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Original research

Hamstring strength and architectural adaptations following inertial flywheel resistance training

Joel D. Presland[a], David A. Opar[a,d], Morgan D. Williams[b], Jack T. Hickey[a], Nirav Maniar[a], Connor Lee Dow[a], Matthew N. Bourne[c], Ryan G. Timmins[a,d,*]

[a] School of Behavioural and Health Sciences, Australian Catholic University, Melbourne, Australia
[b] School of Health, Sport and Professional Practice, University of South Wales, Pontypridd, Wales, UK
[c] School of Allied Health Sciences and Menzies Health Institute Queensland, Griffith University, Gold Coast, Australia
[d] Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Fitzroy, Victoria, Australia

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ABSTRACT

Objectives: To investigate the architectural and strength adaptations of the hamstrings following 6-weeks of inertial flywheel resistance training.
Design: Randomised, stratified training intervention
Methods: Twenty healthy males undertook 6-weeks of a conventional (n = 10) or eccentrically biased (n = 10) flywheel leg-curl training intervention as well as a subsequent 4-week detraining period. Biceps femoris long head (BFlh) architecture was assessed weekly, whilst assessments of eccentric and isometric knee flexor strength and rate of force development (RFD) were conducted prior to and following the intervention and detraining periods.
Results: The participants who undertook the eccentrically biased flywheel intervention showed a significant 14 ± 5% ($p < 0.001$, $d = 1.98$) increase in BFlh fascicle length after 6-weeks of training. These improvements in fascicle length subsequently declined by 13 ± 4% ($p < 0.001$. d=-2.04) following the 4-week detraining period. The conventional flywheel leg-curl training group saw no changes in BFlh fascicle length after the intervention (-0.5%±0.8%, $p = 0.939$, d=-0.04) or detraining (-1.1%±1%, $p = 0.984$, d=-0.03) periods. Both groups saw no changes in any of the strength or RFD variables after the intervention or the detraining period.
Conclusions: Flywheel leg-curl training performed with an eccentric bias led to significant lengthening of BFlh fascicles without a change in RFD, eccentric or isometric strength. These increases in fascicle length were lost following a 4-week detraining period. Conventional flywheel leg-curl training resulted in no changes in fascicle length, strength and RFD. These findings suggest that additional eccentric bias is required during inertial flywheel resistance training to promote fascicle lengthening in the BFlh, however this may still be insufficient to cause alterations to strength and RFD.

Practical Implications

- The consistent provision of eccentric loading is important for the maintenance of architectural adaptations following flywheel leg-curl training with an additional eccentric-bias.
- Architectural adaptations can occur irrespective of alterations in strength. Therefore, the measuring of structure must be considered alongside strength assessments.
- Flywheel leg-curl training with an additional eccentric-bias may be a useful option in hamstring strain injury prevention programs.

1. Introduction

Hamstring strain injuries (HSIs) are the most common injury in sports such as soccer,[1] carrying a high cost to both the athlete and sporting organization.[2] Of these injuries the most commonly injured muscle is the biceps femoris long head (BFlh) which accounts for ~80% of all HSIs.[3] Despite significant research attention on identifying risk factors for HSI[3,4] incidence has not decreased.[5]

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[*] Corresponding author.
E-mail address: Ryan.Timmins@acu.edu.au (R.G. Timmins).

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Of the factors identified to increase the risk of a future HSI, variables that can be modified through interventions are of interest. Two such variables are low levels of eccentric knee flexor strength[4] and short BFlh fascicle length,[3] which have been shown to increase the risk of HSI in professional soccer players[3]. In addition, legs with a history of HSI display deficits in not only eccentric knee flexor strength and BFlh fascicle length but also isometric knee flexor strength and rate of force development (RFD) when compared with the contralateral uninjured leg.[6–8] Deficits in isometric knee flexor strength have been shown to elevate risk of re-injury if present at the completion of HSI rehabilitation,[9] while RFD is considered important for sports performance.[10] The combination of these findings suggests a need to identify interventions capable of altering these variables, which could be applied to HSI prevention and rehabilitation practices.

Strength training interventions employing the Nordic hamstring exercise (NHE) have been shown to promote positive adaptations to eccentric knee flexor strength and BFlh fascicle length,[11,12] as well as preventing first time and recurrent HSIs.[13] Despite its effectiveness, the NHE is underutilized in elite soccer with only 11% of surveyed UEFA football teams claiming to implement the research-based programs.[14] Inertial flywheel resistance training is an alternative mode of strength training which enables an emphasis on the eccentric portion of an exercise which has been shown to increase strength[15] and vastus lateralis fascicle length.[16] Using a leg-curl inertial flywheel training intervention, Askling and colleagues found significant improvements in isokinetic eccentric knee flexor strength as well as a reduced number of HSIs in elite soccer players.[15] However, these previous studies have employed a conventional resistance training approach with both legs performing the concentric and eccentric phases of the movement. An alternative approach yet to be explored is the addition of a greater eccentric bias by having two legs complete the concentric phase, with only one leg undertaking the eccentric portion. Further to this, modifications in isometric knee flexor strength and RFD, eccentric strength (measured during the NHE) and BFlh fascicle length following an inertial flywheel leg-curl training intervention are yet to be investigated.

Therefore, the primary aim of this study was to determine BFlh architectural, knee flexor strength and RFD adaptations following a period of inertial flywheel leg-curl resistance training using either a conventional or eccentrically biased approach. Further, this study aimed to determine the time course of the BFlh architectural adaptations across a 6-week training intervention and a subsequent detraining period. It was hypothesized that 6-weeks of inertial flywheel resistance training with an additional eccentric-bias (using two legs concentrically and only one eccentrically) would result in significant increases in BFlh fascicle length, knee flexor strength and RFD. In conte, 6-weeks of inertial flywheel resistance training with a conventional prescription (one leg for both concentric and eccentric phases), was hypothesised to result in no alterations in fascicle length or any measures of strength or RFD.

2. Methods

Twenty recreationally active males (age 27.8 ± 5.3 yrs; height 178.4 ± 7.7 cm; body mass 80.0 ± 10.7 kg) with no history of lower limb injury in the previous 36 months were recruited to participate. All participants had recreational resistance training experience, with no previous exposure to inertial flywheel devices. All participants provided written informed consent prior to participation. Ethical approval was granted by the University's Human Research Ethics Committee (ethical approval number 2016-139 H).

Participants completed a familiarisation session on both the strength training and testing apparatus no less than seven days prior to their initial assessment taking place. Assessment of BFlh architecture was undertaken during this familiarisation session to pair participants based on their fascicle length and randomly assign them to one of two training groups. The second visit involved baseline strength testing, which consisted of an assessment of eccentric strength during the NHE as well as maximal isometric knee flexor strength and RFD. At baseline, as well as after the intervention and detraining periods, strength testing was undertaken in a randomized fashion to limit order bias with these assessments. Following this, all participants undertook their first training session of the 6-week inertial flywheel resistance training intervention. In a randomly selected leg (matched to the training leg in the opposite group based on fascicle length), one group (n = 10) performed unilateral training (CONV) on the flywheel with their opposite leg acting as a non-exercising control leg. The other group (n = 10) performed flywheel training with an additional eccentric-bias (ECC). This required participants to perform the concentric phase with both legs but only using one leg when undertaking the eccentric portion. The same leg was used throughout the intervention for the eccentric phase, with the contralateral leg completing the concentric phase only. Architecture of the BFlh was assessed prior to the first session of each week as well as at the completion of the training and 4-week detraining periods. Participants also rated their posterior thigh soreness at the start of the first session of each week with the aid of a visual analogue scale (0 = no soreness, 10=unbearable soreness)[12]. Measures of eccentric and isometric strength as well as RFD were retested following the intervention and detraining periods. For the duration of the study participants were asked to maintain habitual activity levels and refrain from performing resistance training involving the hamstrings.

Architectural characteristics of the BFlh were assessed using previously published methodology.[8] Briefly, two-dimensional, B-mode ultrasonography (frequency, 12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-I, Wauwatosa) images were captured along the longitudinal axis of the BFlh. All imaging was undertaken in a prone position with a neutral knee and hip after being inactive for at least 5 minutes.

All architectural assessments and analyses were completed by the same experienced assessor with established reliability,[8] who was blinded to participant ID, group and time. All analyses of ultrasound images were completed offline (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was defined as the distance between superficial and intermediate aponeuroses of the BFlh. Pennation angle was determined by outlining and marking a fascicle of interest on a given image and measuring the angle between this and the intermediate aponeurosis. Aponeurosis angle (superficial and intermediate) was defined as the angle between the marked aponeuroses and a line which intersected horizontally across the image, with the positive difference between the two being used for the analysis. Given entire fascicles were not visible in the linear array probe's field of view, fascicle length was estimated using a validated equation[17]:

$$FL = \sin(AA + 90^\circ) \times MT \div \sin(180^\circ - (AA + 180^\circ - PA))$$

Where FL= fascicle length, AA= aponeurosis angle, MT= muscle thickness and PA=pennation angle. The extrapolation measure and equation, whilst first used in quadriceps,[17] has been validated against cadaveric BFlh tissue and as such is considered a robust method of estimating fascicle length.[18]

Maximal isometric knee flexor strength and RFD were assessed before and after the 6-week intervention as well as following the 4-week detraining period. All isometric strength testing was completed on a custom-built apparatus with established reliability.[6] This device consisted of 2 adjustable ratchet straps hanging in parallel from a power cage, with a wired load cell (MLP-750; Transducer Techniques, LLC,Temecula, CA) and heel strap attached in-series with each strap. Testing consisted of unilateral, maximal isometric knee flexor contractions with the hip and knee joints at 90° of flexion whilst laying supine. To prevent excessive movement of the pelvis and trunk an additional strap was secured immediately inferior to both anterior superior iliac spines. Prior to the maximal assessment participants performed 3 submaximal contractions at 50, 75 and 95% of their perceived maximal effort. Following this, participants were asked to complete three maximal contractions (separated by 30 seconds) by pushing their heel downwards, without countermovement, as hard and fast as possible. To prevent order effects the first leg to be tested was randomly selected.

Maximal isometric knee flexor strength was defined as the highest force recorded of the three repetitions, corrected for limb weight.[6] Peak RFD (N/s) was determined using the repetition with the greatest increase in force over a moving 200-millisecond window from contraction onset (increase in resting force of $\geq$4 N)[6]. To identify the onset of contraction data were low-pass filtered (10 Hz) using a zero-lag, fourth order Butterworth filter.

Eccentric strength was assessed using an NHE field testing device (NordBord, Vald Performance, Queensland, Australia).[19] Participants were instructed to kneel on the device while the investigator secured the ankle braces superior to the lateral malleolus. In this kneeling position participants were to either cross their arms over their chest (if no additional load was required) or to hold a weight centered over the xyphoid process, keeping their hips in a position of full extension throughout the movement. Only the eccentric phase of the NHE was completed. Participants first completed a standard warm up protocol consisting of one repetition at each of 50, 75 and 95% of their perceived maximal effort at bodyweight. Following this, participants completed one set of three maximal NHE repetitions at bodyweight. To ensure testing was supramaximal, participants observed to have sufficient strength to control the descent of their bodyweight (within 10-15° from full knee extension) were required to perform additional repetitions with added weight in increments of 2.5 kg until the force recorded no longer increased by more than 5% (akin to a one-repetition maximum test). Following the intervention and the detraining periods, all participants undertook one set of three bodyweight efforts, as well as the incremental load assessment (if required). This was to ensure both a bodyweight and a supramaximal measure was determined for all time points. Data reported for eccentric strength was the peak force value (in Newtons), recorded during each testing time point, irrespective if it was completed with bodyweight or with additional load.

The training intervention was performed using the nHANCE leg curl inertial flywheel ergometer (YoYo Technology AB, Stockholm, Sweden). The CONV group performed unilateral training where the randomly selected leg performed both the concentric and eccentric phase (Supplementary Video 1). The ECC group performed the training with an eccentric bias to one leg (Supplementary Video 2). Previous investigations using an inertial flywheel leg-curl have used a bilateral variation (two legs up and two legs down), with moment of inertia equaling 0.1 kg.m.[15] As the CONV group undertook the intervention with only one leg, this was halved, with 0.05 kg.m being used throughout their program. The ECC group trained with a moment of inertia equaling 0.1 kg.m as per previous work.[15] During each training session participants were instructed to perform the concentric phase of each repetition as hard and fast as possible whilst attempting to stop the descent of the flywheel arm within the final portion of the eccentric phase and then initiating the next repetition.[15] The flywheel arm and participant position were modified to ensure the knee axis of rotation aligned with the lever arms fulcrum, with the ankle pads being placed superior to the lateral malleolus. Training was preceded by a warm up set consisting of six submaximal repetitions. The training volume for both groups can be found in Table 1.

Table 1
Flywheel leg-curl training intervention variables.

Week	Frequency (sessions/week)	Sets	Repetitions	Total weekly repetitions
1	2	4	6	48
2	2	4	6	48
3	2	5	6	60
4	2	5	8	80
5	2	6	8	96
6	2	5	6	60

All statistical analyses were performed using JMP V.11.01 Pro Statistical Discovery Software (SAS Inc., Cary, North Carolina, USA). Normal distribution of the data was tested using Shapiro-Wilk's analyses. To compare interventions, change in strength and architectural measures were independently analysed from baseline to the end of the intervention using a linear mixed model fitted with the restricted maximum likelihood method (REML). Factors were group (ECC or CONV) and leg (ECC group: eccentrically biased or concentric only, CONV group: training or control) and baseline score (covariate), with participant as the random factor. To assess the detraining effect, change from baseline measures of strength and architecture to end of study were analysed. Where significant main or interaction effects were detected, post-hoc *t* tests were applied to identify where differences occurred. Significance was set at $p < 0.05$ for all analyses. Where appropriate, Cohen's *d* effect sizes,[20] classified as small ($d \geq 0.20$), moderate ($d \geq 50$), and large ($d \geq 0.80$), were also reported.

Calculations of sample size were performed *a-priori* using G*Power, version 3.1.9.2. These calculations were made based on estimated changes in fascicle length following the intervention. The effect size utilized was set at half of the most conservative effect available in relevant literature, where a 16% increase in BFlh fascicle length was shown following 6-weeks of eccentric knee flexor training ($d = 2.5$). Therefore, with an effect size of 1.25, power set at 80% and an alpha level of <0.05, a sample size of 10 participants per group was deemed to be sufficient.

3. Results

The physical characteristics between the ECC (age 29.2 ± 6.2 yr; height 176.9 ± 9.0 cm; mass 78.5 ± 7.2 kg) and CONV (age 26.4 ± 4.1 yr; height 179.6 ± 6.4 cm; mass 81.5 ± 13.5 kg) groups were not different ($p \geq 0.255$, $d \leq 0.58$). Compliance was also acceptable for the ECC group who completed 118/120 training sessions (98.3% compliance), and the CONV group who completed 119/120 sessions (99.2% compliance).

A leg x group interaction was found for change in BFlh fascicle length ($p = 0.002$). Evidence of fascicle lengthening was only observed for the eccentrically trained leg of the ECC group. In this leg fascicle length increased 1.4 cm more than the contralateral concentric only leg (95%CI = 0.8 to 2.1 cm, $p < 0.001$, $d = 1.72$; Fig. 1, Supp Table 1), 1.4 cm more than the conventionally trained leg (95%CI = 0.7 to 2.0 cm, $p < 0.001$, $d = 1.60$) and 1.2 cm more than the control leg of the CONV group (95%CI = 0.5 to 1.8 cm, $p < 0.001$, $d = 1.78$). Baseline scores were negatively related (-0.51, SE=±0.17, $p = 0.006$) to the magnitude of lengthening observed.

Following detraining, fascicle lengths were no different (group main effect $p = 0.933$; limb main effect $p = 0.693$; group by limb interaction $p = 0.719$); when controlled for baseline measures. The differences following the detraining period compared to baseline in the eccentrically trained leg were 0.12 cm more when compared to the contralateral concentric only leg (95%CI=-0.35

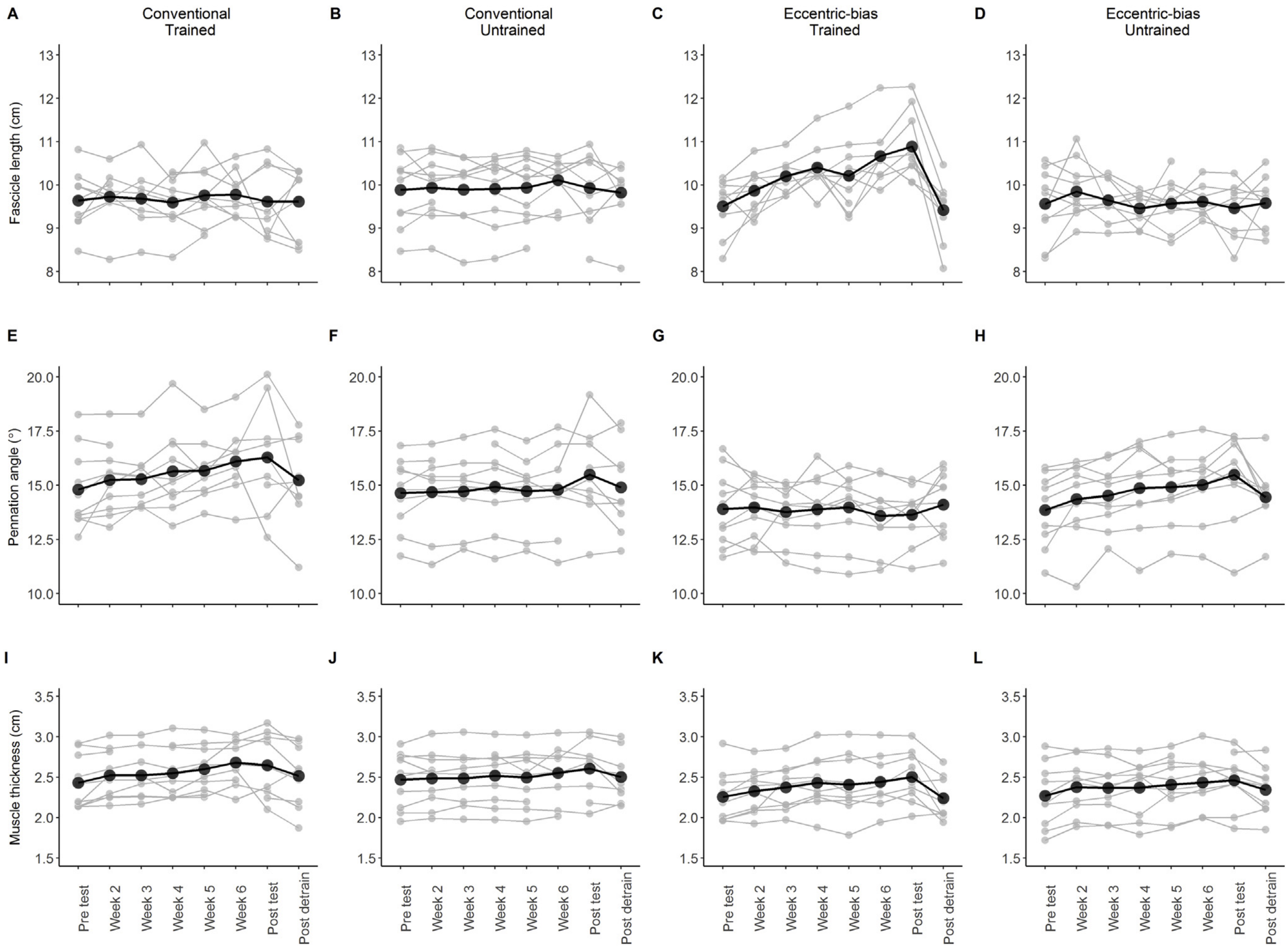

Fig. 1. Biceps femoris long head architectural characteristics throughout the intervention and after the detraining period. A = fascicle length for the training leg in the CONV group, B = fascicle length for the control leg in the CONV group, C = fascicle length for the training leg in the ECC group, D = fascicle length for the non-training leg in the ECC group, E = pennation angle for the training leg in the CONV group, F = pennation angle for the control leg in the CONV group, G = pennation angle for the training leg in the ECC group, H = pennation angle for the non-training leg in the ECC group, I = muscle thickness for the training leg in the CONV group, J = muscle thickness for the control leg in the CONV group, K = muscle thickness for the training leg in the ECC group, L = muscle thickness for the non-training leg in the ECC group.

to 0.61 cm, p = 0.582, *d* = 0.21); 0.08 cm more when compared to control leg in the CONV group (95%CI=-0.41 to 0.58 cm, p = 0.739, *d* = 0.14); and 0.08 cm more when compared to the training leg in the CONV group (95%CI=-0.41 to 0.56 cm, p = 0.752, *d* = 0.15).

Some evidence that eccentrically biased training decreased BFlh pennation angle was found (leg x group interaction p = 0.007). When the change from baseline to the end of the intervention measures of pennation angle were assessed reductions in the eccentrically trained leg were: 1.9° (95%CI = 0.7 to 3.1°, p = 0.005, *d*=-0.95) less than the contralateral concentric only leg; 1.8° (95%CI = 0.4 to 3.2°, p = 0.014, *d*=-0.63) less than the training leg in the CONV group; and trivial (1.1°, 95%CI=-0.3 to 2.5, p = 0.129, *d*=-0.19) compared to CONV control leg. No association was found between baseline pennation angle and change in pennation angle as a result of the intervention (p = 0.268).

When change in pennation angle measures from baseline to end of the detraining period were compared, no group by leg interaction (p = 0.316) was observed, suggesting the changes as a result of eccentric training had returned to baseline.

Muscle thickness remained constant throughout the study. There were no significant leg x group interactions for the intervention (p = 0.565) and detraining periods (p = 0.125) found. Therefore, no post-hoc tests were undertaken.

There were no significant increases in eccentric following the intervention. Whilst not significantly different across the groups or legs (leg x group interaction p = 0.754), the eccentrically biased training leg in the ECC group had a 33 N increase after the intervention (95%CI= -3to 68 N, p = 0.329, *d* = 0.33; Fig. 2, Supp Table 2). The other legs also saw non-significant increases in eccentric strength following the intervention with the contralateral concentric only leg in the ECC group improving by 43 N (95%CI= -15 to 71 N, p = 0.198, *d* = 0.46), the training leg of the CONV group increasing by 37 N (95%CI= -14 to 88 N, p = 0.171, *d* = 0.52) and the control leg of the CONV group getting stronger by 46 N (95%CI= -1 to 94 N, p = 0.125, *d* = 0.61).

After the detraining period, eccentric strength showed no significant change. Leg x group interactions were not significant (p = 0.853). Comparing the changes in strength after the detraining period with baseline measures, the differences were: eccentrically biased leg in the ECC group = 22 N (95%CI= -1to 45 N, p = 0.746, *d* = 0.21), concentric only leg in the ECC group = 18 N (95%CI= -15 to 52 N, p = 0.460, *d* = 0.18), training leg in the CONV group = 43 N (95%CI= -49 to 136 N, p = 0.852, *d* = 0.62) and the control leg of the CONV group = 66 N (95%CI= -22 to 109 N, p = 0.580, *d* = 1.04).

For RFD, there were no interactions found for leg x group at any time point across the intervention (p = 0.293) or detraining periods (p = 0.625).

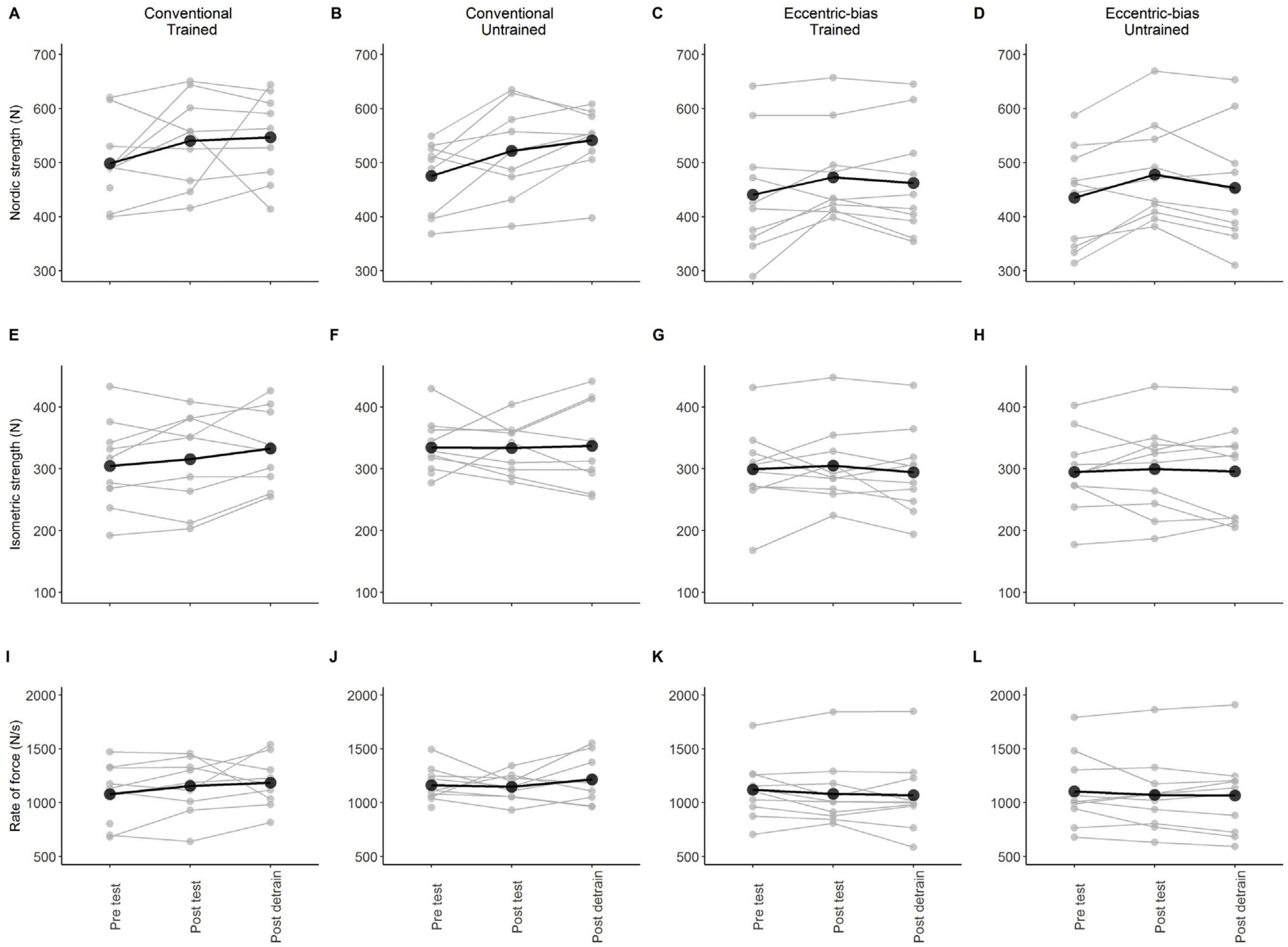

Fig. 2. Measures of knee flexor rate of force development (RFD), eccentric and isometric strength assessed at the beginning and after the intervention and detraining periods. A = eccentric strength for the training leg in the CONV group, B = eccentric strength for the control leg in the CONV group, C = eccentric strength for the training leg in the ECC group, D = eccentric strength for the non-training leg in the ECC group, E = isometric strength for the training leg in the CONV group, F = isometric strength for the control leg in the CONV group, G = isometric strength for the training leg in the ECC group, H = isometric strength for the non-training leg in the ECC group, I = RFD for the training leg in the CONV group, J = RFD for the control leg in the CONV group, K = RFD for the training leg in the ECC group, L = RFD for the non-training leg in the ECC group.

For isometric strength, there were no interactions found for leg x group at any time point across the intervention ($p = 0.777$) or detraining periods ($p = 0.211$).

For posterior thigh soreness, there were no interactions found for group x leg at any time point across the intervention or detraining periods (Supp Table 3). The maximum soreness value reported in the ECC group was a 4 out of 10 and was reported at the start of the second week of training. Whereas in the CONV group the highest was a 3 out of 10 and was reported at the start of the fifth week of training.

4. Discussion

This study is the first to investigate the effects of inertial flywheel resistance training on BFlh architecture and knee flexor strength. The novel findings of this study are: 1) 6-weeks of flywheel leg-curl training significantly lengthens BFlh fascicles only when performed with additional eccentric bias, 2) these alterations in fascicle length occur independent of significant eccentric or isometric strength adaptations and 3) the fascicle lengthening seen following flywheel training with an additional eccentric bias is lost after a 4-week detraining period.

It has been proposed that the lengthening of BFlh fascicles may partly explain the benefit of eccentric training interventions in reducing the risk of future HSI.[11] Recent evidence has shown that prospectively, elite soccer players who possess short BFlh fascicles (<10.56 cm) at the start of pre-season are four times more likely to suffer a HSI in the subsequent season,[3] with a 74% reduction in injury risk for every 0.5 cm increase in fascicle length. Whilst it is unknown if increases in BFlh fascicle length directly reduce HSI risk, in the current study the participants who undertook the eccentrically biased flywheel training increased their fascicle lengths from 9.5 cm to 10.9 cm. This, coupled with evidence showing a reduction of HSI rates following eccentric training interventions,[13] adds weight to speculation that adaptations to BFlh fascicle length may contribute to reducing the likelihood of a future HSI.

In the current study improvements in BFlh fascicle lengths were only seen in the group which performed the flywheel training with an eccentric bias, but not in the CONV group. The CONV group undertook a single leg variation of the typical prescription of hamstring flywheel training in the literature[15,21]. It is possible there were hamstring architectural adaptations within the CONV group, with evidence suggesting that knee-based flywheel efforts are more biased towards the medial hamstrings and not the BFlh, which was the only muscle measured in the current study.[22] Therefore, the added eccentric-bias experienced by the ECC group may have been required to promote architectural adaptations not seen in the BFlh of the CONV group, but there may still have been modifications to the medial hamstring group, however, any undetected in the current study. Comparably, bodyweight NHE interventions have seen no increases in BFlh fascicle following a low volume training protocol[23] and share a similar medially dominant recruitment strategy.[24] However, supramaximal NHE training programs (which are progressively overloaded with additional weight) have shown significant increases in BFlh fascicle length.[11,12] Whilst the BFlh is the most commonly injured of the hamstrings[3] and the adaptations that may reduce the likelihood of future injury in this muscle are of interest, more research is needed to understand the architectural adaptations of the medial hamstrings to these interventions and whether the architecture of the medial hamstrings is associated with future HSI risk.

In the current study, baseline fascicle length was related with the magnitude of change following training with an additional eccentric-bias. To assist with the interpretation, let's compare two hypothetical individuals (A and B). Individual A started the training intervention with additional eccentric bias having a fascicle length of 11 cm. Individual B started the same intervention but had a 10 cm fascicle. The findings of this study suggest that Individual A was likely to see an improvement in fascicle length that was 0.5 cm less than what Individual B may expect. In this example it is possible a greater stimulus may be required to promote improvements in Individual A, or that there may be a ceiling effect regarding the extent of adaptation possible in fascicle length. These findings also suggest that the programming of eccentric training should consider the characteristics of each individual and one should not expect that all individual will respond the same to an identical stimulus.

The reduction in fascicle length seen after the period of detraining may be of interest for hamstring injury prevention and rehabilitation interventions. The shortening of fascicles after the removal of an eccentric stimulus is suggested to be the result of shedding sarcomeres in-series,[25] although this cannot be confirmed in the current investigation. As a result, following the detraining period, it can be hypothesized that participants who see a shortening of their BFlh fascicles may be more prone to muscle damage during eccentric muscle actions (and potentially subsequent injury)[25] compared to those with longer fascicles. Furthermore, the decline in fascicle length after a period of detraining highlights the need for persistent eccentric stimuli to maintain architectural adaptations and potentially offset the risk of future HSI.

Previous research has shown significant improvements in eccentric and concentric, isokinetically derived measures of knee flexor strength following 10-weeks of hamstring flywheel training, in elite soccer players.[15] Conversely the current study found no improvements in isometric RFD, eccentric (measured during the NHE) or isometric peak force from a 6-week intervention in the training limbs of both groups. Additionally, the control limbs for each group showed non-significant changes in eccentric strength of approximately 10% following the intervention. It is possible that neural adaptations in the control limbs across the training intervention may have contributed to these changes. Despite this, within the literature it is not consistent as to what alterations in strength may occur following inertial flywheel resistance training interventions.[26] Some interventions have found large improvements in strength following flywheel training[21,27], however there are others showing no significant changes.[28,29] Therefore, the lack of eccentric or isometric strength improvements in the current study does align with a selection of the inertial flywheel training literature.[28,29]

The findings in this study highlight the possibility for muscle architecture to adapt in the absence of strength modifications. Whilst eccentric training programs have been shown to promote increases in both eccentric strength and fascicle length,[11,30] the two are not always synonymous with each other. This is the first study to show increases in fascicle length independent to any strength alterations after a period of eccentric training. Evidence does exist, however, showing shortening of fascicles after a period of detraining, with no changes in eccentric strength.[12,30] These findings highlight the need to monitor both hamstring architectural adaptations, as well as eccentric strength during periods of training, detraining or offloading.

There are limitations in this study which should be considered. Firstly, the measure of eccentric strength was a bilateral assessment, whereas training was undertaken with unilateral variations. However, the inclusion of the unilateral isometric strength assessment was intended to account for any effects that the bilateral deficit may have had in representing strength adaptations. Furthermore, the assessment of eccentric strength was completed on a practically applied, field testing device which has been shown to indicate a level of risk associated with future HSI.[3,4] Secondly, the transducer field of view utilised in this study did not show an entire BFlh fascicle, with the results being estimated using an equation.[17] Transducers with larger fields of view or panoramic functions would be desirable, however such equipment and techniques are not available in our laboratory. It should be noted that the extrapolation technique and equation has been validated against cadaveric tissues and as such is considered a robust way of estimating fascicle lengths.[17] Furthermore, whilst ultrasound derived measures of fascicle length are complicated by error, the assessor used to collect the ultrasound images in the current study has proven reliability.[8] Finally, architectural assessments were only completed on the BFlh and none of the other hamstring muscles. As the BFlh is the most commonly injured of the hamstrings, understanding the architectural adaptations within it may help better inform injury prevention and rehabilitation practices.

5. Conclusions

Inertial flywheel resistance training, undertaken with an additional eccentric bias, promotes significant increases in BFlh fascicle length without any alterations in RFD, eccentric or isometric strength. The fascicle lengthening as a result of the flywheel training with additional eccentric bias was lost following a 4-week detraining period. Comparably, conventional flywheel leg-curl training, without an additional eccentric-bias, did not promote fascicle lengthening and also did not modify RFD, eccentric or isometric strength. These findings suggest that architectural adaptations can occur without improvements in knee flexor strength and that flywheel leg-curl training might be a beneficial tool in HSI prevention, when employed with an eccentric bias.

Conflicts of interest

A co-author of this paper, David Opar, is listed as a coinventor on a patent filed for a field test of eccentric knee flexor strength (PCT/AU2012/001041.2012), while also being a minority shareholder in a company (Vald Performance) that commercializes the device. David Opar is also the Chair of the Vald Performance Research Committee (a role which is unpaid). Morgan Williams is a member of the Vald Performance Research Committee.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jsams.2020.04.007.

References

1. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. *Br. J. Sports Med* 2011; 45(7):553–558.
2. Hickey J, Shield AJ, Williams MD et al. The financial cost of hamstring strain injuries in the Australian Football League. *Br. J. Sports Med* 2014; 48(8):729–730.
3. Timmins RG, Bourne MN, Shield AJ et al. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br. J. Sports Med* 2016; 50(24):1524–1535.
4. Opar DA, Williams MD, Timmins RG et al. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med. Sci. Sports Exerc* 2015; 47(4):857–865.
5. Ekstrand J, Walden M, Hagglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study. *Br. J. Sports Med* 2016; 50(12):731–737.
6. Hickey JT, Hickey PF, Maniar N et al. A Novel Apparatus to Measure Knee Flexor Strength During Various Hamstring Exercises: A Reliability and Retrospective Injury Study. *J. Orthop. Sports Phys. Ther* 2018; 48(2):72–80.
7. Opar DA, Williams MD, Timmins RG et al. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. *Am. J. Sports Med* 2013; 41(1):116–125.
8. Timmins RG, Shield AJ, Williams MD et al. Biceps femoris long head architecture: a reliability and retrospective injury study. *Med. Sci. Sports Exerc* 2015; 47(5):905–913.
9. De Vos RJ, Reurink G, Goudswaard GJ et al. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. *Br. J. Sports Med* 2014; 48(18):1377–1384.
10. Maffiuletti NA, Aagaard P, Blazevich AJ et al. Rate of force development: physiological and methodological considerations. *Eur. J. Appl. Physiol* 2016; 116(6):1091–1116.
11. Bourne MN, Duhig SJ, Timmins RG et al. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. *Br. J. Sports Med* 2017; 51(5):469–477.
12. Presland JD, Timmins RG, Bourne MN et al. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scand. J. Med. Sci. Sports* 2018; 28(7):1775–1783.
13. Petersen J, Thorborg K, Nielsen MB et al. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. *Am. J. Sports Med* 2011; 39(11):2296–2303.
14. Bahr R, Thorborg K, Ekstrand J. Evidence-based hamstring injury prevention is not adopted by the majority of Champions League or Norwegian Premier League football teams: the Nordic Hamstring survey. *Br. J. Sports Med* 2015; 49(22):1466–1471.
15. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. *Scand. J. Med. Sci. Sports* 2003; 13(4):244–250.
16. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J. Appl. Physiol* 2007; 102(1):368–373.
17. 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.
18. 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):2549–2554.
19. Opar DA, Piatkowski T, Williams MD et al. 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):636–640.
20. Cohen J. *Statistical power analysis for the behavioral sciences*, Hillsdale (NJ), Erlbaum, 1988.
21. de Hoyo M, Pozzo M, Sanudo B et al. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int. J. Sports Physiol. Perform* 2015; 10(1):46–52.
22. Fernandez-Gonzalo R, Tesch PA, Linnehan RM et al. Individual Muscle use in Hamstring Exercises by Soccer Players Assessed using Functional MRI. *Int. J. Sports Med* 2016; 37(7):559–564.
23. Seymore KD, Domire ZJ, DeVita P et al. The effect of Nordic hamstring strength training on muscle architecture, stiffness, and strength. *Eur. J. Appl. Physiol* 2017; 117(5):943–953.
24. Bourne MN, Opar DA, Williams MD et al. Muscle activation patterns in the Nordic hamstring exercise: Impact of prior strain injury. *Scand. J. Med. Sci. Sports* 2016; 26(6):666–674.
25. Morgan DL. New insights into the behavior of muscle during active lengthening. *Biophys. J* 1990; 57(2):209–221.
26. Vicens-Bordas J, Esteve E, Fort-Vanmeerhaeghe A et al. Is inertial flywheel resistance training superior to gravity-dependent resistance training in improving muscle strength? A systematic review with meta-analyses. *J Sci. Med. Sports* 2018; 21(1):75–83.
27. Norrbrand L, Fluckey JD, Pozzo M et al. Resistance training using eccentric overload induces early adaptations in skeletal muscle size. *Eur. J. Appl. Physiol* 2008; 102(3):271–281.
28. Onambele GL, Maganaris CN, Mian OS et al. Neuromuscular and balance responses to flywheel inertial versus weight training in older persons. *J. Biomech* 2008; 41(15):3133–3138.
29. Caruso JF, Coday MA, Ramsey CA et al. Leg and calf press training modes and their impact on jump performance adaptations. *J Strength Cond Res* 2008; 22(3):766–772.
30. Pollard CW, Opar DA, Williams MD et al. Razor hamstring curl and Nordic hamstring exercise architectural adaptations: Impact of exercise selection and intensity. *Scand. J. Med. Sci. Sports* 2019; 29(5):706–715.