance was set at $p<0.05$ and where possible Cohen's *d*[24] was reported for the effect size of the comparisons, with the levels of effect being deemed small (*d*=0.20), medium (*d*=0.50) or large (*d*=0.80). All data were expressed as mean ± SD.

Sample Size

Power analysis was undertaken *a priori* using G-Power[25]. The analysis was based on the estimated changes in BFlh fascicle length following the training intervention in the resistance training group. Effect size estimates were determined using previous research looking at interventional changes in BFlh fascicle length[8]. In this study, fascicle length changes had an effect size of 2.6. Therefore, in the name of being conservative, an effect size of 1.3 was deemed a reasonable starting point. Power was set at 80%, with an alpha of 0.05 returning a calculated sample of 9 per group.

RESULTS

Participant details

The three groups were similar with respect to age, height and body mass at baseline (CONC age 26±4yrs, height 1.77±0.07m, body mass 76.4±10.2kg; RT age 24±6yrs, height 1.82±0.08m, body mass 75.5±10.3kg; END age 24±5yrs, height 1.79±0.07m, body mass 79.5±9.3kg). All groups increased body mass after the intervention period (CONC: 3.9%, p<0.001, *d*=0.39; RT: 4.3%, p<0.001, *d*=0.42; END: 2.7%. p=0.011, *d*=0.24). Training compliance for strength training was 100% in both RT and CONC, while compliance for cycling training was 99.4% and 99.5% in END and CONC, respectively.

BFlh architectural characteristics

A summary of the BFlh architectural alterations during this intervention can be found in Figure 2.

Fascicle length

A significant group x time interaction effect was found for fascicle length (p=0.010). *Post hoc* analyses showed that fascicle length was significantly shorter after the training period, when compared to pre-intervention measures, in both the CONC and END group but not the RT cohort (CONC: difference -0.95cm, 95%CI -1.58 to -0.32cm; p<0.001, *d*=-1.51; END: difference -1.48cm, 95%CI -2.17 to -0.79cm; p<0.001, *d*=-1.87; RT: difference -0.49cm, 95%CI -1.18 to 0.20cm; p=0.476, *d*= -0.71). The fascicle lengths of the CONC and END group were also significantly shorter than pre-training values after week 8 (CONC: difference -0.80cm, 95%CI -1.43 to -0.17cm; p=0.003, *d*= -1.22; END: difference -1.08cm, 95%CI -1.77 to -0.39cm; p<0.001, *d*= -1.34). All other fascicle length comparisons to pre-training values were not significant for all groups.

Muscle thickness

A significant group x time interaction effect was found for muscle thickness (p=0.013). *Post hoc* analyses showed that muscle thickness was significantly increased after the training period, compared to pre-intervention measures, in both the CONC and RT groups but not in the END cohort (CONC: difference 0.16cm, 95%CI 0.03 to 0.28cm; p=0.002, *d*=0.62; RT: difference 0.16cm, 95%CI 0.03 to 0.29cm; p=0.003, *d*=0.65; END: difference -0.01cm, 95%CI -0.13 to 0.12cm; p=0.994, *d*=-0.03; Figure 2). In the CONC group, significant increases in muscle thickness were also found at week 4 (difference 0.16cm, 95%CI 0.03 to 0.28cm; p=0.001; *d*=0.58) and week 8 (difference 0.20cm, 95%CI 0.08 to 0.32cm; p<0.001; *d*=0.76) when compared to pre-intervention values. All other muscle thickness comparisons to pre-training values were not significant for all groups.

Pennation angle

A significant group x time interaction effect was observed for pennation angle (p=0.015). *Post hoc* analyses showed that pennation angle was significantly increased after the training period, compared to pre-intervention, in all three groups (CONC: difference 2.74º, 95%CI 1.57 to 3.90; p<0.001; *d*=1.59; RT: difference 1.90º, 95% CI 0.51 to 3.30; p<0.001; *d*=1.17; END: difference 2.65º, 95% CI 1.27 to 4.02; p<0.001; *d*=1.52; Figure 2). Pennation angle was also significantly greater than pre-training values after week 8 in all three groups (CONC: difference 2.62º, 95%CI 1.47 to 3.80; p<0.001; *d*=1.52; RT: difference 1.67º, 95% CI 0.27 to 3.06; p=0.020; *d*=1.03; END: difference 2.30º, 95% CI 0.92 to 3.66; p=0.002; *d*=1.31). Whereas after 4 weeks of training, pennation angle was significantly greater than pre-training values in only the CONC and END groups (CONC: difference 1.77º, 95%CI 0.62 to 2.94; p=0.003; *d*=1.03; END: difference 1.50º, 95% CI 0.13 to 2.87; p=0.033; *d*=0.85) but not in the RT cohort (RT: difference 1.35º, 95%CI -0.04 to 2.75; p=0.056; *d*=0.83). All other pennation angle comparisons to pre-training values were not significant for all groups.

Strength testing

Three-lift total

A significant group x time interaction effect was found for the three-lift total (p<0.001). *Post hoc* analyses showed that the three-lift total was significantly increased after the training period in both the CONC and RT groups, but not in the END cohort (CONC: difference 109kg, 95%CI 82 to 137kg; p<0.001, *d*=1.00; RT: difference 129kg, 95%CI 99 to 159kg; p<0.001, *d*=1.31; END: difference 25kg, 95%CI -6 to 57kg; p=0.166, *d*=0.46; Table 1).

Body composition

Total body fat free mass

A significant main effect for time (p<0.001), but not group (p=0.901) was found for total body fat free mass. There was no significant group x time interaction (p=0.386). All effect size comparisons showed small to moderate effects for increases in total body fat free mass across the study (*d* range = 0.18 to 0.50; Table 1).

Leg fat free mass

A significant main effect for time (p<0.001), but not group (p=0.995) was found for leg fat free mass. There was no significant group x time interaction (p=0.589). All effect size comparisons showed small to moderate effects for increases in leg fat free mass across the study (*d* range = 0.24 to 0.50; Table 1).

DISCUSSION

This study is the first to investigate the effects of conventional resistance-only, endurance cycling-only and concurrent endurance and resistance training on BFlh architecture. The novel findings of this study are: 1) 12-weeks of cycling only endurance training and concurrent endurance and resistance training significantly increases pennation angle and shortens BFlh fascicles; 2) conventional resistance-only training caused no changes in BFlh fascicle length yet significantly increases pennation angle; and 3) concurrent training and resistance-only training can promote increases in BFlh muscle thickness.

It has been proposed that increasing BFlh fascicle length following eccentric training interventions may be one of the beneficial adaptations that reduces the risk of a future HSI occurring[26]. Prospectively, elite soccer players who had short BFlh fascicles (<10.56cm – with longer fascicles being ≥10.56cm) at the start of pre-season were four times more likely to suffer a HSI in the subsequent season than those who possessed longer fascicles[4]. In these athletes, for every 0.5cm increase in fascicle length, there was a subsequent 74% reduction in HSI risk. While having longer fascicles is associated with a reduced risk of injury, it is unknown if modifying BFlh fascicle lengths through training interventions specifically alters the likelihood of future injury. In the current study, the participants in the concurrent and endurance training groups reduced their fascicle lengths by 0.96cm and 1.48cm respectively, following the intervention. Combining these findings with the prospective evidence presented, it is possible that sustained periods of endurance cycling training, without any eccentric training stimuli, may have a deleterious effect for HSI risk. Further to this, the level of eccentric stimuli provided by conventional barbell training was not enough to offset the shortening effect that endurance cycling had on muscle fascicle length. Therefore, if cycling training is part of an athletic performance program, in order to address HSI prevention practices, practitioners should ensure the intensity of the eccentric resistance training stimulus is sufficient[27].

This study provides further evidence that BFlh fascicle lengths respond differently following training with dissimilar contractions modes. Concentric-only leg curl[28] and isokinetic dynamometry training[8] have resulted in shortening of BFlh fascicles, whereas eccentric-only interventions have been an effective stimulus for lengthening[6,8,27]. The assumed addition of sarcomeres in-series after eccentric training interventions is expected to be the mechanism for increasing fascicle length[13]. Interventions using the *vastus intermedius* of rats support this assumption with significant reductions in the number of in-series sarcomeres after undertaking uphill running training[13]. Comparably interventions utilising downhill running (eccentric in nature) resulted in a significant increase in the number of in-series sarcomeres[13]. As a result, Lynn and colleagues (1998) suggest that the large amount of in-series strain experienced during eccentric contractions is a potent stimulus for increasing the number of sarcomeres in-series[13]. Therefore the reduction of this stimulus (e.g during concentric-only efforts) may result in the shedding of sarcomeres in-series[13]. In the current study, the endurance group was exposed to a cycling-only stimulus for 12-weeks, where the hamstrings are mainly active concentrically, with minimal eccentric activity[12,29]. As such, the significant shortening of the BFlh fascicles may have been driven by a reduced amount of in-series strain and the resultant shedding of sarcomeres in-series.

The concurrent training group was exposed to the same amount of cycling as the endurance cohort, and the same resistance stimuli as the resistance-only group. Despite this, the concurrent group still saw a significant shortening of BFlh fascicle length. This may be a result of the resistance training stimuli only being comprised of conventional movements, where the limiting factor is the weight lifted in the concentric phase. Therefore, all exercises were underloaded during the eccentric portion and as such may have less in-series strain than those efforts with an overloaded lowering phase. As this in-series strain from eccentric-only/overloaded interventions[6,8], or higher training volumes of conventional exercises at long muscle length[7] are needed to promote significant fascicle lengthening in the BFlh, it is possible the concurrent training participants were not exposed to a potent enough eccentric stimulus to counteract the shortening stimuli imposed by the cycling intervention. This may also partially explain the lack of increases in BFlh fascicle length seen in the resistance training group, who did not have the competing stimuli from the cycling intervention yet may have still lacked enough in-series strain to promote fascicular lengthening. As a result, the resistance training participants did not see a change in fascicle length. Additionally, the concurrent group (-0.96cm) saw a lesser reduction in fascicle length than the endurance-only cohort (-1.48cm). It is conceivable that the conventional resistance training intervention may have dampened some of the shortening stimuli provided by the cycling protocol, yet it was not enough to overcome the gross shortening. Future research would benefit from investigating whether a concurrent training program incorporating resistance exercise with more eccentric loading would prevent fascicle length shortening induced by endurance cycling and potentially promote some lengthening above baseline.

Another theory which may explain the shortening of fascicles after significant endurance training comes from the evidence that distance runners possess shorter vastus lateralis and gastrocnemius fascicles than sprinters[30]. Abe and colleagues (2000) proposed that the large eccentric stimulus that sprinters experience through their training may contribute to the adaptation of longer fascicles in the lower limb. The authors also propose that it may have been a genetic pre-disposition where those with longer fascicles were able to produce a greater amount of force during higher shortening velocities, and, as such, became better sprinters than those with shorter fascicles[31]. However, another concept presented by Abe and colleagues (2000) was that chronic endurance training may become more efficient with lesser sarcomeres in-series[30]. This theory centres around the proposition that having less sarcomeres in-series would require less ATP to be used per shortening cycle. As an endurance athlete this may be a beneficial training adaptation that allows them to be more efficient than those with a greater number of sarcomeres in-series who may use more ATP with each step. Therefore, in the current study the fascicular shortening could have been a beneficial adaptation in the endurance and concurrent training cohorts which reduced the amount of ATP used per cycle stroke and as a result made them more efficient during their training.

Following a period of training, changes in pennation angle have been suggested as a mechanism that strongly influences changes in lower limb strength[32]. For example, Aagaard and colleagues (2001) undertook 14 weeks of heavy-resistance training of the lower limbs, assessing maximal isometric knee flexor torque and vastus lateralis pennation angle before and after the intervention. Following the training program, there was a 16% increase in *vastus lateralis* pennation angle, which was strongly associated ($r = 0.62$) with a 14% improvement in isometric knee extensor torque. The authors concluded that the architectural arrangement of pennate muscles in the human body are strongly associated with their function (represented by strength). In the current study, increases in BFlh pennation angle, muscle thickness and the strength were seen following the concurrent and resistance training-only interventions. Whilst this study was the first to determine the changes in BFlh architectural characteristics in response to divergent training stimuli, it was not theoretically plausible to run a correlational analysis of these changes against the improvements in the three-lift total. This is because the BFlh, whilst being involved in the action of hip extension and subsequently the assessment of leg press strength, was not isolated in a measure of single joint strength (e.g. maximal knee flexion). However, when considered together with the findings of Aagaard and colleagues (2001), it is likely that increase in BFlh pennation angle observed in the present study contributed to increases in maximal lower body strength. Future studies are needed to directly assess the extent to which structural changes in the hamstring muscles contribute to knee flexor strength through single- and multi-joint movements.

The results of the current study suggest that cycling endurance training may lead to significant BFlh architectural alterations across a 12-week period. However, the time course of these changes (Figure 2) may allow practitioners a 'window of opportunity' should they still wish to implement a cycling stimulus as part of their program. Whilst there is still shortening within the first 8 weeks in both the concurrent and endurance training groups, the lack of significance creates a small buffer period where, as is commonplace in sporting programs[9,10], practitioners can prescribe 'off-feet' training on a bike to stimulate improvements in cardiovascular performance. However, should this stimulus continue, there is the possibility that fascicular shortening progresses, thus practitioners will need to begin supplementing this with significant eccentric hamstring work.

The effect of nutrition on BFlh fascicle length is also unknown. While we were the first study to control for and implemented a 'high' protein diet (2g/kg/day) throughout the 12-week intervention period to maximise muscle remodelling processes, we did not compare this dietary intervention to a control protein diet group to specifically ascertain if protein intake can positively or negatively alter BFlh fascicle length. However it may not be feasible to tease out the impact that nutritional interventions have on muscle architectural adaptations due to the malleability of these structural characteristics to the various forms of interventions as well as periods of detraining [6,8,27]. Therefore, controlling for protein intake is the first and possibility most reasonable step in this process.

There are limitations in this study which should be considered. Firstly, the measure of fascicle length is an estimation made from a validated equation. This is due to the small transducer field of view being unable to capture an entire BFlh fascicle. However, whilst the results are still an estimation, the methodology and equation employed has been validated against cadaveric samples and shows excellent agreement between dissection and estimation methods[17,18]. Secondly, we did not compare different forms of endurance training (such as running). Whilst not the primary form of concurrent training within sporting environments, cycling interventions still have a strong place in performance programs and are often utilised for 'off-feet' sessions or as a cardiovascular stimulus during rehabilitation[9]. Finally, the concurrent training intervention was undertaken on alternating days, which is different to elite, professional sporting environments who may undertake two/ multiple sessions/day. However, the requirement to have participants train twice a day (morning and afternoon) to mimic those elite environments would have been too extensive a request for volunteers to undertake.

PRACTICAL APPLICATIONS

Possessing short BFlh fascicles has been associated with an increased risk of future hamstring injury. Therefore, interventions which modify fascicle length are of interest to practitioners. However, these interventions are typically investigated in isolation and without concurrent endurance training, which is a common feature of elite sporting programs. This study investigated the effect of conventional resistance, endurance and concurrent training on hamstring structural adaptations. A significant shortening in BFlh fascicle length was evidenced following endurance-only and concurrent training interventions, with no change after resistance-only training. These findings suggest that the inclusion of a cycle endurance training stimulus may result in alterations to hamstring architecture that increase the risk of future injury. Therefore, the incorporation of endurance cycling training within concurrent training paradigms should be re-evaluated when trying to modulate injury risk.

CONCLUSION

In conclusion, this is the first study to investigate the effect of conventional resistance, endurance and concurrent training on hamstring structural adaptations and strength. Following a 12-week progressive overload training program, we observed a significant shortening in BFlh fascicle length following endurance-only and concurrent training interventions, with no change after resistance-only training. Further, we reported significant improvements in muscle thickness, pennation angle and maximal strength following resistance-only and concurrent training interventions. These findings suggest that the inclusion of a cycle endurance training stimulus may result in alterations to hamstring architecture that increase the risk of future injury; thus, incorporation of cycling as a stimulus within concurrent training paradigms should be re-evaluated.

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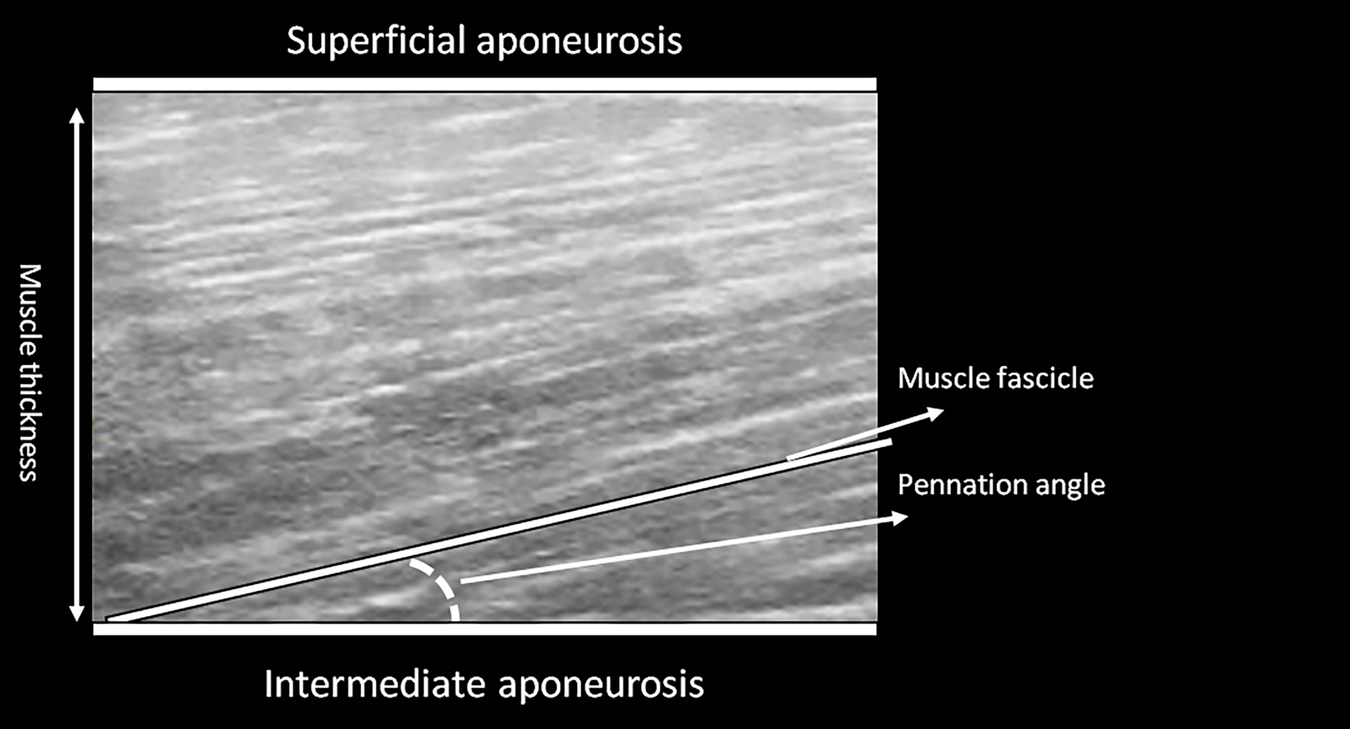
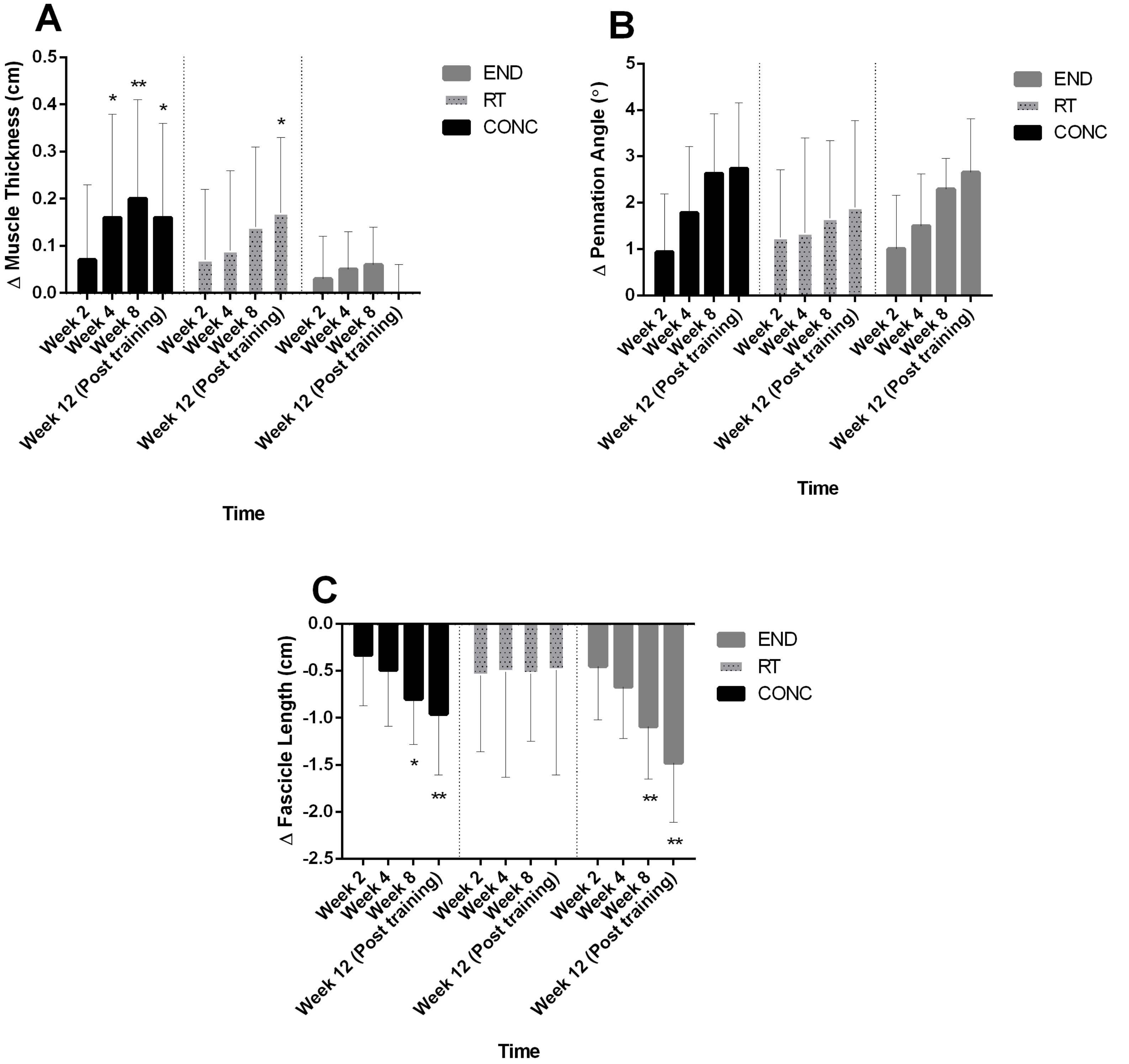
FIGURE LEGENDS

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: The change in biceps femoris muscle thickness (A), pennation angle (B) and fascicle length (C) following 12-weeks of either resistance, endurance and concurrent training. ** $=p<0.001$ compared to baseline, *$=p<0.05$ compared to baseline. CONC = concurrent training group, RT = resistance training group, END = endurance training group, Δ = change compared to baseline.


Superficial aponeurosis
Muscle thickness
Muscle fascicle
Pennation angle
Intermediate aponeurosis



A
Δ Muscle Thickness (cm)
0.5
0.4
0.3
0.2
0.1
0.0
*
**
*
*
END
RT
CONC
Week 2
Week 4
Week 8
Week 12 (Post training)
Time
B
Δ Pennation Angle (°)
5
4
3
2
1
0
END
RT
CONC
Week 2
Week 4
Week 8
Week 12 (Post training)
Time
C
Δ Fascicle Length (cm)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
*
**
**
**
END
RT
CONC
Week 2
Week 4
Week 8
Week 12 (Post training)
Time

Table 1. The effect of conventional resistance, endurance and concurrent training on body composition and strength

	Resistance-only group			Endurance-only group			Concurrent group		
	Total FFM (kg)	Leg FFM (kg)	3-lift Total (kg)	Total FFM (kg)	Leg FFM (kg)	3-lift Total (kg)	Total FFM (kg)	Leg FFM (kg)	3-lift Total (kg)
Baseline	62.8 ±6.94	21.9 ±2.47	419 ±99	62.2 ±5.77	22.1 ±2.40	433 ±58	61.6 ±6.65	21.9 ±2.96	441 ±112
Week 4	64.1 ±6.70	22.7 ±2.40		63.2 ±6.10	22.9 ±2.60		62.9 ±6.80	22.7 ±2.96	
Week 8	64.8 ±6.80	22.8 ±2.40		63.3 ±5.53	22.7 ±2.38		63.8 ±7.00	23.0 ±2.95	
Week 12 (Post training)	65.1 ±6.84	23.1 ±2.30	548** ±99	63.8 ±5.34	23.2 ±2.50	458 ±53	63.8 ±6.76	23.1 ±2.88	550** ±105

Data is presented as mean ± standard deviation. **p<0.001 vs baseline, * p<0.05 vs baseline, FFM = fat free mass