The Effect of Eccentric or Isometric Training on Strength, Architecture, and Sprinting across an Australian Football Season

RYAN G. TIMMINS[1,2], DEAN FILOPOULOS[3], JAKE GIANNAKIS[3], VICTOR NGUYEN[3], JOSHUA D. RUDDY[1], JACK T. HICKEY[1,2], NIRAV MANIAR[1,2], CHRISTOPHER W. POLLARD[1], NICHOLAS MORGAN[1,3], JONATHON WEAKLEY[1,2,4], and DAVID A. OPAR[1,2]

[1]School of Behavioural and Health Sciences, Australian Catholic University, Fitzroy, Victoria, AUSTRALIA; [2]Sports Performance, Recovery, Injury and New Technologies (SPRINT) Research Centre, Australian Catholic University, Fitzroy, Victoria, AUSTRALIA; [3]Strength and Conditioning Department, Collingwood Football Club, Melbourne, Victoria, AUSTRALIA; and [4]Carnegie Applied Rugby Research (CARR) Centre, Institute of Sport, Physical Activity and Leisure, Leeds Beckett University, Leeds, UNITED KINGDOM

ABSTRACT

TIMMINS, R. G., D. FILOPOULOS, J. GIANNAKIS, V. NGUYEN, J. D. RUDDY, J. T. HICKEY, N. MANIAR, C. W. POLLARD, N. MORGAN, J. WEAKLEY, and D. A. OPAR. The Effect of Eccentric or Isometric Training on Strength, Architecture, and Sprinting across an Australian Football Season. *Med. Sci. Sports Exerc.*, Vol. 56, No. 3, pp. 564–574, 2024. **Purpose:** This study aimed to investigate the effect of an isometric (ISO) or Nordic hamstring exercise (NHE) intervention, alongside a sprint training program on hamstring strength, architecture, and sprinting performance in Australian footballers. **Methods:** Twenty-five male athletes undertook NHE (n = 13) or ISO (n = 12) training across a 38-wk period (including preseason and in season). Biceps femoris long head (BFlh) architecture, ISO, and eccentric knee flexor strength were assessed at baseline, at the end of preseason (14 wk), and at the conclusion of the intervention. Sprint times and force–velocity profiles were determined at baseline and at the end of preseason. **Results:** After the intervention, both groups had significant improvements in BFlh fascicle length (NHE: 1.16 cm, 95% CI = 0.68 to 1.63 cm, d = 1.88, P < 0.001; ISO: 0.82 cm, 95% CI = 0.57 to 1.06 cm, d = 1.70, P < 0.001), muscle thickness (NHE: 0.11 cm, 95% CI = 0.01 to 0.21 cm, d = 0.51, P = 0.032; ISO: 0.21 cm, 95% CI = 0.10 to 0.32 cm, d = 0.86, P = 0.002), and eccentric strength (NHE: 83 N, 95% CI = 53 to 114 N, d = 1.79, P < 0.001; ISO: 83 N, 95% CI = 17 to 151 N, d = 1.17, P = 0.018). Both groups also finished the intervention weaker isometrically than they started (NHE: −45 N, 95% CI = −81 to −8 N, d = −1.03, P = 0.022; ISO: −80 N, 95% CI = −104 to −56 N, d = −3.35, P < 0.001). At the end of preseason, the NHE group had improved their 5-m sprint time by 3.3% ± 2.0%), and their maximum horizontal velocity was 3% ± 2.1% greater than the ISO group who saw no changes. **Conclusions:** Both ISO and NHE training with a periodized sprinting program can increase BFlh fascicle length, thickness, and eccentric strength in Australian footballers. NHE training also improves 5-m sprint time and maximum velocity. However, both interventions reduced ISO strength. These findings provide unique, contextually relevant insights into the adaptations possible in semiprofessional athletes.
Key Words: SKELETAL MUSCLE INJURY AND REPAIR, INJURY PREVENTION

Hamstring strain injuries (HSI) remain the most common cause of time lost from competition in field-based team sports (1), such as Australian Rules Football (ARF) (2). Athletes are required to perform regular sprinting efforts during ARF competition (3), which likely elevates the risk of an HSI occurring, because of the biomechanical demands placed on the hamstrings (4). Rather than stopping athletes from sprinting, researchers and practitioners aim to identify interventions that address modifiable variables associated with HSI risk, such as hamstring muscle architecture and strength (5–8). It is important to consider the effect that these interventions have on sprint acceleration performance, given this is a key requirement of ARF and many other field-based team sports.

Including the Nordic hamstring exercise (NHE) as part of a training program reduces HSI risk in athletes (9,10). This risk reductive effect may be driven by increases in biceps femoris long head (BFlh) fascicle length and eccentric knee flexor strength noted after NHE interventions (11–13). The NHE has also been shown to result in improvements in sprinting performance (11,14). Despite these apparent benefits, the NHE is still not widely implemented in field-based team sports (15). The lack of NHE implementation may be due to fear of muscle soreness caused by this relatively high-intensity eccentric stimulus

Address for Correspondence: Ryan G. Timmins, Ph.D., School of Behavioural and Health Sciences, Australian Catholic University, 1100 Nudgee Road, Banyo, 4014, Brisbane, Queensland, Australia; E-mail: Ryan.Timmins@acu.edu.au.
Submitted for publication April 2023.
Accepted for publication October 2023.
Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.acsm-msse.org).

0195-9131/24/5603-0564/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000003326

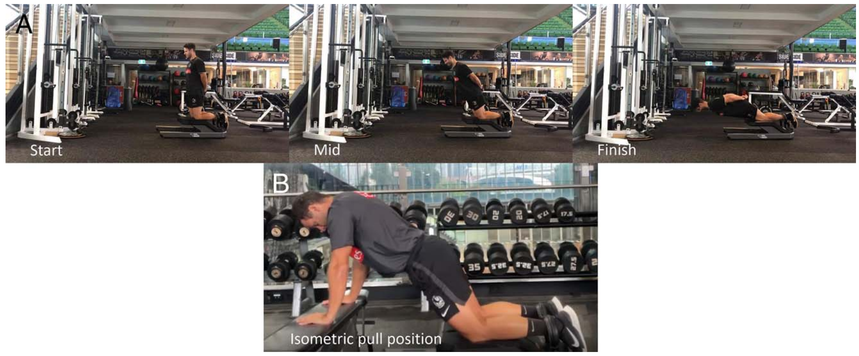

FIGURE 1—Examples of the exercises prescribed for either the NHE group (A) or the isometric group (B).

(16), which has led to interest in isometric hamstring exercises interventions.

Despite interest in isometric hamstring exercises, there has been limited research into the potential benefits of these interventions on HSI risk factors and sprint performance. One study found that an isometric hip extension exercise leads to greater improvements in the single-leg hamstring bridge to fatigue test compared with the NHE (17). However, the single-leg hamstring bridge to fatigue test is not a valid measure of hamstring strength (18), and this study did not investigate sprinting performance or muscle architecture. In a more recent study (19), an isometric hip extension exercise was shown to improve isometric hamstring strength but failed to significantly change BFlh fascicle length. However, this study did not assess sprinting performance, and participants were recreationally active, which highlights the need for further research into the effect of isometric hamstring exercise interventions on HSI risk factors and sprinting performance in athletes.

The aim of this study was to compare the effect of an isometric knee flexion exercise intervention to an NHE intervention on hamstring muscle architecture, strength, and sprinting performance in semiprofessional ARF athletes across a competitive season.

METHODS

Participants

This interventional cohort trial was undertaken across the preseason and in-season period of the Victorian Football League (VFL) competition. The VFL is a second tier, semiprofessional ARF competition. Ethical approval for the study was granted by the Australian Catholic University Human Research Ethics Committee (approval no. 2019-129E). All athletes from a single VFL team were invited to participate and provide written, informed consent. In total, 25 male athletes (age = 22 ± 3 yr, height = 1.85 ± 0.07 m, body mass = 81.3 ± 6.7kg) were recruited and consented to participating.

Study Design

Before the commencement of the intervention, all participants undertook a familiarization session with the NHE (Fig. 1, Supplemental Video 1, Supplemental Digital Content 1, https://kmc.kaltura.com/index.php/kmcng/content/entries/entry/1_84xgjrlg/metadata), the isometric knee flexion hold (ISO; Fig. 1, Supplemental Video 2, Supplemental Digital Content 2, https://kmc.kaltura.com/index.php/kmcng/content/entries/entry/1_yr9pf8jq/metadata), and all testing methods. After the familiarization session (median = 5, range 5–7 d), all participants had the following baseline measures assessed:

1. BFlh architecture
2. Maximal eccentric knee flexor strength during the NHE
3. Maximal isometric knee flexor strength with 90° of hip and knee flexion (90/90) (20)
4. 40-m sprint performance with splits at 5, 10, 20, 30 and 40 m
   a. With force–velocity profiles subsequently determined (21)

After these baseline assessments, participants were allocated into either the NHE group (n = 13) or the ISO group (n = 12). Participants in each intervention group only performed the one hamstring-specific resistance training exercise for the entire preseason and in-season period. Additionally, all participants performed periodized sprinting as part of their on-field football-specific training sessions, with the prescribed intensity and volume matched between the groups (Fig. 2, Supplemental Tables 1a–1c, Supplemental Digital Content 3, http://links.lww.com/MSS/C934, The actual versus planned weekly sprint distance (in meters), sprint efforts, and velocities undertaken at ≥25 km·h^{-1} for the sprinting intervention, and The actual versus planned weekly sprint efforts undertaken at ≥25 km·h^{-1} for the sprinting intervention). All resistance and sprint training sessions were undertaken with supervision from the members of research team, as part of their roles in the strength and conditioning department of the football club (D.F., V.N., J.G., and N.Mo.). All participants undertook an initial 6 wk of training after which there was a 4-wk break for the Christmas holiday period. Over these 4 wk, the participants were specifically instructed to refrain from resistance and sprint training. After the holiday period, there was an additional 8 wk of training in the preseason period (November to March, total of 14 wk; Fig. 2). The subsequent in-season training period occurred over the remaining 24 wk between March and August.

Architectural assessments of the BFlh using two-dimensional ultrasound were completed at baseline and after 14 wk (end of

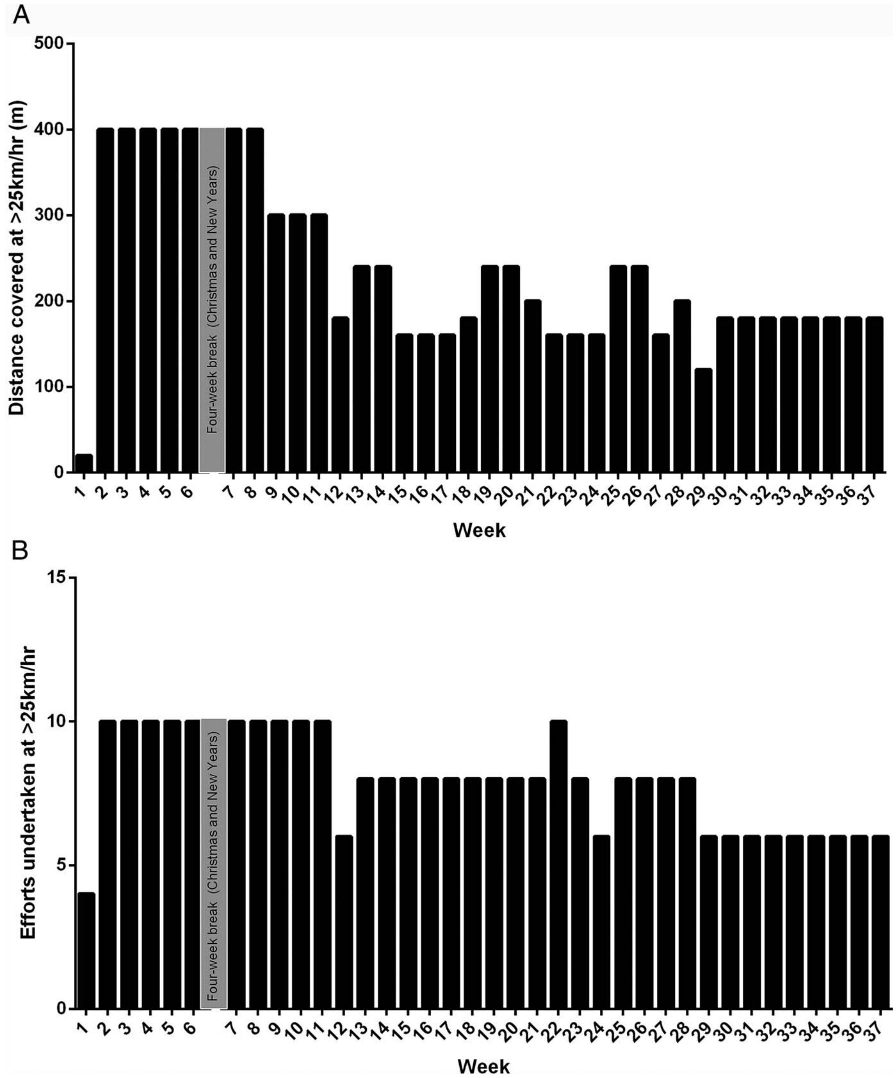

FIGURE 2—An overview of the sprinting distance (A) and efforts (B) prescribed across the intervention period.

preseason) as well as at the end of the intervention (38 wk). Both strength assessments (NHE and 90/90) were undertaken at baseline, after 14 (end of preseason) and 29 wk, and at the end of the intervention (38 wk). The maximal sprinting assessment was undertaken at baseline and after 14 wk of training (end of preseason). During all on-field sessions (sprint training, football-specific match, and competitive match), GPS (OptimEye S5, 10 Hz; Catapult Sports, Melbourne, Australia) data were used to monitor the external load metrics of each group. These metrics included total distance covered, efforts undertaken at >25 $km \cdot h^{-1}$, distance covered at >25 $km \cdot h^{-1}$, and peak and average velocity of sprint efforts, which were made relative to each participant's maximum recorded value.

Training Intervention

As part of their weekly team resistance training sessions, all participants completed one of either the NHE or the ISO hold exercises. During the training intervention, all participants also undertook a periodized sprint training intervention (Fig. 2) before their on-field football-specific sessions. The frequency of both the sprinting and the resistance training sessions during the in-season period depended on the match schedule, with either one or two sessions undertaken per week, with the sprinting and resistance training interventions matched between the groups. When two sessions per week (both sprinting and resistance training) were undertaken, these were completed on nonconsecutive days of the week (typically a Tuesday and Thursday with a Saturday match). The training prescription was matched for the NHE and ISO hold exercises across the entire intervention period and was two sets of four repetitions (Table 1). Both the NHE and the ISO hold exercises were undertaken for 4-s repetitions to match total time under tension between the groups.

NHE training. A video of the NHE can be found in Supplemental Video 1 (Supplemental Digital Content 1, https://kmc.kaltura.com/index.php/kmcng/content/entries/entry/1_84xgjrlg/metadata). Participants undertook the NHE with their ankles secured underneath a fixed piece of gym equipment that allowed a standardized kneeling height and position for

TABLE 1. Prescription of the Nordic and isometric training efforts for the 37-wk training period.

Exercise	Sets	Repetitions	Repetition Time	Interset Rest	Resistance
Nordic	2	4	4 s	2 min	Body weight, 5, 7.5, 10 kg[a]
Isometric	2	4	4 s	2 min	Nil[b]

[a] Additional resistance included for the NHE in a 4-wk cycle: week 1, body weight; week 2, 5 kg; week 3, 7.5 kg; week 4, 10 kg. After each cycle, participants returned to bodyweight efforts and began the cycle again. This process was followed for the entire length of the intervention period (37 wk, nine 4-wk cycles).
[b] All isometric repetitions were performed with maximal effort.

all repetitions. This was preferred to the partner held version of the NHE, where the strength of the partner may limit the effectiveness of the effort. For each repetition, participants only performed the lowering (eccentric) portion of the NHE over a 4-s period. After each repetition, participants were instructed to use their arms and flex their hips to assist themselves in returning to the starting position, avoiding any concentric contraction of the hamstrings. Once additional weight was used, the participants were required to hold weight plates totaling 5, 7.5, or 10 kg over their xiphoid process, per previous work (R.E.F.). All NHE training was preceded by a warm-up set of three submaximal, bodyweight repetitions, and after each training set, participants were afforded a 2-min rest. For all NHE training sessions across the intervention period, participants completed two sets of four repetitions, which has previously been shown as an effective dose to maintain eccentric knee flexor strength and BFlh fascicle lengths in recreational individuals (13).

Isometric hamstring training. A video of the ISO hold can be found in Supplemental Video 2 (Supplemental Digital Content 2, https://kmc.kaltura.com/index.php/kmcng/content/entries/entry/1_yr9pf8jq/metadata). Participants started in a kneeling position, with their ankles secured under a piece of gym equipment. The position was similar to the typical break point of the NHE, where their hips were slightly flexed, with a forward lean of approximately 45° at the knee and using their arms to brace the upper body on a bench placed in front of them. With the cues "hips under, quiet bum," participants were instructed to "pull up" as hard and fast as they can against the fixed gym equipment for 4 s. Before each training session, participants undertook a submaximal warm-up consisting of three ISO hold repetitions at 50%, 75%, and approximately 95% of their perceived maximum. After each training effort, participants were afforded a 30-s rest before the next attempt, with a 2-min rest between sets. For all ISO training sessions across the intervention period, participants completed two sets of four repetitions, with training time matched between the NHE and the ISO groups.

Periodized sprint training. Before all on-field football-specific training sessions, participants undertook a periodized sprint intervention for the entire study period (Supplemental Tables 1a–1c, Supplemental Digital Content 3, http://links.lww.com/MSS/C934). All sprint training was preceded by an on-field group warm-up, after which participants undertook submaximal sprinting efforts before any maximal attempts. For all the maximal efforts, participants were paired together based on their maximal sprint velocity and undertook their efforts in a race format where they were motivated to run faster than the person next to them. Across the study period, the number and distance of the sprinting exposures was periodized to provide a progressive stimulus (Fig. 2). This periodization was planned on the assumption that the participants could potentially not undertake any sprinting efforts during their football-specific sessions or matches. Therefore, should this occur, they will have still been exposed to a sprinting stimulus as part of this prescription. During all sprint training efforts ($\geq$25 km·h^{-1}), velocity was collected using GPS data (OptimEye S5, 10 Hz, Catapult Sports) and recorded as absolute and relative values. Relative velocity was determined as a percentage of each participant's maximum recorded velocity, which was updated if it increased throughout the study.

Outcome Measures

BFlh architecture. The methods to assess BFlh architecture have been previously reported (5,22,23). 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 using a two-dimensional, B-mode ultrasound (frequency, 12 MHz; depth, 8 cm; field of view, 14 × 47 mm) (GE Healthcare Vivid-*i*, Wauwatosa, WI). 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 then manipulated by the assessor (R.G.T.) whose reliability has been previously reported (23).

Once the images were collected, analysis was undertaken offline (Version 0.7.8; MicroDicom, Sofia, Bulgaria). Muscle thickness was defined as the distance between the superficial and the 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 (24,25). As the entire fascicle was not visible in the field of view of the probe, its length was estimated via the following equation (25):

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

where FL is the fascicle length, AA is the aponeurosis angle, MT is the muscle thickness, and PA is the pennation angle. Fascicle length was reported in absolute terms (cm). The extrapolation measure and equation has been validated against cadaveric BFlh tissue and is considered a robust way of estimating fascicle lengths (25). The same assessor (R.G.T.) collected and analyzed all scans and was blinded to participant identifiers during the analysis.

Eccentric knee flexor strength. The assessment of eccentric knee flexor strength during the NHE has previously been reported (26,27). Participants knelt on the device (NordBord, Vald Performance, Queensland, Australia) while an investigator

APPLIED SCIENCES

placed ankle braces superior to each lateral malleolus. While in this kneeling position, participants were required to cross their arms over their chest or position a weight plate (as required) over the xyphoid process. Once the movement commenced, participants were cued to keep their hips in a position of full extension throughout the effort. Only the eccentric phase of the NHE was completed. Participants undertook a standardized warm-up protocol consisting of one repetition at each of 50%, 75%, and 95% of their perceived maximal effort at bodyweight. After this, participants completed one set of three maximal NHE repetitions. The average of the three peak values (in newtons) during the assessment was used for the analysis.

Isometric knee flexor strength. The assessment of maximal isometric knee flexor strength used in this study has previously been reported (20), showing excellent levels of reliability (coefficient of variation ≤ 5.5%, intraclass correlation = 0.95). All assessments were undertaken with the force plates (ForceDecks FD4000, Vald Performance; sampling frequency, 1000 Hz) positioned on top of a wooden box. Participants were required to lay supine, with the heel of the limb being tested positioned on top of the force plate with the hip and knee both positioned at 90° of flexion. The nontesting limb was rested on the floor next to the wooden box and was held in place by one of the investigators. Participants were instructed to push their heel into the force plate as hard and fast as possible without lifting their hips or head off the floor. Participants undertook a standardized warm-up protocol consisting of one repetition at each of 50%, 75%, and 95% of their perceived maximal effort. After this, participants completed one set of two maximal isometric knee flexion repetitions. Each maximal effort was undertaken over a period of 3 s with a 30-s rest between contractions. The peak force value (in newtons during the assessment was used for the analysis.

Sprint assessment. Sprint performance was assessed using a 40-m overground sprint, with timing gates (SmartSpeed, Fusion Sport, Brisbane, Australia) collecting split times at 5, 10, 20, 30, and 40 m. Participants initiated the sprint themselves by maximally accelerating from a staggered standing start in line with the first timing gate. Each gate was set at a height approximate to the level of the hip when in upright stance. Each participant completed two trials, with the best 40-m attempt used for all analysis.

A custom-made Microsoft Excel spreadsheet derived from the work of Samozino et al. (21) was used to determine the theoretical maximal horizontal force (F_0) and velocity (V_0) using the data obtained during the sprint assessment. These values were determined using the quickest sprint test, its associated split times, and the body mass of the participant. Using the spreadsheet, any calculations where the squared difference (e.g., the difference between the experimental and the estimated values) was >0.1 were excluded from further analyses. The maximal horizontal force and velocity outputs were reported as newton-kilogram and meters per second, respectively.

Statistical Analysis

All statistical analyses were performed using the R statistical programming language and the following packages: dplyr, lme4, and car (28). Where appropriate, data were screened for normal distribution using the Shapiro–Wilk test. Linear mixed models were fitted and used to assess changes in each of the outcome variables across the study period as well as comparing the sprinting loads between groups. For each outcome variable, covariates were group (NHE or ISO) and time, with participant ID included as a random effect. For BFlh architecture, eccentric, and isometric knee flexor strength, the left and right limbs were averaged as they did not differ at any time point. Where significant main or interaction effects were detected, *post hoc t*-tests were used to determine where any differences occurred. Significance was set at $P < 0.05$, and where possible, Cohen's d was reported for the effect size of the comparisons, with the levels of effect being deemed small ($d = 0.20$ to 0.49), medium ($d = 0.50$ to 0.79), or large ($d \geq 0.80$). All data were expressed as mean ± SD, unless otherwise stated.

Power Calculation

Power analysis was undertaken *a priori* using G-Power (29). The effect size estimates used in the analysis were based on the estimated changes in BFlh fascicle length after a similar NHE training intervention (30). In this previous study, fascicle length changes had an effect size of 2.8. Considering we used a lower volume and intensity prescription of the NHE in this intervention, a conservative effect size of 1.4 was deemed a reasonable starting point. Power was set at 95%, with an alpha of 0.05 returning a calculated minimum sample of 12 per group.

RESULTS

Participant Details and Intervention Compliance

The two groups were similar with respect to height and body mass (NHE height = 183 ± 8 cm, body mass = 79.5 ± 7.2 kg; ISO height = 185 ± 6 cm, body mass = 83.4 ± 5.6 kg; height $P = 0.445$, body mass $P = 0.152$). However, on average, the ISO group (24 ± 3 yr) was older than the NHE cohort (21 ± 2 yr, $P = 0.02$). Of the 76 total resistance training sessions, the NHE group had an average compliance of 81% ± 15% (range, 41 to 76 sessions completed). The ISO group had a similar level of compliance with 78% ± 14% (range, 40 to 76 sessions completed).

External Load Metrics

There were no significant differences between the groups, at any of the weeks throughout the intervention when comparing the number of weekly sprinting efforts (P range across all weeks = 0.231 to 0.982) and distance covered ≥25 $km \cdot h^{-1}$ (P range across all weeks = 0.203 to 0.986), as well as the average relative velocity of these sprinting efforts ≥25 $km \cdot h^{-1}$ (P range across all weeks = 0.161 to 0.998).

BFlh Architectural Characteristics

A summary of the BFlh architectural variables during this intervention can be found in Figure 3 and Supplemental Table 2a (Supplemental Digital Content 3, http://links.lww.com/MSS/C934).

APPLIED SCIENCES

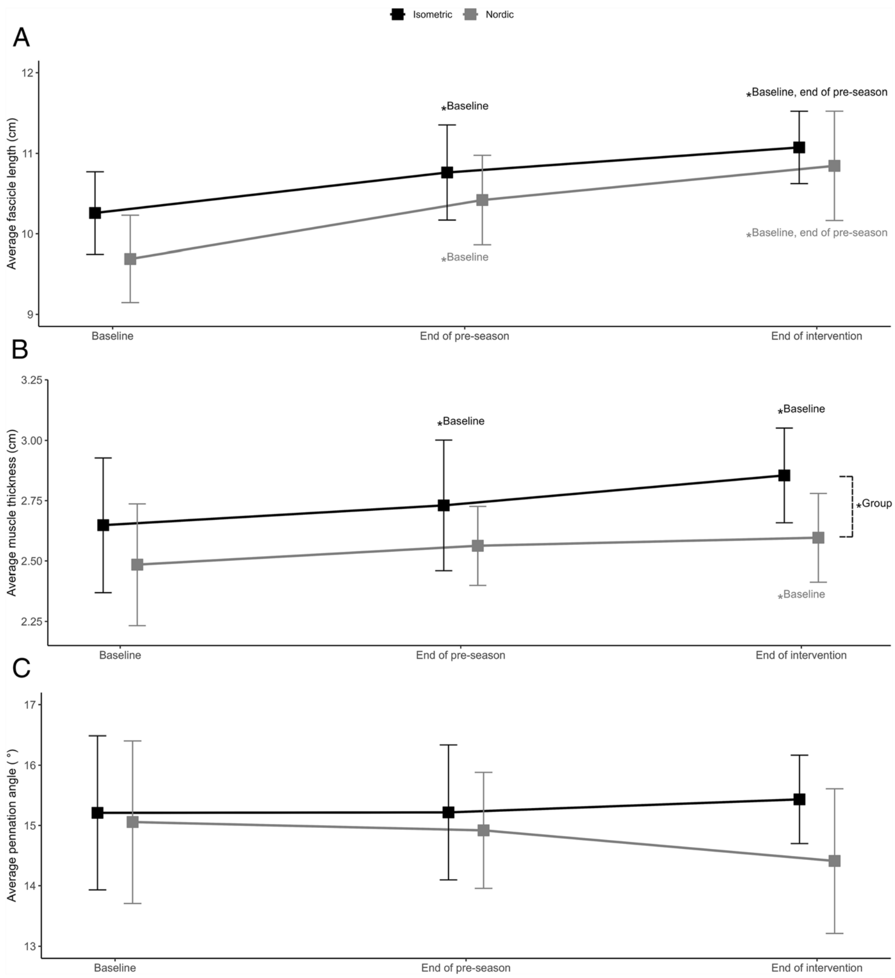

FIGURE 3—Architectural measures of the BFlh at baseline, at the end of preseason, and the end of the intervention. Fascicle length (A), muscle thickness (B), pennation angle (C). Significant differences ($P < 0.05$) within each group as well as between groups are indicated on each panel.

Fascicle length. There was a significant main effect for time ($P < 0.001$), but not for group ($P = 0.081$), on BFlh fascicle length. Both the NHE and the ISO groups had a significant increase in fascicle length from the baseline to the end of preseason (NHE group: difference = 0.73 cm, 95% CI = 0.53 to 0.94 cm, d = 1.33, $P < 0.001$; ISO group: difference = 0.51 cm, 95% CI = 0.34 to 0.67 cm, d = 0.92, $P < 0.001$). At the end of the intervention, both groups saw a further significant increase in fascicle length compared with the end of preseason (NHE group: difference = 0.42 cm, 95% CI = 0.03 to 0.88 cm, d = 0.68, $P = 0.038$; ISO group: difference = 0.31 cm, 95% CI = 0.05 to 0.57 cm, d = 0.59, $P = 0.021$). These changes were also significantly increased when compared with baseline measures for both groups (NHE group: difference = 1.15 cm, 95% CI = 0.68 to 1.63 cm, d = 1.88, $P < 0.001$; ISO group: difference = 0.81 cm, 95% CI = 0.58 to 1.06 cm, d = 0.81, $P < 0.001$). The NHE group had significantly shorter fascicles than the ISO group at baseline (difference = 0.57 cm, 95% CI = 0.13 to 1.01 cm, d = 1.07, $P = 0.013$), but there were no differences at the other time points (d range = 0.39 to 0.59, P range = 0.151 to 0.322).

Muscle thickness. BFlh muscle thickness showed a significant main effect for group ($P = 0.013$) and time ($P < 0.001$). *Post hoc* analysis indicated that both groups demonstrated a significant increase in muscle thickness from the baseline to the end of the intervention (NHE: difference = 0.11 cm, 95% CI = 0.01 to 0.21 cm, d = 0.51, $P = 0.032$; ISO: difference = 0.21 cm, 95% CI = 0.10 to 0.32 cm, d = 0.86, $P = 0.002$). However, only the ISO group demonstrated a significant increase when compared with the end of preseason (difference = 0.13 cm, 95% CI = 0.01 to 0.25 cm, d = 0.52, $P = 0.048$), whereas the NHE group did not (difference = 0.03 cm, 95% CI = −0.03 to 0.11 cm, d = 0.19, $P = 0.332$). Between-group comparisons showed that the ISO group had a significantly thicker muscle than the NHE group at the end of the intervention (difference = 0.26 cm, 95% CI = 0.10 to 0.42 cm, d = 1.37, $P = 0.002$), but there were no differences at other time points.

Pennation angle. There were no significant main effects for group ($P = 0.188$) or time ($P = 0.471$) found for BFlh pennation angle. Therefore, no *post hoc* analyses were undertaken.

APPLIED SCIENCES

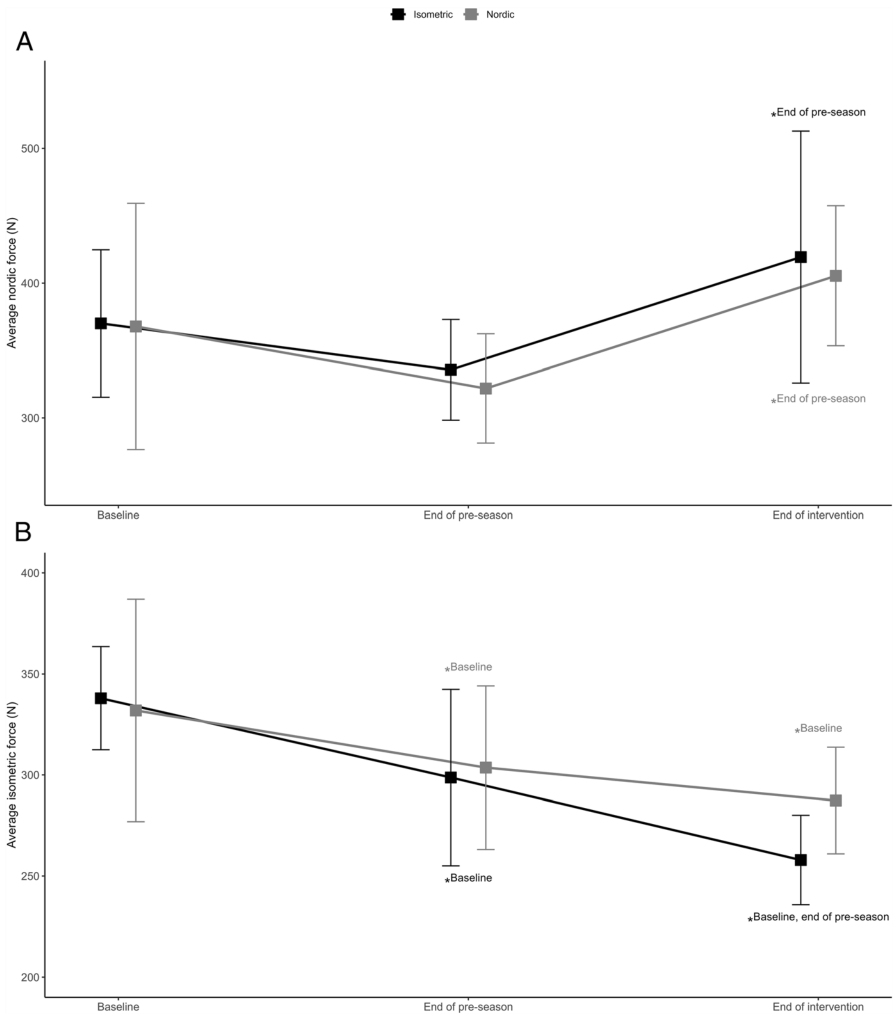

FIGURE 4—Eccentric (A) and isometric (B) measures of knee flexor strength at baseline, at the end of preseason, and the end of the intervention. Significant differences ($P < 0.05$) within each group are indicated on each panel.

Eccentric Knee Flexor Strength

A significant main effect for time ($P < 0.001$) but not group ($P = 0.503$) was found for eccentric knee flexor strength. *Post hoc* analyses showed a significant increase in eccentric knee flexor strength at the end of the intervention when compared with the end of preseason for both groups (NHE: 83 N, 95% CI = 53 to 114 N, $d = 1.79$, $P < 0.001$; ISO: 83 N, 95% CI = 17 to 151 N, $d = 1.17$, $P = 0.018$; Fig. 4 and Supplemental Table 2b, Supplemental Digital Content 3, http://links.lww.com/MSS/C934). There were no differences between groups at any time point (d range = 0.02 to 0.35, P range = 0.384 to 0.940).

Isometric Knee Flexor Strength

A significant main effect for time ($P < 0.001$) but not group ($P = 0.340$) was found for isometric knee flexor strength. *Post hoc* analyses showed a significant decrease in isometric knee flexor strength from the baseline to the end of preseason for both groups (NHE: −28 N, 95% CI = −51 to −5 N, $d = -0.58$, $P = 0.020$; ISO: −39 N, 95% CI = −65 to −13 N, $d = -1.10$, $P < 0.001$; Fig. 4 and Supplemental Table 2b, Supplemental Digital Content 3, http://links.lww.com/MSS/C934). These reductions persisted through the intervention for both groups (NHE: −45 N, 95% CI = −81 to −8 N, $d = -1.03$, $P = 0.022$; ISO: −80 N, 95% CI = −104 to −56 N, $d = -3.35$, $P < 0.001$), with only the ISO group getting weaker during the in-season period (difference in NHE: −16 N, 95% CI = −46 to 16 N, $d = -0.47$, $P = 0.268$; difference in ISO: −41 N, 95% CI = −74 to −8 N, $d = -1.18$, $P = 0.019$). The NHE group was stronger isometrically than the ISO group at the end of the intervention (difference = 29 N, 95% CI = 9 to 49 N, $d = 1.20$, $P = 0.006$).

Sprint Assessment

Split results. A significant main effect for time ($P = 0.003$) but not group ($P = 0.619$) was found for the 5-m split times. *Post hoc* analyses showed a significant decrease in the 5-m split times (i.e., improved performance) from the baseline to the end of the preseason period in the NHE group only (NHE: −0.037 s, 95% CI = −0.681 to −0.014 s, $d = -0.83$, $P = 0.043$; ISO: −0.021 N, 95% CI = −0.693 to 0.010, $d = -0.82$, $P = 0.056$; Fig. 5 and Supplemental Table 2c, Supplemental Digital

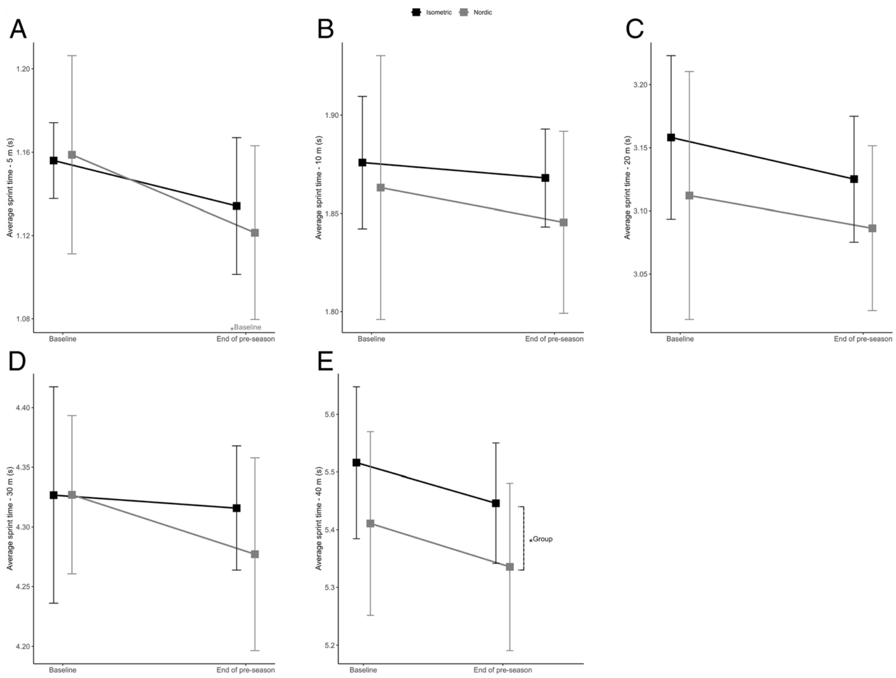

FIGURE 5—Sprint assessment splits of 5 (A), 10 (B), 20 (C), 30 (D), and 40 m during testing at baseline and the end of preseason. Significant differences (*P* < 0.05) within each group as well as between groups are indicated on each panel.

Content 3, http://links.lww.com/MSS/C934). There were no differences in the 5-m split times at any time point when comparing between the groups (*d* range = −0.07 to 0.72 and *P* range = 0.102 to 0.876).

A significant main effect for group ($P = 0.009$) and time ($P = 0.023$) was also found for the 40-m sprint performance. *Post hoc* analyses found that the NHE group was significantly faster over 40 m when compared with the ISO group at the end of preseason (difference = 0.110 s, 95% CI = 0.006 to 0.214 s, $d = 0.87$, $P = 0.039$). There were no other significant within- or between-group changes in the 40-m sprint performance (*d* range = 0.03 to 0.72, *P* range = 0.085 to 0.993).

Horizontal force–velocity profile. A significant main effect for group ($P = 0.007$) and time ($P = 0.021$) was found for maximal horizontal velocity. *Post hoc* analyses found that the NHE group had a significantly greater horizontal velocity than the ISO group at the end of preseason (difference = 0.26 $m{\cdot}s^{-1}$, 95% CI = 0.01 to 0.51 $m{\cdot}s^{-1}$, $d = 0.82$, $P = 0.049$; Supplemental Table 3, Supplemental Digital Content 3, http://links.lww.com/MSS/C934). There were no other significant within- or between-group changes in horizontal force–velocity profiles (*d* range = 0.06 to 0.82, *P* range = 0.057 to 0.876).

DISCUSSION

This is the first study to investigate the effect of a long-term (38 wk) NHE or isometric knee flexor training intervention, alongside a periodized sprinting program, on BFlh architecture, strength, and sprinting performance in ARF athletes. The novel findings of this study are as follows:

1. Undertaking an NHE or isometric knee flexor training intervention, alongside a periodized sprinting program, significantly improves BFlh fascicle length and muscle thickness across 38 wk.
2. Both interventions also significantly increase eccentric strength across the in-season period, with no alterations during preseason.
3. Isometric knee flexor strength significantly reduced at the end of both the preseason for both groups, with the ISO group getting weaker in season.
4. Undertaking NHE training, alongside a periodized sprinting program, across a 14-wk preseason period can significantly improve the 5-m split time.
5. An NHE intervention, alongside a periodized sprinting program, can significantly improve maximal sprinting velocity over 40 m when compared with an ISO training intervention after a 14-wk preseason period.

This is the first study to prescribe a single-mode hamstring-specific exercise intervention, alongside a periodized sprinting program, in semiprofessional competitive athletes. Previous research in this area is limited with its application to athletic populations as it has either implemented a single-exercise intervention in recreationally active participants (12,13,19,31) or has not controlled and prescribed a periodized sprinting program as part of the training prescription (11). The key inclusion of the periodized sprinting program alongside a single-mode hamstring-specific exercise intervention in this study allows for a more holistic and translatable set of findings as it shows the outcomes when both are prescribed together, which is commonplace in applied settings.

Elite ARF athletes who possess short BFlh fascicles are more likely to suffer an HSI than those who have longer fascicles (7). In a similar elite ARF cohort, possessing low levels of eccentric knee flexor strength has also been shown to increase the likelihood of an HSI occurring (32), although this is not a consistent finding (6,7,33). Although it is unknown if modifications in these variables are associated with a change in the risk of HSI occurring, those who undertook the NHE intervention in the current study saw a 1.15-cm (11%) and a 38-N (9%) increase in fascicle length and eccentric strength across the study, respectively. Similarly, the ISO training group saw a 0.82-cm (7%) and a 49-N (12%) increase in both fascicle length and eccentric strength, respectively. The findings for the ISO training group in the current study are the first to show that it is possible to increase BFlh fascicle length and eccentric strength while undertaking a period of isometric training. However, the current study does differ compared with previous isometric hamstring training studies (17,19). All previous interventions have been undertaken using a single-exercise approach (17,19), whereas the current study includes a periodized sprinting program, which was undertaken alongside the resistance training stimuli. As the BFlh is hypothesized to undergo significant lengthening during sprinting (4), it is possible that the inclusion of the periodized sprinting program may have contributed to the increases in BFlh fascicle length and eccentric strength for both groups. There is also some evidence to support the idea that sprint training alone is capable of increasing BFlh fascicle lengths (34). When considering these findings alongside the prospective risk factor evidence for BFlh fascicle length and eccentric strength, it is possible that completing NHE or ISO exercise alongside a periodized sprinting program may have a beneficial effect on HSI risk mitigation, although this would require further investigation.

Muscle thickness of the BFlh was significantly increased after the preseason period in both groups. This is the first evidence that isometric training interventions can improve muscle thickness in the BFlh (19), whereas NHE interventions have previously been shown to increase muscle thickness (13,34). Similar to the fascicle length improvements in the ISO group, the inclusion of a sprint training stimulus in the current study may have contributed to these improvements as a period of sprint only training has been shown to increase BFlh muscle thickness (34). These results suggest that training programs aiming at improving muscle thickness and fascicle length of the BFlh could include either an eccentric or isometric resistance training stimuli alongside a periodized sprinting program.

We found a significant reduction in isometric knee flexor strength for both groups at the end of the intervention. An assessment of isometric knee flexor strength was included in the current study to assist in the detection of any contraction mode–specific adaptations to the two divergent training interventions. However, there are several factors that may need to be considered when interpreting these findings. It has been previously shown that there is a joint-angle specificity for adaptations after isometric training interventions (35). As such in the ISO group, the difference in joint position between the isometric strength testing (90° hip and knee flexion) and the training stimuli (approximately 45° at the knee and a neutral hip) may have led to the reductions seen. The isometric strength testing position used in this study has been previously shown as reliable when implemented in athletic populations (20). Previous evidence has found no association between isometric strength and HSI risk (8); however, this assessment of isometric knee flexor strength is regularly used as part of screening batteries to track athlete recovery (36) and training management as required (37). Considering the joint-angle specificity of isometric training adaptations (35), it is possible that if we had tested isometric knee flexor strength in the joint positions where it was trained, we may have seen significant improvements in the ISO group. However, the assessment of isometric knee flexor strength was chosen because of its proven reliability and its capacity to allow a greater throughput when assessing individuals in an applied setting. Conversely, undertaking a period of eccentric training has been shown to improve eccentric but not isometric strength (19). Therefore, although the testing position may have affected the ability to see significant increases in the ISO group, in the NHE group, it may be a case of a contraction mode–specific adaptation leading to the current findings. Considering these findings alongside the methodological intricacies of the current study, future research should consider measuring isometric strength at various joint positions in athletic cohorts to determine if there is a joint-angle specificity to the adaptations seen after a period of isometric training.

In ARF, the evolution of the game has resulted in a significant increase of the number of short-distance sprinting efforts (3). As a result, high-performance programs aim to improve acceleration capacity (5-m sprint performance) more than longer distance sprinting efforts (e.g., over 30 m) (38). In the current study, at the end of preseason, the NHE group had significantly improved their 5-m split time by 3.3%. To contextualize these findings in a sporting context, an average participant from the NHE group may gain an extra 15- to 20-cm advantage across 5 m when competing against an ISO group participant. In addition to this, the NHE group also possessed a greater maximum velocity than the ISO group at the end of the preseason. In ARF, this improvement may be crucial to improving an athlete's ability to best their opponent during contests (3). The improvement in a performance metric such as the 5-m split time may also assist the "buy-in" and implementation of an exercise-based injury prevention strategy in a high-performance setting where the balance between performance and prevention is a key component of the role (39).

There are limitations in the current study. The measurement of fascicle length from the BFlh is an estimation made using an equation validated in comparison with cadaveric data (24,25). This estimation is required because of the small field of view being unable to capture the entire fascicle. This methodology was chosen because the fascicle length measures using it have been prospectively associated injury (8). This technique has also been shown to be reliable and has a high level of agreement with cadaveric samples (25). Minimal clinical importance difference values for the architectural or strength measures were not determined as no previous interventions have directly investigated whether changes in fascicle length or eccentric strength are associated with a reduction in injury incidence. Finally, there was no control group, and as such, we were unable to determine the effect that ARF or sprint training alone would have on the outcome measures. However, this is the first study to prescribe a periodized sprinting program alongside a single-exercise intervention to ensure that as much of the stimuli related to hamstring adaptation were controlled.

CONCLUSIONS

In conclusion, undertaking an NHE or isometric knee flexor training intervention alongside a periodized sprinting program appears to improve fascicle length, muscle thickness, and eccentric knee flexor strength in ARF athletes. However, isometric knee flexor strength appears to decline with either intervention, although this could be due to joint-angle or contraction mode–specific adaptations. Additionally, undertaking an NHE training intervention, alongside a periodized sprinting program, significantly improves acceleration capacity and maximum velocity. These findings provide unique, contextually relevant insights into the adaptations that may be possible in trained athletes.

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

A coauthor of this paper, Associate Professor David Opar, is listed as a coinventor on a patent, filed by the Queensland University of Technology (QUT), for a field-testing device of eccentric hamstring strength, which is now known commercially as the NordBord. Associate Professor Opar has received revenue distributions from QUT based on the revenue that QUT has generated through the commercialization of his intellectual property. He is a minority shareholder in Vald Performance Pty Ltd., the company responsible for commercialization of the NordBord and ForceDecks, among other devices. He has received research funding from Vald Performance, for work unrelated to the current manuscript. He was previously the chair of the Vald Performance Research Committee, a role that was unpaid. He has family members who are minor shareholders and/or employees of Vald Performance.

The coauthors of this paper, Christopher Pollard and Joshua Ruddy, were previously employed with Vald Performance who manufacture the Nordbord and ForceDecks used in this study. However, neither were employed by Vald Performance at the time of completing this study.

REFERENCES

1. Maniar N, Carmichael DS, Hickey JT, et al. Incidence and prevalence of hamstring injuries in field-based team sports: a systematic review and meta-analysis of 5952 injuries from over 7 million exposure hours. *Br J Sports Med*. 2023;57(2):109–16.
2. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. *Am J Sports Med*. 2013;41(4):734–41.
3. Johnston RD, Murray NB, Austin DJ, Duthie G. Peak movement and technical demands of professional Australian football competition. *J Strength Cond Res*. 2021;35(10):2818–23.
4. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. *Med Sci Sports Exerc*. 2011;43(3):525–32.
5. Lee Dow C, Timmins RG, Ruddy JD, et al. Prediction of hamstring injuries in Australian football using biceps femoris architectural risk factors derived from soccer. *Am J Sports Med*. 2021;49(13):3687–95.
6. Opar DA, Timmins RG, Behan FP, et al. Is pre-season eccentric strength testing during the Nordic hamstring exercise associated with future hamstring strain injury? A systematic review and meta-analysis. *Sports Med*. 2021;51(9):1935–45.
7. Opar DA, Ruddy JD, Williams MD, et al. Screening hamstring injury risk factors multiple times in a season does not improve the identification of future injury risk. *Med Sci Sports Exerc*. 2022;54(2):321–9.
8. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. 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):1524–35.
9. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2019;53(21):1362–70.
10. Hu C, Du Z, Tao M, Song Y. Effects of different hamstring eccentric exercise programs on preventing lower extremity injuries: a systematic review and meta-analysis. *Int J Environ Res Public Health*. 2023;20(3):2057.
11. Timmins RG, Filopoulos D, Nguyen V, et al. Sprinting, strength, and architectural adaptations following hamstring training in Australian footballers. *Scand J Med Sci Sports*. 2021;31(6):1276–89.
12. Pollard CW, Opar DA, Williams MD, Bourne MN, Timmins RG. Razor hamstring curl and Nordic hamstring exercise architectural adaptations: impact of exercise selection and intensity. *Scand J Med Sci Sports*. 2019;29(5):706–15.
13. Behan FP, Vermeulen R, Whiteley R, Timmins RG, Ruddy JD, Opar DA. The dose-response of the Nordic hamstring exercise on biceps femoris architecture and eccentric knee flexor strength: a randomized interventional trial. *Int J Sports Physiol Perform*. 2022;17(4):646–54.
14. Ishoi L, Holmich P, Aagaard P, Thorborg K, Bandholm T, Serner A. Effects of the Nordic hamstring exercise on sprint capacity in male football players: a randomized controlled trial. *J Sports Sci*. 2018;36(14):1663–72.
15. Ekstrand J, Bengtsson H, Walden M, Davison M, Hagglund M. Still poorly adopted in male professional football: but teams that used the Nordic hamstring exercise in team training had fewer hamstring injuries—a retrospective survey of 17 teams of the UEFA elite Club injury study during the 2020-2021 season. *BMJ Open Sport Exerc Med*. 2022;8(3):e001368.
16. Behan FP, Opar DA, Vermeulen R, Timmins RG, Whiteley R. The dose-response of pain throughout a Nordic hamstring exercise intervention. *Scand J Med Sci Sports*. 2023;33(4):542–6.
17. Macdonald B, O'Neill J, Pollock N, Van Hooren B. Single-leg Roman chair hold is more effective than the Nordic hamstring curl in improving hamstring strength-endurance in Gaelic footballers with previous hamstring injury. *J Strength Cond Res*. 2019;33(12):3302–8.
18. Gasparin GB, Ribeiro-Alvares JBA, Baroni BM. Single leg bridge test is not a valid clinical tool to assess maximum hamstring strength. *Int J Sports Phys Ther*. 2022;17(4):613–21.
19. Carmichael DS, Hickey JT, Tofari PJ, Bourne MN, Ward MR, Timmins RG. Effect of an isometric or eccentric hip extension exercise intervention on hamstring strength, architecture, and morphology. *Med Sci Sports Exerc*. 2022;54(12):2196–207.
20. McCall A, Nedelec M, Carling C, Le Gall F, Berthoin S, Dupont G. Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional football players. *J Sports Sci*. 2015;33(12):1298–304.
21. Samozino P, Rabita G, Dorel S, et al. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scand J Med Sci Sports*. 2016;26(6):648–58.
22. Timmins RG, Shamim B, Tofari PJ, Hickey JT, Camera DM. Differences in lower limb strength and structure after 12 weeks of resistance, endurance, and concurrent training. *Int J Sports Physiol Perform*. 2020;15(9):1223–30.
23. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head architecture: a reliability and retrospective injury study. *Med Sci Sports Exerc*. 2015;47(5):905–13.

24. 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.
25. Kellis E, Galanis N, Natsis K, Kapetanos G. Validity of architectural properties of the hamstring muscles: correlation of ultrasound findings with cadaveric dissection. *J Biomech*. 2009;42(15):2549–54.
26. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris architecture and strength in athletes with a previous anterior cruciate ligament reconstruction. *Med Sci Sports Exerc*. 2016;48(3):337–45.
27. Duhig SJ, Bourne MN, Buhmann RL, et al. Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. *J Sci Med Sport*. 2019;22(7): 769–74.
28. Team R Coding. R: a language and environment for statistical computing. In. Vienna: R Foundation for Statistical Comput Secur; 2013.
29. Faul F, Erdfelder E, Lang AG, Buchner A. G*power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–91.
30. Presland JD, Timmins RG, Bourne MN, Williams MD, Opar DA. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scand J Med Sci Sports*. 2018;28(7):1775–83.
31. Presland J, Opar D, Lee Dow C, et al. Eccentrically overloaded flywheel training increases biceps femoris long head fascicle length. *J Sci Med Sport*. 2017;20:11.
32. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. *Med Sci Sports Exerc*. 2015;47(4):857–65.
33. Ruddy J, Shield A, Maniar N, et al. Predicting hamstring strain injury incidence in elite Australian footballers. *J Sci Med Sport*. 2017;20-(Suppl 3):10–1.
34. Mendiguchia J, Conceicao F, Edouard P, et al. Sprint versus isolated eccentric training: comparative effects on hamstring architecture and performance in soccer players. *PLoS One*. 2020;15(2):e0228283.
35. Lanza MB, Balshaw TG, Folland JP. Is the joint-angle specificity of isometric resistance training real? And if so, does it have a neural basis? *Eur J Appl Physiol*. 2019;119(11–12):2465–76.
36. Nedelec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. The influence of soccer playing actions on the recovery kinetics after a soccer match. *J Strength Cond Res*. 2014;28(6):1517–23.
37. McCall A, Carling C, Nedelec M, et al. Risk factors, testing and preventative strategies for non-contact injuries in professional football: current perceptions and practices of 44 teams from various premier leagues. *Br J Sports Med*. 2014;48(18):1352–7.
38. Schimpchen J, Skorski S, Nopp S, Meyer T. Are "classical" tests of repeated-sprint ability in football externally valid? A new approach to determine in-game sprinting behaviour in elite football players. *J Sports Sci*. 2016;34(6):519–26.
39. Gabbett TJ, Whiteley R. Two training-load paradoxes: can we work harder and smarter, can physical preparation and medical be teammates? *Int J Sports Physiol Perform*. 2017;12(Suppl 2):S250–4.