Title: The effect of concentric and eccentric knee flexor strength training on recovery from sprint training sessions, eccentric strength and biceps femoris muscle architecture.

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Abstract

PURPOSE: To investigate whether five-weeks of concentric (CON) or eccentric (ECC) knee flexor (KF) strength training have different effects on recovery from sprint running, eccentric strength and architecture of the biceps femoris long head (BF_{LH}). **METHODS:** Thirty males (age, 22.8 ± 4.1y; height, 180.1 ± 6.4cm; weight, 85.2 ± 14.6kg) were allocated into either a CON or ECC group, both performing nine sessions of resistance training. Prior to and immediately after the five-week intervention, each participant's BF_{LH} fascicle length (FL), pennation angle (PA), muscle thickness (MT), peak isometric KF torque and Nordic eccentric strength were assessed. Post intervention, participants performed two timed sprint sessions (10x80m) 48 hours apart. Blood samples and passive KF torques were collected before, immediately after, 24 hours and 48 hours after the first sprint session. **RESULTS:** After five-weeks of strength-training, fascicles lengthened in the ECC ($p<0.001$; $d = 2.0$) and shortened in the CON group ($p<0.001$; $d = 0.92$), while PA decreased for the ECC ($p=0.001$; $d = 0.52$) and increased in the CON group ($p<0.001$; $d = 1.69$). Nordic eccentric strength improved in both ECC ($p<0.001$; $d = 1.49$) and CON ($p<0.001$; $d = 0.95$) groups. No between-group differences were observed in peak isometric strength ($p=0.480$), passive KF torques ($p=0.807$), sprint performance decrements between sprint sessions ($p = 0.317$) and creatine kinase ($p=0.818$). **CONCLUSION:** Despite inducing significant differences in BF_{LH} muscle architecture, there were no significant between group differences in sprint performance decrements across two sprint sessions.

Introduction

Eccentric and concentric training programs have unique effects on skeletal muscle. For example, eccentric training decreases and concentric training increases the susceptibility of skeletal muscles to strength loss, shifts in the torque-joint angle relationship and delayed soreness consequent to a bout of eccentric actions (1). Eccentric training of the human hamstrings has also recently been reported to increase fascicle lengths within the long head of the biceps femoris, while concentric training through the same range of motion decreased them (2).

Eccentric strength training interventions employing the Nordic hamstring exercise (NHE) have been shown to decrease hamstring strain rates in sport (3-6), while low levels of Nordic eccentric strength have been reported to be associated with an increased risk of injury in some (7, 8), but not all prospective studies (9, 10). While the mechanisms mediating the effectiveness of eccentric strength training are not entirely understood (11) it has been proposed that the addition of in-series sarcomeres may at least partially explain an increased resistance to microtrauma and muscle strain injury (12-14). Indeed, short biceps femoris long head (BF_{LH}) fascicles have recently been reported to be associated with a higher risk of hamstring strain injury in elite Australian soccer players (7). The NHE is also known to be an effective means of increasing BF_{LH} fascicle lengths (15).

We have shown that large and rapid changes in high-speed running loads over a 1-4 week period are associated with an increased risk of hamstring strain injury (16). This is consistent with the possibility that hamstring injuries may not always be isolated acute events caused by a single over-long stride, kick or stretch but instead they may occur as a consequence of accumulated microtrauma which eventually becomes macroscopic and presents as a strain injury (16). However, such trauma may be mitigated by use of eccentric hamstring strength training.

The effects of eccentric and concentric strength training of the human hamstrings on running performance and recovery from bouts of sprint running are not well known. High-speed running involves high knee flexor forces and is proposed to involve powerful eccentric actions during terminal swing which is thought to be a likely time for hamstring strain injury (17, 18). These powerful eccentric actions in running are also likely to cause hamstring microtrauma, soreness and a loss of strength which may result in a performance decrement when two high-speed running sessions are planned within 24-72 hours of each other. Theoretically, eccentric conditioning should better prepare the hamstrings for repeated bouts of such exercise. Accordingly, this study was designed to investigate the effects of eccentric and concentric hamstring conditioning on the change in running performance that occurred between two consecutive running sessions held 48 h apart. We hypothesised that adaptations induced by eccentric training would, in comparison with concentric training, result in a better maintenance of sprint performance between sessions and reduced markers of muscle damage (passive knee flexor torques, perceived muscle soreness and venous creatine kinase levels (CK)). For the purpose of this study, 'recovery' was assessed by monitoring performance in two sprint sessions conducted 48 hours apart.

Methods

Participants and study design

This strength training intervention was conducted between July and September, 2016. Thirty recreationally active males (age, 22.8 ± 4.1 y; height, 180.1 ± 6.4 cm; weight, 85.2 ± 14.6 kg) provided written informed consent and completed a cardiovascular screening questionnaire before participating. All participants were free from soft tissue and orthopaedic injuries to the lower limbs, hips, and trunk with no prior history of hamstring strain or knee ligament injury. The university's research ethics committee approved this study.

Participants had their relaxed bicep femoris long head architecture, isometric peak knee flexor torque and Nordic eccentric strength assessed prior to and after the five-week intervention. Once pre-intervention assessments had been conducted, participants were ranked and paired in order of fascicle lengths and an individual from each pair was randomly allocated to either the concentric-only (CON) group or eccentric-only (ECC) group, with the remaining individual from each pair allocated to the other group. Both groups completed nine strength training sessions over a five week period (Table 1) and were instructed not to participate in any additional hamstring strength training. Seven to nine days after the final strength training session, participants performed a sprint running session (Sprint 1) (10 x 80 m) on a flat grass sports field, followed 48 hours later by an identical sprint session (Sprint 2). An isokinetic dynamometer (Biodex System 3, Shirley, USA) was used to measure passive knee flexor torque during knee extension and perceived muscle soreness, as determined during passive knee extension, was recorded using a 0-10 numeric pain rating scale, 24 and 48 hours after the first sprint training session. Blood samples were drawn using standard venipuncture techniques at four time points (prior to the first sprint session, immediately, 24 h and 48 h after sprint session 1). Figure 1 provides a schematic diagram for the above methods.

INSERT FIGURE 1 HERE

Biceps femoris long head architecture assessment

Bicep femoris long head fascicle lengths were estimated using ultrasound images taken along the longitudinal axis of the muscle belly utilising a two-dimensional, B-mode ultrasound (frequency, 12Mhz; depth, 8 cm; field of view, 14 x 47 mm) (GE Healthcare Vivid-*i*, Wauwatosa, U.S.A). Participants were positioned prone on a plinth with their hips in neutral and knees fully extended and images were acquired from a point midway between the ischial tuberosity and the popliteal fold, parallel to the presumed orientation of BF_{LH} fascicles. After the scanning site was determined, the distance of the site from various anatomical landmarks was recorded to ensure its reproducibility for post testing. These landmarks included the ischial tuberosity, head of the fibula and the popliteal fold at the mid-point between BF and ST tendon. For post testing, the scanning site was determined and marked on the skin and then confirmed by replicated landmark distance measures. Images were obtained from both limbs following at least five minutes of inactivity. 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 affect the accuracy of the measures (19). The orientation of the probe was manipulated slightly by the ultrasonographer if the superficial and intermediate aponeuroses were not parallel.

Ultrasound images were analysed using MicroDicom software (Version 0.7.8, Bulgaria). For each image, 6 points were digitised as described by Blazevich and colleagues (20). Following the digitising process, muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of the BF_{LH}. A fascicle of interest was outlined and marked on the image. Fascicle length was determined as the length of the outlined fascicle between aponeuroses and was reported in absolute terms (cm). As the entire fascicles were not visible in the probe's field of view, their lengths were estimated using the following equation:

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

Where *FL*= fascicle length, *AA*= aponeurosis angle, *MT*= muscle thickness and *PA*= pennation angle (20).

All images were collected and analysed by the same investigator (RGT) who was blinded to training group allocation. The assessment of BF_{LH} architecture using the aforementioned procedures by this ultrasonographer is highly reliable (intraclass correlations >0.90; minimal detectable changes at 95% confidence interval; MT=0.18, PA=0.96, FL=0.74) (21).

Strength assessments

Nordic eccentric strength test (NeST)

The assessment of eccentric knee flexor force using the NHE has been reported previously (8, 9). Participants knelt on a padded board, with the ankles secured by individual ankle straps that were attached to uniaxial load cells (MLP-1K, Transducer Techniques, CA, USA). The load cells were calibrated immediately prior to testing by progressively applying known ~200N loads up to a load of ~800N (~600 N forces are the highest our group has previously recorded in tests of the Nordic hamstring curl). The distal ends of the straps were placed level with the most prominent point of the lateral malleoli. The ankle braces and load cells were secured to a pivot which allowed the force generated by the knee flexors to be measured through the long axis of the load cells. From the initial kneeling position with their ankles secured in padded yokes, arms on the chest and hips extended, participants lowered their bodies as slowly as possible to a prone position. Participants performed only the lowering (eccentric) portion of the exercise and were instructed to use their arms and flex at the hips and knees in order to reassume the starting position with minimal knee flexor activity. Participants initially performed five submaximal but progressively more intense repetitions of the bilateral NHE as a way of warming up for subsequent maximal efforts. The NeST involved performing single repetitions of the NHE as slowly as possible, initially with body mass and thereafter with extra loads held centred over the xiphoid process. The first extra load was 5 kg and this was increased in 5 kg increments until the sum of the two ankle forces did not increase. A single repetition was performed at each load and the highest sum of the left and right leg forces was recorded. Three minutes rest was allowed after warm-up and three minutes was allowed between single maximal repetitions. Participants were encouraged to maintain a fully extended hip angle throughout each repetition. To calculate knee flexor torques from the forces applied at the ankle, a measurement of the distance between the femoral lateral epicondyle and middle of the ankle strap was made with a flexible steel tape measure.

Knee flexor passive torque

The resistance of the relaxed knee flexors to passive stretch, measured as gravity corrected knee flexion torque (Nm), was also assessed via isokinetic dynamometry (22). Prior to testing, neonatal ECG electrodes (10 mm in diameter, 15 mm interelectrode distance) (Ambu®, Ballerup, Denmark) were placed over the intersection of the medial and lateral hamstring muscle bellies. Subsequently, participants were seated on the dynamometer with a hip angle of approximately 85°, and a 5 cm thick foam pad was then placed between the seat and upper back of the participant to increase hip flexion to approximately 90º. Straps were placed around the tested thigh, waist, and chest to minimise compensatory movements. All seating variables (e.g., seat height, pad position) were recorded to ensure the replication of positions in post-intervention testing. The lever angle range of motion was set at 0° and 90° (0° representing full knee extension) with gravity correction for limb weight conducted at 30° from full knee extension. The warm-up prior to the assessment of passive knee flexor torque and isometric strength involved two sets of four maximal concentric knee extension and flexion contractions at an angular velocity of 240°·s^{-1} and 120°·s^{-1}, respectively.

Passive knee flexor torque was determined by measuring the maximum torque produced during extension of the knee. Participants were instructed to completely relax their lower limbs while the dynamometer extended their knee at 10°·s^{-1} across three repetitions (23). Real-time surface EMG traces displayed to both the participant and the researcher provided confirmation of hamstring muscle relaxation throughout these tests. Participants were asked to rate their muscle soreness at the point of full knee extension using a numerical pain rating scale between 0 and 10 (0 = no pain; 10 = severe pain).

Isometric peak torque

Isometric knee flexor strength was assessed via isometric dynamometry (22). Isometric contractions were performed at five different knee angles (10°, 30°, 50°, 70° and 90°) with 2 x 3 s maximal voluntary contractions at each angle. The order of knee angles was randomised for each participant and replicated in post-training tests. Thirty second rest periods were employed between contractions at the same angle and one minute rests were employed between tests at different angles. The investigators loudly exhorted participants to exert maximal effort during all contractions.

Sprint times

For both running sessions, participant's had their 80 m sprint times measured using timing gates (SMARTSPEED LITE, Fusion sport, Brisbane, Australia), which have previously been shown to be reliable (24). The standardised warm-up consisted of a 3 min jog followed by four 80 m run-throughs with increasing speed (60%, 70%, 80% and 90% of each participant's perceived maximum) interspersed with three minutes of lower limb dynamic stretches. A recovery period of three minutes was applied between maximum efforts.

Hamstring strength training program

Participants were required to complete a training program consisting of nine supervised exercise sessions over the course of five weeks (Table 1) with a minimum recovery period of 48 hours between each session. The training program design was similar to previous training studies using the NHE (4, 25) (Table 1) and has been shown to produce morpholical adaptations (28). To ensure procedural consistency, all sessions were conducted in the same laboratory, using the same exercise equipment and supervised by the same investigators.

Table 1 - *Training program variables*

Week	Training sessions	Sets	Repetitions
1	**2**	**2**	**6**
2	**2**	**3**	**6**
3	**2**	**4**	**6**
4	**2**	**5**	**6**
5	**1**	**5**	**6**

Nordic hamstring exercise (ECC) training

The NHE was performed on the device employed for the NeST. Participants were instructed to lean forward at the knee at the slowest possible speed whilst maximally resisting the descent and maintaining the trunk and hips in an upright position, with only the eccentric phase being performed. The hands were kept pronated and wrists hyper-extended next to the chest to catch the fall. The exercise was performed initially with body mass alone but once participants displayed adequate strength to completely stop the movement at ~10^0 from full knee extension, they were required to hold a weight plate (range = 5 – 10 kg) to their chest (centred over the xiphoid process). This external load was increased in 5 – 10 kg increments when participants were again able to stop the movement at ~10º from full knee extension.

Leg curl (CON) training

The concentric unilateral leg curl was performed on a prone leg curl machine (CALGYM, Australia) using a 6-7RM load. Each repetition started at full knee extension and finished at approximately 90^0 of knee flexion. Once this point was reached a research assistant held the machine's lever arm allowing the participant to return their shank, without external load, to the starting position of full knee extension. The assistant then lowered the lever arm. Training loads were increased whenever participants could perform all repetitions of their planned training session.

Blood collection and analysis

Blood samples were collected before the first sprint session, <15 min after, 24 h, and 48 h post sprint. The blood samples were collected from an antecubital vein into an EDTA tube (BD, Franklin Lakes, NJ). Tubes were then centrifuged at 1000 rpm at 4ºC for 10 min and stored at -80ºC until the day of analysis. Creatine kinase activity was measured using a spectrophotometric assay on an automated analyser (Cobas Mira, Roche diagnostics GmbH, Germany).

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. The forces collected during the NeST were converted to torque and expressed as torque per kilogram of bodyweight (Nm/kg). Repeated measures split plot ANOVAs were used to explore group by time effects of the training interventions on BF_{LH} fascicle length, pennation angle and muscle thickness, NeST peak torque, passive knee flexor torque and perceived muscle soreness, 80 m sprint performance and venous CK. For isometric peak knee flexor torque, a three way ANOVA was used with the *time (pre vs post)* and *angle (10, 30, 50, 70 and 90º)* the within-subject variables and *group (CON vs ECC)* the between-subject variable. For the analysis of BF_{LH} architecture and NeST results the within-subject variable was *time (pre and post training intervention)* and the between-subject variable was *group (CON vs ECC)*. The 80 m sprint performance within-subject variable was *time (sprint session one and sprint session two)* and the between-subject variable was *group (CON vs ECC)*. The between limbs (dominant vs non-dominant) BF_{LH} architecture was not significantly different at either time point ($p>0.05$), therefore dominant and non-dominant limbs were averaged to provide a single value for each participant. The 80m sprint performance decrement was reported as the slowest (maximum) time – fastest (minimum) for each sprint session. To explore changes in passive knee flexor torque and perceived muscle soreness and CK the within-subject variable was *time* (*before and* *immediately after first sprint session then at 24 h and 48 h post*) and the between-subject variable was *group (CON vs ECC)*. Descriptive statistics were used to report 24 h post-training session ratings of perceived soreness. For all analyses, post hoc independent *t*-tests with Bonferroni corrections were used to determine which comparisons differed significantly. The mean differences were reported with their 95% confidence intervals (CIs). Cohen *d* effect sizes were calculated using the thresholds; trivial < 0.20, small = 0.20-0.49, medium = 0.50-0.79 and large > 0.80 (26).

Results

No significant differences were observed for age, height or body mass between the groups ($p > 0.05$; Table 2). Training session compliance rates were 100% and 99.3% for the CON and ECC groups, respectively.

Table 2 - *Participant characteristics*

Group	Age (years)	Stature (cm)	Mass (kg)
CON	22.7 ± 3.9	178.3 ± 5.8	86.2 ± 15.4
ECC	23.7 ± 4.8	181.3 ± 6.9	83.8 ± 14.6

Biceps femoris long head architecture

As a consequence of the training intervention, a significant group by time interaction was found for BF_{LH} fascicle length ($p<0.001$) (Figure 2) and pennation angle ($p<0.001$) (Figure 2). No significant group by time interaction was seen for muscle thickness ($p=0.193$). Before training there were no significant between group differences in fascicle length (CON = 10.39cm; ECC = 10.22cm; mean difference = 0.17cm; 95% CI = -0.32 to 0.66; $p = 0.484$; $d = 0.25$), pennation angle (CON = 14.18º; ECC = 14.16º; mean difference = 0.02º; 95% CI = -0.93 to 0.98; p = 0.964; *d* = 0.01) or muscle thickness (CON = 2.55cm; ECC = 2.49cm; mean difference = 0.06cm; 95% CI = -0.14 to 0.25; p = 0.523; *d* = 0.22). Post hoc analyses showed significant BF_{LH} fascicle elongation in the ECC group (mean difference= 1.40 cm (13%); 95% CI = 1.05 to 1.75; p<0.001; *d* = 2.0) and shortening in the CON group (mean difference = 0.66 cm (6%); 95% CI = -0.92 to -0.40; p<0.001; *d* = 0.92) (Figure 2). After training, the differences between the groups' fascicle lengths were significant (mean difference = 1.90cm; 95% CI = 1.34 to 2.45; p<0.001; *d* = 2.57). There was a significant decrease in pennation angle for the ECC group (mean difference = 0.77º (5%); 95% CI = -0.98 to -0.30; p = 0.001; *d* = 0.52) and an increased pennation angle in the CON group (mean difference = 1.73º (12%); 95% CI = 1.40 to 2.06; p<0.001; *d* = 1.69) (Figure 2). After training, a significant between group difference in pennation angle was found (mean difference = 2.52º; 95% CI = 1.60 to 3.45; p<0.001; *d* = 2.07). A significant increase in muscle thickness was shown for both the ECC (mean difference = 0.19cm (7%); 95% CI = 0.12 to 0.29; p<0.001; *d* = 0.73) and CON groups (mean difference = 0.11 cm (4%); 95% CI = 0.39 to 0.19; p=0.005; *d* = 0.43) (Figure 2). However, there was no significant difference between groups after training (mean difference = 0.01cm; 95% CI = -0.20 to 0.23; p=0.868; *d*=0.03).

Insert Figure 2 here

Eccentric knee flexor strength

Peak knee flexor torques were typically obtained with 5-15kg and 10-20kg of load added to body mass during the pre- and post-training NeST tests, respectively. There was no significant group by time interaction (p=0.065) detected for NeST scores (Pre, CON = 3.88Nm/kg ± 0.47, ECC = 3.69Nm/kg ± 0.53; Post, CON = 4.40Nm/kg ± 0.62, ECC = 4.55 ± 0.55). Furthermore, there was no significant between groups differences found in eccentric knee flexor strength prior to the intervention (CON = 3.88Nm/kg; ECC = 3.68Nm/kg; mean difference = 0.20Nm/kg; 95% CI = -0.18 to 0.58; p = 0.299; *d* = 0.39). There were strength improvements for both the ECC (mean difference = 0.83Nm/kg (24%); 95% CI = 0.59 to 1.0; p<0.001; *d* =1.49) and CON (mean difference = 0.51Nm/kg (13%); 95% CI = 0.29 to 0.75; p<0.001; *d* = 0.95) groups (Figure 3), however, there was no significant difference between groups after training (mean difference = 0.15Nm/kg; 95% CI = -2.87 to 0.59; p=0.480; *d*=0.25).

Insert Figure 3 here

Peak isometric knee flexor torque

There was no significant group by time by angle interaction observed for peak isometric knee flexor torques (p=0.480). There were no significant differences between groups at any angle before training (10º, CON = 153Nm; ECC = 161Nm; mean difference = 7Nm; 95% CI = -32 to 16; p = 0.511; *d* = 0.19; 30º, CON = 151Nm; ECC = 158Nm; mean difference = 7Nm; 95% CI = -30 to 16; p = 0.542; *d* = 0.22; 50º, CON = 145Nm; ECC = 149Nm; mean difference = 3Nm; 95% CI = -23 to 15; p = 0.705; *d* = 0.03; 70º, CON = 127Nm; ECC = 130Nm; mean difference = 3Nm; 95% CI = -20 to 13; p = 0.705; *d* = 0.08; 90º, CON = 96Nm; ECC = 102Nm; mean difference = 5Nm; 95% CI = -18 to 6; p = 0.351; *d* = 0.31) or after training (10º, CON = 154Nm; ECC = 151Nm; mean difference = 3Nm; 95% CI = -21 to 26; p = 0.819; *d* = 0.09; 30º, CON = 151Nm; ECC = 153Nm; mean difference = 2Nm; 95% CI = -25 to 22; p = 0.898; *d* = 0.22; 50º, CON = 140Nm; ECC = 145Nm; mean difference = 5Nm; 95% CI = -26 to 17; p = 0.666; *d* = 0.15; 70º, CON = 129Nm; ECC = 128Nm; mean difference = 1Nm; 95% CI = -16 to 17; p = 0.931; *d* = 0.04; 90º, CON = 99Nm; ECC = 105Nm; mean difference = 6Nm; 95% CI = -20 to 7; p = 0.352; *d* = 0.31).

Peak isometric torques did not change at any angle as a consequence of concentric (10º, mean difference = 0.60Nm; 95% CI = -11.02 to 12.24; p = 0.917; *d* = 0.03*;* 30º, mean difference = 0.53Nm; 95% CI = -13.61 to14.68; p = 0.939 ; *d* = 0.00; 50º, mean difference = -5.26Nm; 95% CI = -17.75 to 7.22; p = 0.395; *d* = 0.16*;* 70º, mean difference = 2.33Nm; 95% CI = -7.79 to 12.46; p = 0.641; *d* = 0.08*;* 90º, mean difference = 2.20Nm; 95% CI = -6.26 to 10.66; p = 0.599; *d*=0.15) or eccentric strength training (10º, mean difference = -10.00Nm; 95% CI = -21.62 to 1.62; p = 0.089; *d* = 0.32*;* 30º, mean difference = -5.00Nm; 95% CI = -19.14 to 9.14; p = 0.475; *d* = 0.17*;* 50º, mean difference = -4.33Nm; 95% CI = -16.82 to 8.15; p = 0.483; *d* = 0.16*;* 70º, mean difference = -1.60Nm; 95% CI = -11.73 to 8.53; p = 0.749; *d* = 0.10*;* 90º, mean difference = 2.80Nm; 95% CI = -5.66 to 11.26; p = 0.504; *d* = 0.19).

Passive knee flexor torque and perceived muscle soreness

No significant group by time interactions were observed for the knee flexor's peak passive torque (p=0.807) or perceived muscle soreness (p=0.700). There were no significant pre-intervention differences in peak passive gravity corrected knee flexor torque (CON = 12Nm; ECC = 13Nm; mean difference = 1Nm; 95% CI = -4.74 to 6.61; p=0.737; *d*=0.29) or perceived muscle soreness (CON = 1.7; ECC = 1.5; mean difference = 0.2; 95% CI = -1.25 to 1.72; p = 0.750; *d* = 0.10). Similarly, no between group differences were observed after the training period in passive peak knee flexor torque (CON = 8Nm; ECC = 10Nm; mean difference = 2Nm, 95% CI = -1.17 to 5.37; p = 0.198 ; *d* = 0.55) or perceived muscle soreness (CON = 0.9; ECC = 0.7; mean difference = 0.1, 95% CI = -0.80 to 1.08; p = 0.766; *d* = 0.17). Twenty-four hours after sprint session 1 there were no between-group differences in passive peak torque (CON = 11Nm; ECC = 11Nm; mean difference = 0Nm, 95% CI = -6.99 to 6.72; p = 0.96; *d* = 0.01) or perceived muscle soreness (CON = 1.0; ECC = 1.3; mean difference = 0.3, 95% CI =

-1.31 to 0.75; p = 0.580; *d* = 0.23). The lack of differences between groups was also evident 48 hours post sprinting (passive peak torque; CON = 10Nm; ECC = 12Nm; mean difference = 2Nm, 95% CI = -3.48 to 7.12; p=0.485; *d*=0.28; perceived muscle soreness CON = 1.8; ECC = 1.4; mean difference = 0.4, 95% CI = -0.83 to 1.81; p = 0.643; *d* = 0.30).

Eighty-metre sprint performance

No significant between-group differences in best times were observed in the first (CON = 11.51s; ECC = 11.32s; mean difference = 0.18s; 95% CI = -0.60 to 0.98; p = 0.630; *d* = 0.07) or second sprint sessions (CON = 11.70s; ECC = 11.43s; mean difference = 0.27s; 95% CI = -0.52 to 1.07; p = 0.483; *d* = 0.27). There were no significant between-group differences in performance decrement in the first (CON = 3.01s; ECC = 2.57s; mean difference = 0.44s; 95% CI = -2.13 to 1.25; p = 0.595; *d* = 0.21) or second sprint session (CON = 1.97s; ECC = 1.93s; mean difference = 0.04s; 95% CI = -0.88 to 0.79; p = 0.910; *d* = 0.04). However, the performance decrement declined significantly between the first (2.92 ± 2.15s) and second (1.98 ± 1.12s) sprint session in the CON group (mean difference = 1.04s; 95% CI = -1.92 to -0.15, p = 0.023; *d* = 0.56) but did not change significantly between first (2.46 ± 1.65s) and second (1.93 ± 0.86s) sprint sessions in the ECC group (mean difference = 0.64s; 95% CI = -1.46 to 1.67; p = 0.114; *d* = 0.48).

Two of 15 participants from the CON group were unable to finish the second sprint session. One sustained a hamstring strain during the first sprint session and the other participant was ‘too sore’ and fearful of an injury to participate in the second sprint session. All participants from the ECC group were able to complete both sessions.

Creatine kinase

There was no significant group by time interaction found for creatine kinase ($p = 0.818$). No significant differences in the levels of CK were observed between groups before the first sprint session (CON = 177 $U \cdot L^{-1}$; ECC = 226 $U \cdot L^{-1}$; mean difference = 49 $U \cdot L^{-1}$; 95% CI = -158.31 to 59.08; $p = 0.353$; $d = 0.41$), immediately after (CON = 239 $U \cdot L^{-1}$; ECC = 327 $U \cdot L^{-1}$; mean difference = 88 $U \cdot L^{-1}$, 95% CI = -217 to 41; $p = 0.171$; $d = 0.60$), 24 hours after (CON = 951 $U \cdot L^{-1}$; ECC = 972 $U \cdot L^{-1}$; mean difference = 21 $U \cdot L^{-1}$, 95% CI = -538 to 495; $p = 0.933$; $d=0.03$) or 48 hours after (CON = 607 $U \cdot L^{-1}$; ECC = 609 $U \cdot L^{-1}$; mean difference = 2 $U \cdot L^{-1}$, 95% CI = -320 to 316; $p = 0.990$; $d = 0.00$) the first sprinting session. CK levels increased significantly after running for both the concentric (immediately after sprinting, mean = +62 $U \cdot L^{-1}$; 95% CI = 11 to 114; $p = 0.011$; $d = 0.53$; 24h post, mean = +774 $U \cdot L^{-1}$; 95% CI = 242 to 1305; $p = 0.002$; $d = 1.80$; 48h post, mean = +430 $U \cdot L^{-1}$; 95% CI = 85 to 775; $p = 0.009$; $d = 1.53$) and eccentric groups (immediately after sprinting, mean difference = 101 $U \cdot L^{-1}$; 95% CI = 55 to 146; $p<0.001$; $d = 0.67$; 24h post, mean difference = 745 $U \cdot L^{-1}$; 95% CI = 279 to 1211; $p = 0.001$; $d = 1.75$; 48h post, mean difference = 383 $U \cdot L^{-1}$; 95% CI = 80 to 685; $p = 0.008$; $d = 1.44$).

Discussion

As far as we are aware, this study is the first to investigate the effects of eccentric and concentric knee flexor conditioning on the change in running performance during or between sprint sessions. Contrary to our hypothesis and despite significant between- group differences in BF_{LH} fascicle lengths and pennation angles before sprint session 1, there were no between-group differences for sprint performance decrements or markers of muscle damage. Concentrically trained rat vastus intermedius muscles lose more force and have their force-length relationships shifted further towards longer muscle lengths than eccentrically trained muscles after a single bout of maximal electrically stimulated eccentric contractions (1). There is also evidence in humans that muscle soreness and weakness induced by eccentric contractions are elevated after periods of concentric training (27) and there is significant evidence that eccentric training has the opposite effects (13, 14, 28). These previous findings led to the hypothesis that eccentrically trained hamstrings would recover significantly better than concentrically trained muscles and that this would influence the recovery of sprint performance when two sprint sessions were performed 48 hours apart.

There are a number of possible explanations for the lack of differences between the eccentrically and concentrically trained participants in this study. Firstly, the extent of muscle soreness and the changes to indices of muscle damage (CK) were modest, although similar to that found after one study of downhill running (29). Previous studies employing maximal eccentric contractions of single muscle groups such as the elbow flexors (30) have reported blood CK levels in the region of 10000 $U \cdot L^{-1}$ and the enzyme elevations seen in the current study were only about 7% of this. This suggests only moderate muscle damage as a consequence of sprinting and whether or how much of this CK originated from the hamstrings is not known. Van Hooren and Bosch (31) have recently argued that human hamstring fascicles perform isometric rather than eccentric actions during the late swing phase of gait. This suggestion runs contrary to the results of modelling studies which suggest that the hamstrings actively lengthen in late swing (32, 33), however, the low CK and soreness levels reported after sprinting do suggest limited exposure to eccentric actions to which the concentrically trained participants were unaccustomed. The relatively low sprint training status of the sampled participants may have also contributed to the high variability in performance, thereby masking any effects of hamstring conditioning. Future studies may benefit from recruiting more highly trained participants or including regular sprint sessions within the training program. The degree of hip flexion during the passive knee flexor torque assessment was less than that in a previous report (23) which may be the reason no between-group differences were found for peak passive torque or perceived muscle soreness.

Despite no group differences in the measures muscle damage, two participants from the CON group were unable to finish the second sprint session due to one hamstring strain injury in the first repetition of the second session and one withdrawal due to severe hamstring soreness after the first sprint session. These incidents suggest, for at least two of the participants from the CON group, that there may have been substantial microtrauma caused by high-speed running in the first session that had not completely recovered after 48 h. Furthermore, the injured participant had the shortest biceps femoris fascicles after training and it is possible that other participants experienced less muscle damage because their fascicles, although shortened by concentric training, were sufficiently long to minimise muscle damage.

This study provides further evidence that BF_{LH} fascicle lengths and pennation angles respond differently to eccentric and concentric training (2). Fascicle lengthening, consequent to the addition of in-series sarcomeres, is expected to reduce the strain experienced per sarcomere at any given muscle length and thereby reduce the risk of muscle strain injury (12-14, 28). The torque-joint angle relationship and the joint angle at which muscles generate peak torques are proposed to shift in response to changes in muscle fascicle lengths (13), although the current results do not support this as no such shifts occurred, despite a ~2 cm fascicle length difference between groups after training.

We acknowledge that there are some other limitations to the current study. Muscle architectural change was only assessed in the BF_{LH} and these adaptations may differ between knee flexors. There is also a degree of estimation required with the measurement of fascicle length using 2D ultrasound because the entire length of the BF_{LH} fascicles is not visible in ultrasound images. While the estimation equation used in this study has been validated against cadaveric samples (19), we recognise the room for error and suggest future studies employ extended field-of-view ultrasonography to reduce this. Despite our recreationally active participants displaying similar, or higher, levels of Nordic eccentric strength compared with elite Australian Rules footballers (8) and professional soccer players (7), it remains to be seen if the sprint recovery results are applicable to other 'well-trained' populations.

This is the first study to show that concentric and eccentric knee flexor training do not have different effects on decrements in sprint performance when two sprint training sessions are held 48 h apart.

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Figure Captions

Figure 1 – Methods timeline.

Figure 2 – (top) Pre and post intervention individual and mean changes in bicep femoris long head fascicle lengths; (middle) pennation angles.; (bottom) and muscle thickness. CON = green squares; ECC = red circles. The dashed red line represents the ECC group average and the green line shows the CON group average. Shaded areas represent 95% CI.

Figure 3 – Pre and post intervention individual and mean changes in Nordic eccentric strength. CON = green squares; ECC = red circles. Dashed red line represents the ECC group average and the green line shows the CON group average. Shaded areas represent 95% CI.