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Sprinting, Strength, and Architectural Adaptations Following Hamstring Training in Australian Footballers

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The aim of this study was to determine the sprinting, strength, and architectural adaptations following a hip-dominant flywheel (FLY) or Nordic hamstring exercise (NHE) intervention in Australian footballers. Twenty-seven male athletes were randomized to FLY (n = 13) or NHE (n = 14) training across a 39-week period (inclusive of pre-season and in-season). Biceps femoris long head (BFlh) architecture was assessed throughout. Eccentric hamstring strength and 40 m sprint times (with force-velocity profiling) were assessed at baseline, end of pre-season, and following the intervention. After the intervention, BFlh fascicle length was longer in both groups compared to baseline (FLY: 1.16 cm, 95%CI: 0.66 to 1.66 cm, $d = 1.99$, $p < 0.001$; NHE: 1.08 cm, 95%CI: 95%CI 0.54 to 1.61 cm, $d = 1.73$, $p < 0.001$). Both groups also increased their eccentric strength (FLY: mean change 82 N, 95%CI 12 to 152 N, $d = 1.34$, $p = 0.026$; NHE: mean change 97 N, 95%CI 47 to 146 N, $d = 1.77$, $p = 0.001$). After pre-season, the NHE group improved their 5 m sprint time by 3.5% (±1.2%) and were 3.7% (±1.4%) and 2.0% (±0.5%) faster than the FLY group across 5 m and 10 m, respectively. At the end of pre-season, the FLY group improved maximal velocity by 3.4% (±1.4%) and improved horizontal force production by 9.7% in-season (±2.2%). Both a FLY and NHE intervention increase BFlh fascicle length and eccentric strength in Australian Footballers. An NHE intervention led to enhanced acceleration capacity. A FLY intervention was suggested to improve maximal sprint velocity and horizontal force production, without changes in sprint times. These findings have implications for hamstring injury prevention but also programs aimed at improving sprint performance.

KEYWORDS
football, hamstring, injury prevention, muscle injuries

1 | INTRODUCTION

In the Australian Football League (AFL), hamstring strain injuries (HSI) are the most common cause of time lost from training and matches [1] and have a relatively high rate of recurrence compared to other lower limb muscle injuries.[1] These injuries also place a large financial burden on the athlete and their organization with estimates in the AFL placing the average cost of games missed in a season due to an HSI at $242,842 per club.[2] Therefore, more research is required to assist in developing HSI risk mitigation practices within the AFL.

Recently, the role that variations in biceps femoris long head (BFlh) architectural characteristics (assessed via two-dimensional ultrasound) have in the etiology of a HSI has been of interest.[3] Elite soccer players with BFlh fascicle lengths shorter than 10.56 cm at the start of pre-season were at a 4.1-fold increased risk of suffering an HSI in the subsequent season.[3] Furthermore, low levels of eccentric strength during the Nordic hamstring exercise (NHE), while not showing a strong ability to predict HSI,[4] have been associated with an increased risk of HSI in elite AFL.[5] Therefore, interventions which can promote improvements in eccentric strength and BFlh fascicle length in AFL athletes may be beneficial in mitigating the risk of HSI.

Various exercises have been investigated to determine whether they are effective at improving eccentric strength and fascicle length. Significant increases in both were found following hamstring-specific interventions utilizing eccentric isokinetic dynamometry,[6] the NHE,[7,8] and a 45° back extension.[7] However, these interventions have been undertaken in recreationally active males and lack application to high-level athletes. Recently, research in elite junior soccer players has been undertaken using a short-term (6 weeks), multiple exercise approach which resulted in significant increases in both eccentric strength and fascicle length.[9] Despite this, there is still no evidence highlighting the impact of single exercise, longer term hamstring-specific interventions in higher athletes. Understanding the impact of a single exercise intervention in this environment will assist practitioners in determining the benefits of a minimalistic approach, should they be in an environment where less time is given to resistance training interventions (eg, elite soccer).[10]

Despite the evidence supporting the use of the NHE as an effective tool in reducing the incidence of HSIs [11,12] and promoting increases in eccentric strength and fascicle length,[7,8] the implementation of the exercise in professional sport is limited.[10] This may be due to some sports medicine and strength and conditioning professionals suggesting the NHE as ineffective [13] for improving performance. However recent evidence has shown that 10 weeks of NHE training is effective at improving 10 m sprint time in amateur soccer players.[8] While this provides support for the use of the NHE not only for HSI risk mitigation but also from a performance aspect, the amateur status of these athletes creates a question around what impact this type of intervention may have in higher-level footballers. Furthermore, recent approaches to profiling the force-velocity capabilities of athletes during sprinting [14] has highlighted that improvements in performance may be specific to the individual's theoretical maximal horizontal force or velocity.[15] Therefore, better understanding the impact of an NHE intervention on these sprinting performance properties is of interest to further establish the potential performance benefits, if any, of the NHE.

Due to the limited implementation of evidence-based NHE protocols in elite sporting practices, alternative exercises such as inertial flywheel leg curl[16,17] have been proposed as different options for HSI risk mitigation programs. Recently, a new device known as "the kBox" (Exxentric, Bromma, Sweden) has been introduced as an alternative lower limb strength training modality with the ability to overload the eccentric phase of a movement.[18] Compared to the inertial flywheel leg curl, the kBox uses inertial flywheel resistance training for the prescription of (among others) hip-dominant inertial flywheel resistance training for hamstring-specific adaptations. However, it is unknown if a hip-dominant inertial flywheel training intervention is effective at improving sprint performance, eccentric strength, and fascicle length.

Therefore, the primary aim of this study was to determine the BFlh architectural, eccentric strength, and sprint performance adaptations following a hamstring-specific exercise intervention utilizing either the NHE or a hip-dominant flywheel exercise, in Australian Footballers. It was hypothesized that both interventions will significantly improve sprinting performance, eccentric strength, and fascicle length.

2 | METHODS

2.1 | Participants

This interventional cohort trial was undertaken during the pre-season (November 2017-March 2018) and in-season period (March 2018-August 2018) of the 2018 Victorian Football League competition, a semi-professional second tier competition to the fully professional AFL. Ethical approval for the study was granted by the Australian Catholic University Human Research Ethics Committee (approval number: 2017-234H). All players were invited to participate and provide written, informed consent. In total, twenty-seven male athletes (age =22 ± 3 yrs; height =1.85 ± 0.07 m; body mass =81.2 ± 7.0 kgs) were recruited.

2.2 | Study design

Participants undertook an initial familiarization session with the NHE and the hip-dominant, kBox flywheel exercise. Following the familiarization session (median =5, range 5–7 days), participants underwent a pre-intervention assessment of their BFlh architecture, maximal knee flexor strength during the NHE and a 3-repetition maximum (3RM) effort with the kBox flywheel device (Exxentric, Bromma, Sweden). Participants also had their maximal isometric strength assessed using an isometric mid-thigh pull (IMTP).[19,20] A 40-meter sprint assessment with splits collected at 5, 10, 20, 30, and 40 meters was also undertaken, with the force-velocity profiles of these efforts subsequently determined.[14] After this initial testing battery, the participants were randomized (1:1 allocation) to either the NHE only (NHE; n = 14) or the hip-dominant kBox flywheel only group (FLY; n = 13). Subsequently, throughout the intervention period the only hamstring-specific resistance training stimulus they received was either 1) the NHE or 2) a hip-dominant kBox inertial flywheel exercise, based on their group allocation. All participants then began the first session of their 39-week training intervention under the guidance of the research team (DF, VN, and JG). A video of the NHE and hip-dominant kBox flywheel exercise can be found in Video S1 and S2, respectively. After the first 6 weeks of training, there was a 4-week break for a Christmas holiday period, where neither group performed their allocated exercise. Post-Christmas, there was an additional 8 weeks (total of 14) of training in the pre-season period (November to March). The remaining 25 weeks of training occurred during the in-season period (March to August). All participants were experienced (>2 years) in hamstring resistance training regimes undertaken in a high-level sporting context.

Throughout the training intervention, the participants had their BFlh architecture assessed at baseline as well as after 5, 9, 16, 23, 27, 35 weeks, and at the end of the intervention (39 weeks). All strength assessments (NHE, flywheel 3RM, and IMTP) were undertaken at baseline and after 16, 23, 27, 35 weeks, and at the end of the intervention (39 weeks). The sprint assessment was undertaken at baseline, after 16 weeks, and at the end of the intervention (39 weeks). Across the course of the study period, global positioning (GPS—OptimEye S5, 10 Hz, Catapult Sports, Melbourne, Australia) data were used to monitor the external load metrics of each group. Finally, the occurrence of any HSIs during the study period was also collected.

2.3 | Training intervention

For the duration of the intervention, participants undertook one to two sessions a week (depending on the match schedule) of either the NHE or FLY exercise (Figure 1). These exercises were undertaken as part of their weekly team resistance training sessions which were always completed after an on-field team training session. The majority of training weeks consisted of two sessions per week. There were four training weeks across the entire intervention where short timeframes between matches resulted in only one session per week being completed. When two sessions

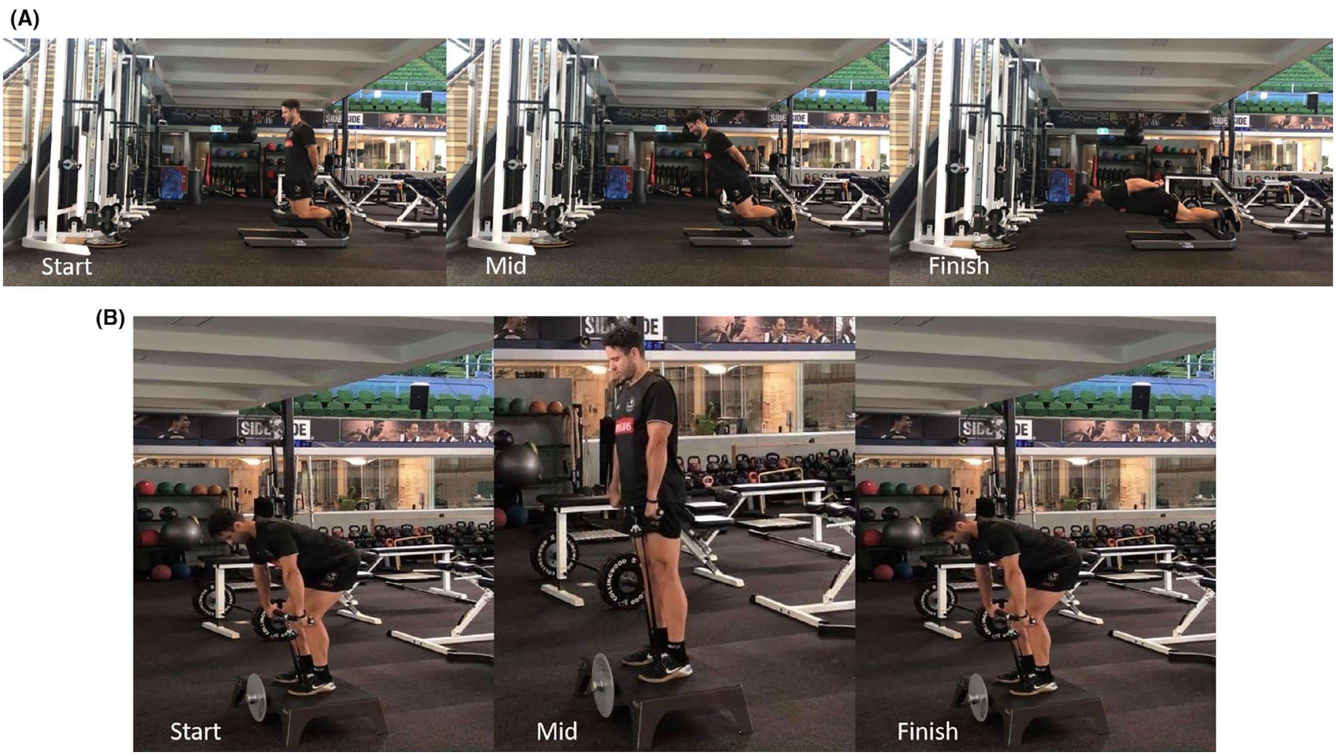

FIGURE 1 The Nordic hamstring (A) and inertial flywheel (B) exercises. With the Nordic hamstring exercise, the participants control the fall by contracting eccentrically with the knee flexors. After completing a repetition, the participants return to their starting position by pushing back up with their hands (not shown). With the inertial flywheel exercise, participants are instructed to perform the concentric phase of the exercise as fast as possible. Then, once they reach the top of the range of motion, the kBox device will pull them into hip flexion. The participants are then instructed to resist action with an eccentric contraction of the hip extensors

per week were completed, the resistance training sessions were undertaken on non-consecutive days of the week. Both training programs were periodized by progressively modifying the volume and additional weight used during training, across both the pre-season and in-season periods, to provide an appropriate stimulus. Figure S1outlines the progression of the NHE and FLY volume for the duration of the intervention. A detailed outline of the entire resistance training program for both groups, during the pre-season and in-season periods, can be found in Tables S1 and S2, respectively.

2.4 | Outcome measures

2.4.1 | BFlh architecture

The methods to assess BFlh architecture has been previously reported.[21-23] Briefly, muscle thickness, pennation angle, and fascicle length of the BFlh were determined from ultrasound images taken along the longitudinal axis of the muscle belly utilizing 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). 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 mins of inactivity. The orientation of the probe was then manipulated by the assessor (RGT) whose reliability has been previously reported (intraclass correlations: >0.95, coefficient of variation: <5.0%).[24]

Once the images were collected, analysis was undertaken offline (MicroDicom, Version 0.7.8, Bulgaria). Muscle thickness was defined as the distance between the superficial and intermediate aponeuroses of the BFlh. Pennation angle was defined as the angle between the inferior aponeurosis and a fascicle of interest. The aponeurosis angle for both aponeuroses was determined as the angle between the line marked as the aponeurosis and an intersecting horizontal reference line across the captured image.[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]:

$$\mathrm{FL} = \sin\ (\mathrm{AA} + 90^\circ)x\ \mathrm{MT}/\sin(180^\circ - (\mathrm{AA} + 180^\circ - \mathrm{PA}))$$

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

2.4.2 | Eccentric knee flexor strength

The assessment of eccentric knee flexor strength during the NHE has been previously reported.[7,23] Participants were instructed to kneel on the device (NordBord, Vald Performance, Queensland, Australia) 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 or hold a weight (as required) at the level of the xiphoid process while 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. The average of the three peak values (in Newtons (N)) during the assessment was used for the analysis.

2.4.3 | Hip-dominant kBox flywheel 3RM

Flywheel 3RM strength was assessed using the kBox device (Exxentric, Bromma, Sweden). Participants were instructed to stand on the kBox device, holding the handlebar of the device (Video S2). From this position, the participants were instructed to flex the hip, while not moving their knees, until their hips were at 90 degrees with their trunk parallel with the floor. Following this, the participants were instructed to extend their hips as hard and fast as they can to perform the concentric phase of the repetition. This phase was the beginning of the first effort of their assessment. Once they had extended their hips to neutral, the participants were instructed to flex at the hip again, while holding the bar and attempting to stop the flywheels movement while performing the eccentric phase. Participants completed three repetitions with all the concentric efforts undertaken as hard and as fast as possible, while trying to stop the flywheel movement during the eccentric portion. Data reported from the kBox assessment were as follows: average power (average power for all three repetitions for both the concentric and eccentric phase in Watts), concentric peak power (average of the peak power recordings during the three concentric phases in Watts), and eccentric peak power (average of the peak power recordings during the three eccentric phases in Watts).[18] kBox strength was assessed at baseline, 16, 23, 27, 35 weeks, and at the end of the intervention (39 weeks).

2.4.4 | Maximal isometric strength (IMTP)

Maximal isometric strength was assessed using an isometric mid-thigh pull (IMTP) test. Participants were required to stand on a force plate (Fitness Technologies, South Australia, Australia) and held an immovable barbell which was fixed at mid-thigh height. Each participant had the height of the bar adjusted for their specific requirements to allow a hip angle of ~155–165 degrees and a knee angle of ~125–135 degrees (full extension =180 degrees for both joints, respectively). Bar height was kept consistent across all testing sessions and participants wore wrist straps to assist their grip. To assess their maximal isometric strength, the participants were instructed to pull up as hard and fast as possible for five seconds. Maximal IMTP force was reported relative to body weight (Newtons per kilogram (N/kg)). Maximal isometric strength was assessed at baseline, 16, 23, 27, 35 weeks, and at the end of the intervention (39 weeks).

2.4.5 | Sprint assessment

The assessment of sprint performance was undertaken 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 standing start through the timing gates. Each gate was set at a height approximate to the level of the hip when in upright stance for all participants. This system uses a dual-beam photocell and positioning laser to create the gates for each split. Once the path of the photocell and laser are broken by the participant, the time taken to travel between the gates is recorded. Each participant completed three trials, with the best trial used for all analysis. Sprinting performance was assessed at baseline, after 16 weeks, and at the end of the intervention (39 weeks).

2.4.6 | Sprint horizontal force-velocity outputs

A custom-made Microsoft Excel spreadsheet derived from the work of Samozino et al.[14] was used to determine the theoretical maximal horizontal force (F_0), velocity (V_0), and power output (P_{max}) using the data obtained during the sprint assessment. These values were determined using the best individual sprint test, its associated split times, and the body mass of the participant. Using the spreadsheet, any calculations where the squared differences (eg, the difference between the experimental and estimated values) were >0.1, were excluded from further analyses. The maximal horizontal force, velocity, and power outputs were reported as N/kg, meters per second (m/s), and watts per kilogram (W/kg), respectively.

2.4.7 | Prospective HSI reporting

The occurrence of any HSI during the intervention period, which was later diagnosed by the club medical staff, was recorded by the investigators. A HSI was defined as any acute posterior thigh pain that resulted in the immediate cessation of exercise. The injury reporting involved specifics around which limb was injured (dominant/non-dominant), the muscle injured (BFlh/biceps femoris short head/semimembranosus/semitendinosus), activity type performed at time of injury (eg, running and kicking), and the number of days taken to return to full participation in training/competition. Once a participant suffered a HSI during the intervention, they were excluded from any future analysis.

2.5 | Training interventions

2.5.1 | Nordic hamstring exercise training

A video of the NHE can be found in the online Table S1. Participants undertook the NHE with their ankles secured underneath a piece of gym equipment (Figure 1B). This was preferred to the partner held version of the NHE, where the strength of the companion may limit the effectiveness of the effort. For each repetition, participants only performed the lowering (eccentric) portion of the NHE. After each effort, participants were instructed to use their arms and flex their hips in order to assist themselves in returning to the starting position. Once additional weight was utilized as per the progressive overload presented in Figure S1, the participants were required to hold a weight plate (range 5 to 10 kg) over their xiphoid process, per previous work.[21,26] Training was preceded by a warm-up set of three submaximal repetitions, and following each set, participants were afforded a 2-min rest.

2.5.2 | Hip-dominant kBox flywheel training

A visual representation of the hip-dominant kBox flywheel exercise can be found in the online Table S2. Participants undertook the FLY intervention utilizing a kBox flywheel device (Exxentric, Bromma, Sweden, Figure 1A). Participants started in position similar to the bottom of a deadlift and were instructed to hold the handle of the kBox flywheel device and stand up as hard fast as they could by extending both the hip and the knee simultaneously to complete the concentric phase of the repetition. During the eccentric phase, they were instructed to have no movement at the knee and try to stop the descent of the flywheel handlebar by hinging at the hip only. Participants undertook their efforts with a moment of inertia of the flywheel of either 0.05 or 0.075 kgm^2, which was periodized as presented in Figure S1. Training was preceded by a warm-up set of three submaximal repetitions. Following each set, participants were afforded a 2-min rest.

2.6 | Statistical analysis

All statistical analyses were performed using the R statistical programming language and the following packages: dplyr, lme4, and car. 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. For each outcome variable, covariates were group (NHE or FLY) and time, with participant ID included as a random effect. For BFlh architecture and eccentric 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 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 ($d \geq 0.20$), medium ($d \geq 0.50$), or large ($d \geq 0.80$). All data were expressed as mean ±SD, unless otherwise stated.

2.7 | Power calculation

Power analysis was undertaken *a priori* using G-Power. The effect size estimates used in the analysis were based on the estimated changes in BFlh fascicle length following the NHE training intervention.[26] In this study, fascicle length changes had an effect size of 2.8. Therefore, 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 sample of 9 per group.

3 | RESULTS

3.1 | Participant, compliance, and external load details

The two groups were similar with respect to age, height, and body mass (NHE age 23 ± 3 yrs, height 1.86 ± 0.07 m, body mass 82.7 ± 3.9 kg; FLY age 22 ± 3 yrs, height 1.84 ± 0.07 m, body mass 78.3 ± 6.8; age $p = 0.162$, height $p = 0.577$, body mass $p = 0.052$). Of the 72 sessions, the NHE group had an average compliance of 75 ± 8% (range: 43 to 72 sessions completed). The FLY group had a similar level of compliance with 73 ± 10% (range: 46 to 72 sessions completed). There were no differences in the average weekly total distance (NHE group =7368 ± 3156 m, FLY group =7227 ± 3221 m; $d = 0.04$; $p = 0.775$), average weekly total distance performed above 25 km/hr (NHE group =173 ± 167 m, FLY group =157 ± 174 m; $d = 0.09$; $p = 0.532$), and average weekly number of efforts performed above 25 km/hr (NHE group =6.2 ± 3.5, FLY group =5.2 ± 3.1; $d = 0.32$; $p = 0.059$) between the two groups across the training intervention.

3.2 | Injury occurrence

During the study period, a total of three (11% of total participants) HSIs were reported with two participants (15%) being in the FLY group and one in the NHE group (7%). Of these injuries, one occurred in the pre-season period and two in-season. All injuries occurred in the BFlh of the dominant leg with two occurring during high speed running and one during an acceleration effort. All injuries occurred during matches with participants missing 14, 24, and 35 days, respectively.

3.3 | BFlh architectural characteristics

A summary of the BFlh architectural alterations during this intervention can be found in Figure 2 and Table S3.

3.3.1 | Fascicle length

A significant main effect of time was found for fascicle length ($p < 0.001$). *Post hoc* analyses showed a significant increase in fascicle length from baseline to week 5 of training in both groups (NHE group: difference 0.8 cm, 95%CI 0.2 to 1.5 cm, $d = 0.99$, $p < 0.001$; FLY group: difference 0.5 cm, 95%CI 0.2 to 1.2 cm, $d = 0.83$, $p < 0.001$; Figure 2). When re-assessed post-Christmas, both groups had a significant reduction in fascicle length when compared to the week 5 measure (NHE group: difference −1.0 cm, 95%CI −1.8 to −0.4 cm, $d = -1.72$, $p < 0.001$; FLY group: difference −0.7 cm, 95%CI −1.4 to −0.2 cm, $d = -1.27$, $p < 0.001$; Figure 2). At the end of pre-season, both groups had significantly longer fascicles than baseline (NHE group: difference 0.7 cm, 95%CI 0.2 to 1.2 cm, $d = 1.27$, $p = 0.01$; FLY group: difference 0.5 cm, 95%CI 0.04 to 1.0 cm, $d = 0.93$, $p = 0.03$; Figure 2). When compared to the end of pre-season, only the

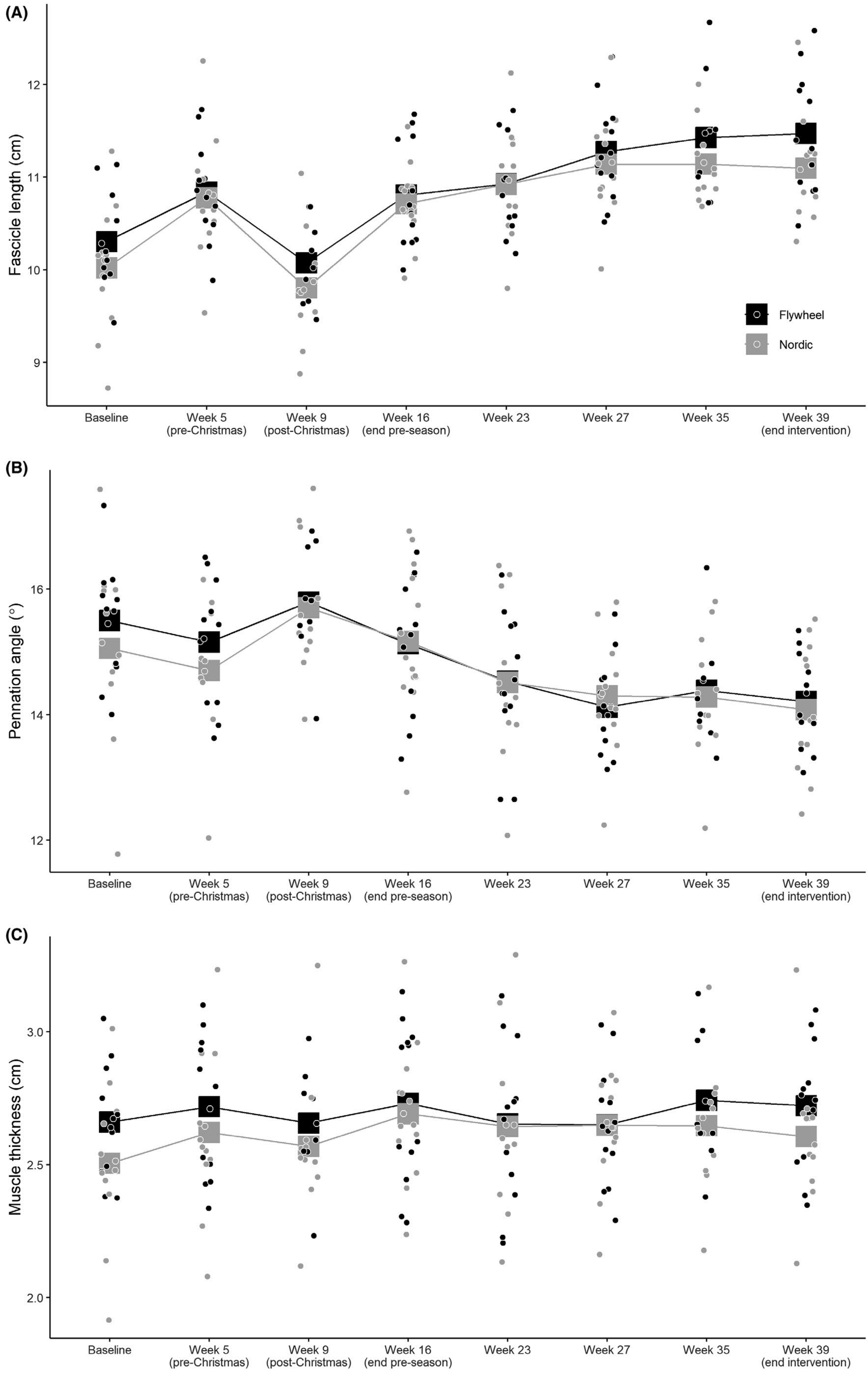

FIGURE 2 Biceps femoris long head fascicle length (A), pennation angle (B), and muscle thickness (C) throughout the intervention period for both groups

FLY group saw a significant improvement in fascicle length in-season (NHE difference 0.4 cm, 95%CI 0.02 to 0.8 cm, $d = 0.80$, $p = 0.062$; FLY group: difference 0.7 cm, 95%CI 0.1 to 1.2 cm, $d = 1.07$, $p = 0.016$; Figure 2). However, at the end of the in-season period, both groups had significantly longer fascicles when compared to baseline (NHE group: difference 1.1 cm, 95%CI 0.5 to 1.6 cm, $d = 1.73$, $p < 0.001$; FLY group: difference 1.2 cm, 95%CI 0.7 to 1.7 cm, $d = 1.99$, $p < 0.001$; Figure 2). There was no difference in fascicle length between the groups at any time (*d* range: 0.19 to 0.61, p range: 0.149 to 0.639).

3.3.2 | Muscle thickness

A significant main effect for time was found for muscle thickness ($p < 0.001$). *Post hoc* analyses showed no significant changes in muscle thickness of either group across the entire study when compared to baseline (NHE group *d* range: −0.33 to 0.69, p range: 0.094 to 0.401; FLY group *d* range: −0.03 to 0.27, p range: 0.512 to 0.938; Table S3). There were no differences in muscle thickness between the groups at any time (*d* range: 0.14 to 0.61, p range: 0.147 to 0.726).

3.3.3 | Pennation angle

A significant main effect for time was found for pennation angle ($p < 0.001$). *Post hoc* analyses showed a significant reduction in pennation angle at the end of the intervention when compared to the end of pre-season for both groups (NHE group difference −1.1°, 95%CI −1.9 to −0.2°, $d = 1.00$, $p = 0.017$; FLY group difference −0.9°, 95%CI −1.7 to −0.1°, $d = 0.98$, $p = 0.025$). There was no difference between groups at any time (*d* range: −0.28 to 0.53, p range: 0.128 to 0.618).

3.4 | Eccentric knee flexor strength

A significant main effect for time was found for eccentric knee flexor strength ($p < 0.001$). *Post hoc* analyses showed a significant increase in eccentric knee flexor strength at the end of pre-season when compared to baseline for both groups (NHE group difference 19.4%, 73 N, 95%CI 16 to 131 N, $d = 1.11$, $p = 0.015$; FLY group difference 13.9%, 57 N, 95%CI 12 to 103 N, $d = 1.10$, $p = 0.016$; Table 1). At the end of the intervention, both groups had significant increases in eccentric knee flexor strength compared to baseline (NHE group difference 24.0%, 96 N, 95%CI 47 to 146 N, $d = 1.77$, $p = 0.001$; FLY group difference 18.9%, 82 N, 95%CI 12 to 152 N, $d = 1.34$, $p = 0.026$), but not in comparison with the

TABLE 1 Measures of eccentric knee flexor strength, kBox three repetition maximum (3RM) variables as well as isometric mid-thigh pull strength throughout the intervention for both

	Flywheel Group					Nordic Group				
	Eccentric knee flexor strength (N)	kBox 3RM Average Power (W)	kBox 3RM Concentric Peak Power (W)	kBox 3RM Eccentric Peak Power (W)	Isometric mid-thigh pull strength (N/Kg)	Eccentric knee flexor strength (N)	kBox 3RM Average Power (W)	kBox 3RM Concentric Peak Power (W)	kBox 3RM Eccentric Peak Power (W)	Isometric mid-thigh pull strength (N/Kg)
Baseline	352 ± 54	561 ± 111	853 ± 139	898 ± 190	38.2 ± 4.8	307 ± 66	487 ± 152	775 ± 187	893 ± 206	40.8 ± 6.1
Week 16 (End pre-season)	409 ± 50*	540 ± 111	839 ± 190	978 ± 270	40.4 ± 4.5	381 ± 65*	476 ± 87	764 ± 126	798 ± 181	40.1 ± 3.8
Week 23	404 ± 39	552 ± 106	856 ± 142	989 ± 304	39.8 ± 4.8	399 ± 68	489 ± 98	788 ± 137	871 ± 174	38.5 ± 3.0
Week 27	412 ± 31	536 ± 252	842 ± 361	994 ± 506	38.7 ± 3.7	384 ± 74	401 ± 61	629 ± 87	702 ± 103	38.6 ± 3.6
Week 35	409 ± 67	544 ± 91	855 ± 130	1044 ± 271	42.8 ± 4.1	393 ± 55	417 ± 111	675 ± 170	732 ± 196	42.5 ± 2.6
Week 39 (End intervention)	434 ± 71*	543 ± 126	890 ± 183	1034 ± 302	37.3 ± 4.0	404 ± 37*	514 ± 105	824 ± 158	857 ± 164	37.9 ± 3.3

Note: Eccentric knee flexor strength is the average of both limbs.

Abbreviations: N, Newtons of force; N/Kg, Newtons of force relative to body mass; W, Watts.

*$p < 0.05$ compared to baseline.

end of pre-season (NHE group difference 1.2%, 23 N, 95%CI −24 to 70 N, d = 0.42, p = 0.312; FLY group difference 6.9%, 25 N, 95% CI −44 to 93 N, d = 0.42, p = 0.440). There was no difference in eccentric knee flexor strength between the groups at any time (d range: 0.48 to 0.73, p range: 0.103 to 0.340).

3.5 | kBox flywheel 3RM

There were no significant main effects detected for kBox average (p range: 0.094 to 0.757; Table 1), concentric (p range: 0.102 to 0.981), or eccentric peak power (0.071 to 0.572). Therefore, no *post hoc* analyses were undertaken.

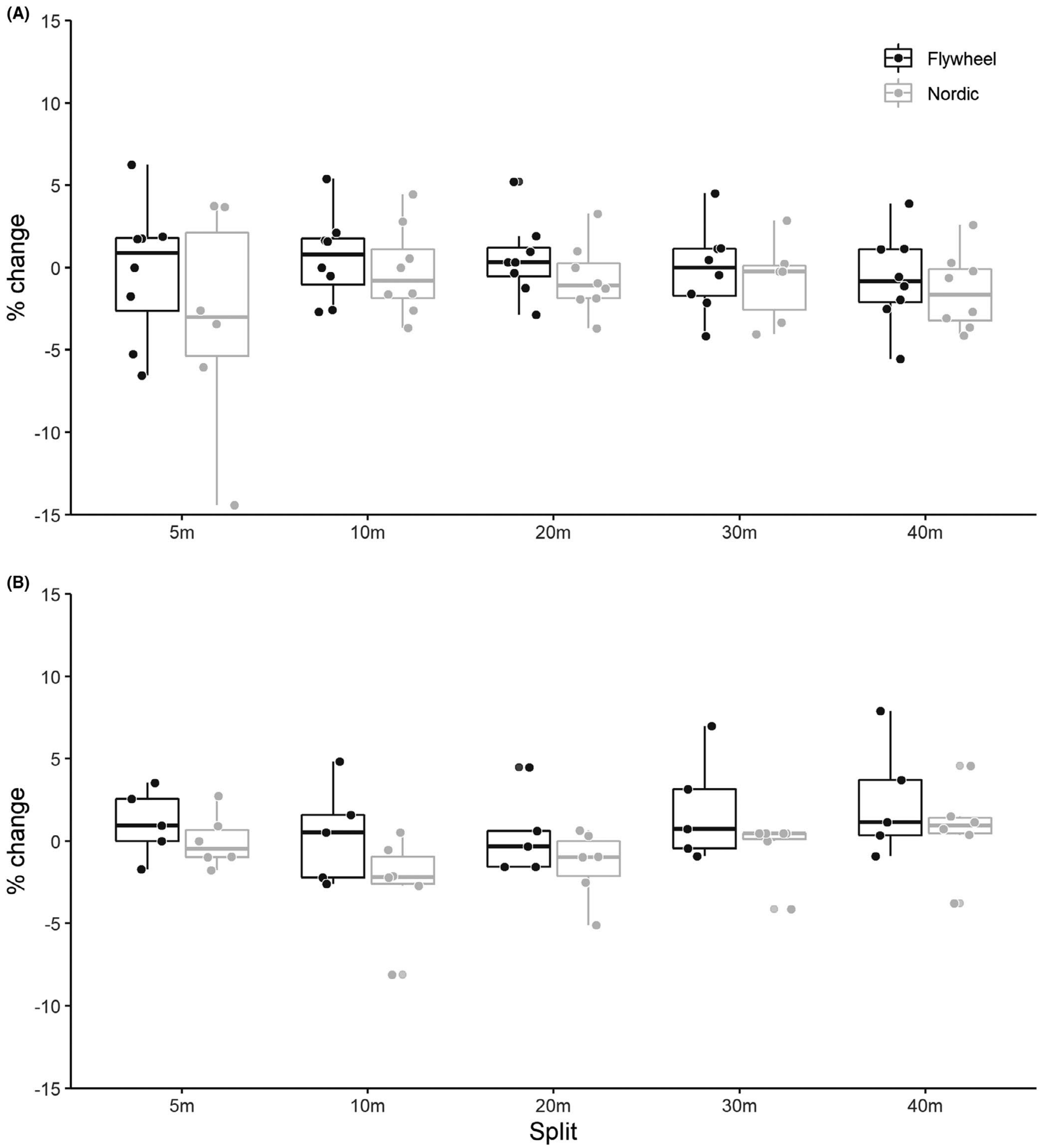

FIGURE 3 Percentage change in sprinting split times at 5 m, 10 m, 20 m, 30 m, and 40 m from baseline to the end of pre-season (A) and from the end of pre-season to the end of the intervention (B) for both groups. Horizontal line represents median value

3.6 | Maximal isometric strength (IMTP)

There were no significant main effects detected for maximal isometric strength (p range: 0.076 to 0.557). Therefore, no *post hoc* analyses were undertaken.

3.7 | Sprint assessment

3.7.1 | Split results

A significant main effect for time ($p = 0.032$) and group ($p = 0.036$) was found for 5 m split times. A significant main effect for group ($p = 0.031$) was also found for 10 m split times. *Post hoc* analyses showed a significant 3.5% improvement in 5 m split time at the end of pre-season when compared to baseline for the NHE group only (NHE group difference −0.039 s, 95%CI −0.08 to −0.003 s, $d = 1.02$, $p = 0.046$; FLY group difference −0.008 s, 95%CI −0.044 to 0.027 s, $d = 0.24$, $p = 0.611$, Figure 4, Table S4). Between group comparisons found that the NHE group was 3.7% faster than the FLY group over 5 m (difference 0.040 s, 95%CI 0.001 to 0.077 s, $d = 1.03$, $p = 0.038$) and 2.0% (difference 0.032 s, 95%CI 0.005 to 0.068 s, $d = 0.87$, $p = 0.045$) quicker across 10 m at the end of pre-season. All other within and between groups comparisons were not significantly different.

3.7.2 | Horizontal force-velocity profile

A significant main effect for time was found for relative maximal horizontal force ($p = 0.008$) and velocity ($p = 0.013$). A significant main effect for group was found also for maximal horizontal force ($p = 0.046$) and power output (0.023). *Post hoc* analyses showed a significant increase in maximal velocity in the FLY group of 3.4%, but not in the NHE group at the end of pre-season when compared to baseline (NHE difference 0.17 m/s, 95%CI −0.10 to 0.42 m/s, $d = 0.57$, $p = 0.224$; FLY difference 0.29 m/s, 95%CI 0.01 to 0.51 m/s, $d = 1.08$, $p = 0.033$, Figure S2, Table S5). At the end of the intervention, maximal velocity was reduced by 5.3% in the FLY group when compared to the end of pre-season, with no changes seen in the NHE group (NHE group difference −0.08 m/s, 95%CI −0.32 to 0.17 m/s, $d = -0.28$, $p = 0.534$; FLY group difference −0.47 m/s, 95%CI −0.95 to −0.02 m/s, $d = 1.08$, $p = 0.047$). However, while there was a reduction in maximal velocity in the FLY group at the end of the intervention when compared to the end of pre-season, there was a significant 9.7% increase in maximal, relative horizontal force (difference 1.1 N/kg, 95%CI 0.04 to 2.01 N/Kg, $d = 1.12$, $p = 0.041$), with a non-significant 6.2% increase in the NHE group (difference 0.7 N/kg, 95%CI −0.8 to 2.2 N/kg, $d = 0.51$, $p = 0.325$). All other within and between group comparisons (including the maximal power output measures) were not significantly different.

4 | DISCUSSION

This is the first study to investigate the impact of the NHE and a hip-dominant flywheel resistance training intervention on BFlh architecture, eccentric hamstring strength, and sprint performance in Australian Footballers across 39 weeks. The novel findings of this study are:

- 1): undertaking NHE or hip-dominant flywheel training significantly improved eccentric strength and BFlh fascicle length to a similar extent across the study period,
- 2): undertaking NHE training across a 14-week pre-season period can significantly improve 5 m sprint split time and
- 3): a hip-dominant flywheel intervention can improve maximal sprint velocity across a pre-season period, while also increasing maximal horizontal force production during the in-season period.

This is the first study to prescribe single-mode hamstring-specific exercise training during pre-season and in-season for competing athletes. Comparably other single exercise training interventions have either been undertaken in recreationally active males [6,7,21,26] or have a smaller intervention period (<12 weeks) if being done in athletes.[9,16] Recent research in elite youth soccer has shown that 12 weeks of NHE and stiff-leg deadlifts can promote increases in both fascicle length and eccentric strength.[9] The current study utilized a single exercise approach for each group (NHE or FLY) which enables a more direct comparison between exercises, the stimulus they provide and subsequent adaptation. Additionally, the training volume in the current study was a smaller dose compared to previous single exercise and elite athlete interventions.[6,7,9,21,26] This approach was employed for two reasons: 1) to see if an adaptation can be facilitated in this athletic population with a smaller dose which does not result in excessive soreness or take too much time and 2) to manage the progressive overload, especially in-season, which is critical during this phase of competition. As this is the first study to have investigated the effectiveness of a lower volume, single exercise, season long intervention at promoting strength and architectural changes in an athletic population, it does create further questions around the efficacy of a more 'holistic', multi-modal hamstring injury risk mitigation program.

Elite soccer players who possessed short BFlh fascicles at the start of pre-season (<10.56 cm) were ~4 times more likely to suffer an HSI in the subsequent season.[3] In elite, Australian Football possessing eccentric strength measures of <279 N at the end of pre-season increased the risk of a future HSI ~4 fold.[5] While it is unknown if improving these two measures directly reduces the likelihood of an HSI occurring, those who undertook the NHE intervention in the current study saw a 1.08 cm (11%) and a 96 N (31%) increase in fascicle length and eccentric strength across the study, respectively. Similarly, the FLY group saw a 1.16 cm (12%) and an 82 N (31%) increase in both fascicle length and eccentric strength, respectively. Considering the findings of the current study in context with previous prospective evidence,[3,5] it is possible that an intervention containing either NHE or FLY training, in Australian Footballers, may have a beneficial impact on HSI risk mitigation. However, due to the small number of injuries in the current study, further research is required with bigger sample sizes to determine a possible link between risk factors, training interventions, and the subsequent occurrence of injury.

In the current study, the improvements in BFlh fascicle length for the NHE group (~1 cm) are less than those found in other, shorter interventions.[7,21,26] Additionally, the improvements in eccentric strength in the NHE group were ~50 N less than those seen in previous research.[7,21,26] Comparably, these previous studies had their training interventions undertaken at a much higher training volume (some weeks included up to 100 repetitions per week) and were across a shorter period (the longest being 10 weeks). Additionally, they were all undertaken in a recreational cohort who had limited prior exposure to eccentric training and were also not concurrently undertaking footballing-related activities. The current study was undertaken at a lower volume which was periodized across 39 weeks in a high-level, athletic population who were concomitantly undertaking football-related training. Therefore, it is possible that they may have been closer to their theoretical 'adaptive ceiling'. When comparing the results of the current study to previous research, the vastly different training status and physical capacity between the previously researched recreational individuals and those higher-level athletes in this project should be considered.

This is the first study to have utilized a hip-dominant, inertial flywheel resistance training intervention. Currently, the only evidence regarding hamstring adaptations following inertial flywheel resistance training have utilized a leg curl device.[16] As leg curl, inertial flywheel resistance exercise has been shown to preferentially recruit the medial hamstring muscles,[27] it was of interest to determine the impact of a hip-dominant flywheel training intervention on BFlh architecture and eccentric strength. It has been shown that a hip-dominant movement (such as a 45° hip extension) preferentially recruit the BFlh,[28] which is the most commonly injured of the hamstrings.[3] Therefore, we utilized the kBox device [18] to perform a hip-dominant inertial flywheel resistance training intervention. We found increases in BFlh fascicle length following the FLY training (~1.2 cm) that were comparable to previous research utilizing a 45° hip extension intervention.[7] The FLY group also saw similar improvements in eccentric strength when compared to the previous 45° hip extension research.[7] While the movements (flywheel vs 45° hip extension) may be similar in that they are both a hip-dominant hamstring exercise, there are variances in how they are performed which may impact the adaptations seen. For example, it is known that eccentric and concentric training interventions result in divergent architectural adaptations, with eccentric stimuli being effective at lengthening fascicles, whereas concentric training results in a shortening.[6] Therefore, the combination of both an eccentric and concentric stimulus (eg, the 45° hip extension) may limit the extent to which BFlh fascicles can be lengthened. While both the hip-dominant inertial flywheel and 45° hip extension exercises utilize both a concentric and eccentric phase, it is possibly the greater resistance during the eccentric phase associated with the flywheel technology that may provide a greater impetus for fascicle lengthening and increasing strength.[7] Combine this stimulus with the potential that the participants in the current study may have a lower ceiling for adaptation and the net overall adaptive result may be similar to the 45° hip extension research. However, as this is the first study utilizing a hip-dominant inertial flywheel resistance training intervention, more research is needed to better understand the ideal prescription of this exercise.

In Australian Rules Football, there has been an increase in the number of short-distance sprint efforts as the game has evolved over the past three decades.[29,30] Therefore, being able to improve acceleration capacity (5 m and 10 m sprint performance) may be more crucial for match performance than improving the physical capacity for longer and less frequent prolonged sprinting (eg, over 30 m).[31] In the current study, participants in the NHE group had a 3.5% improvement in 5 m split time at the end of the pre-season period. When compared to the FLY group (who saw no within-group improvements for sprinting split times across the intervention), the NHE group were 3.7% and 2.0% faster over 5 m and 10 m at the end of pre-season, respectively. When considering the data from the current study in a sporting context, this means that an average participant from the NHE group may gain a 15 to 20 cm advantage across 5 m to 10 m when competing against a FLY group participant. In football, this may be a crucial advantage that can assist the athlete bettering their opponent in contests during a match.[30] The improvement in sprinting times seen in the NHE group may also assist practitioners with the prescription of the exercise intervention within a high-performance setting where balancing injury prevention with performance improvements is a key component of the role.[32]

Recently, there has been a progression from simply measuring sprinting split times during maximal efforts, to understanding the athletic properties by which sprinting ability can improve.[14,15] These properties include maximal horizontal force, velocity, and power which can all be assessed by analyzing an athlete's force-velocity profile during a maximal sprinting effort.[14,15] In the current study, we profiled the force-velocity properties of all the participants during a maximal sprinting test at the beginning of the study, the end of pre-season, and at the end of the intervention. Following the pre-season period, the participants in the FLY group had a 3.4% (~0.30 m/s) improvement in maximal velocity, which was subsequently reduced by the end of the intervention by 5.3% when compared to the end of pre-season (~1.08 m/s). However, despite the reduction in maximal velocity across the in-season period, the FLY group saw a significant 9.7% improvement in maximal horizontal force production across the same period. When considering that the hip extensor muscles play a crucial role in the production of horizontal force,[33] a training intervention using a hip extension movement (such as the hip-dominant inertial flywheel device) may promote more favorable outcomes than an intervention which implemented a knee flexion action (such as the NHE). Additionally, training utilizing heavy sled towing interventions, which also incorporate hip extension,[34] have been shown to improve horizontal force production, without concomitant increases in maximal velocity. Therefore, while the FLY group showed no improvements in sprinting split time, they did manage to alter key components of their force-velocity profiles throughout the intervention, indicating the importance of considering these variables when assessing sprint performance.[15] The lack of change in force-velocity properties in the NHE group despite a 3.5% improvement in 5 m sprinting split time further supports this and suggests that high-performance programs should consider these assessments periodically in their athletes.

There are limitations associated with the current study. Firstly, the measure of fascicle length is an estimation made from a validated equation.[25] This is due to the small transducer field of view being unable to capture an entire BFlh fascicle. However, while the results are still an estimation, the methodology and equation employed have been validated against cadaveric samples and show excellent agreement between dissection and estimation methods.[25] While recent work [35] has suggested that the current technique used for estimating BFlh fascicle length contains errors when compared to extended field of view (EFOV) ultrasound assessments, it should be noted that EFOV assessment of BFlh fascicle length has never been validated against cadaveric data. Given the automation algorithms used to reconstruct EFOV architecture scans, and the error associated with this reconstruction, is typically unspecified, the lack of agreement between these two techniques is not indicative of one approach being superior over the other. Therefore, given the existence of data comparing cadaveric tissue with the current technique of estimating fascicle length, we believe this to be a valid and robust approach. Secondly, there was no control group, and therefore, we are unable to determine the impact of just football training on these outcome measures. However, the lack of changes in IMTP and kBox performance variables across pre-season (which is a period that is designed to improve strength) indicates that the impact of football only training on lower limb strength may be limited in the current cohort. Thirdly, the training prescription was not based on a percentage of a repetition maximum. The intervention was designed to be transferrable to practice, and as such, the external resistance (weight held for the NHE group or moment of inertia for the FLY group) was the same for all participants in each group. Finally, on-field training and exposure to maximum velocity during matches and training may impact the extent of BFlh fascicle length and eccentric strength changes. Undertaking research in an applied environment will always have these associated limitations; however, the contextual relevance of the data is of great benefit to practitioners. Additionally, we did collect and assess if the high velocity running exposures were not significantly skewed to one group over the other across the training intervention. Despite this, future research should aim to determine the impact of football-specific training and matches on BFlh fascicle length and eccentric strength.

In conclusion, both NHE and hip-dominant flywheel training appeared to produce significant improvements in eccentric strength and elongated BFlh fascicle length in Australian Rules Footballers. These changes were noted during both pre-season and in-season periods. Additionally, undertaking bi-weekly NHE training during pre-season led to improved acceleration capacity (5 m sprint time). Notably also, undertaking hip-dominant flywheel intervention was suggested to result in gains in maximal sprint velocity and horizontal force production, which happened to occur without measurable changes in 5 m split times. These results provide novel insight into the effect of either a knee or hip-dominant intervention on a range of lower limb strength and architectural variables in trained athletes.

5 | PERSPECTIVE

Despite the evidence supporting the use of the NHE as an effective tool in reducing the incidence of HSIs, the successful implementation of the exercise within professional sport is limited. There is also no evidence regarding the sprinting, strength and architectural adaptations in professional athletes to an NHE intervention. Due to the poor uptake of the NHE within professional sport, alternative exercises such as those using inertial flywheels have been suggested. However, it is unknown if these exercises promote any favorable adaptations in professional athletes. This study shows that a hip-dominant inertial flywheel training intervention is as effective as the NHE at limiting HSI rates and improving eccentric strength and BFlh fascicle length in high-level athletes. However, an NHE intervention in athletes can significantly improve 5 m sprint time and assist individuals in being faster over 10 m when compared to a hip-dominant inertial flywheel. Despite not improving sprint times, a hip-dominant inertial flywheel intervention can improve estimated maximum sprint velocity and horizontal force production. This study has a high level of ecological significance and therefore has implications for hamstring injury prevention programs that are to be undertaken in a practical setting that also need to consider potential performance benefits of their interventions.

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CONFLICT 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). A co-author of this paper, Joshua Ruddy, has recently obtained employment with Vald Performance who manufacture the Nordbord. However, Dr Ruddy was not employed by Vald Performance during the completion of this study.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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