Hamstring Injury Prevention in Soccer: Before or After Training?

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Executive Summary

Hamstring muscle strains account for 12-16% of all injuries sustained in professional soccer (1), and almost half (47%) of all hamstring strains occur during the last third of the 1st and 2nd halves of soccer matches. Muscle fatigue is therefore considered an aetiological risk factor, and injury prevention programs such as the FIFA 11+ are administered during the warm-up before training. Nordic Hamstring exercises (NHE) are part of the FIFA 11+ program and they have been shown to increase eccentric hamstring strength and reduce the injury risk to players, but the optimal scheduling of NHE relative to soccer training sessions is unknown. We hypothesized that the adaptation to strengthening exercises may be optimized when performed in a “fatigued” state, after a soccer training session. Therefore, in this research program we undertook two separate studies to examine the acute responses and chronic adaptations to performing NHE’s either before or after soccer training sessions.

In the first study, 8 amateur players attended the laboratory on two separate occasions and performed a 60-min simulated soccer training session. Players performed a program of NHE (6 sets of 5 repetitions) either before (PRE) or after (POST) training, in a randomized manner. Surface electromyography signals (sEMG) of the hamstring muscles were recorded during both NHE and maximal eccentric contractions of the knee flexors, performed at 30°·s⁻¹. Peak torque assessments were administered before and after the NHE program, and at 15-min intervals during the session. 10m sprint times were recorded on 3 occasions during each 15 min segment. Contrary to our initial hypothesis, sEMG during NHE was not different between trials. A greater fatiguing effect was observed in eccentric hamstring strength in PRE (15.6%; likely moderate effect). PRE increased sprinting performance (1.9%; likely small effect), but decreased eccentric hamstring peak torque (-15.3%; likely small effect) during soccer-specific exercise. The results from this study suggested that performing NHE prior to soccer training reduces eccentric hamstring strength and may increase the risk of muscular injury during the subsequent session.

In the second study, amateur soccer players were randomized into 3 training groups for a 12-week intervention. The control group (CON; n=10) undertook core stability exercises, whereas a periodized NHE program was delivered either PRE (n=11) or POST (n=10) bi-weekly training sessions. Outcome measures included peak torque and concomitant peak sEMG of the hamstring muscles during maximal eccentric contractions of the knee flexors, performed at 30°·s⁻¹. Ultrasonography was used to determine muscle thickness and muscle fiber pennation angle. Hamstring extensibility was determined as players self-determined maximum range of motion via passive hip flexion at 5° per second on an isokinetic dynamometer. Performing the NHE derived likely small peak torque increases in both PRE (+12.5%) and POST groups (+8.2%), relative to CON. There were also likely small increases in muscle thickness (PRE: +6.0; POST: 5.7%), and most-likely moderate increases pennation angle (PRE: +23.3%; POST: 17.5%) in the PRE and POST groups versus CON. Between-group differences in sEMG changes were unclear. The NHE program derived hamstring extensibility increases in both PRE (+4.5%; possibly small) and POST (+9.2%; likely small). In this study we concluded that a 12-week eccentric hamstring-strengthening program increased strength via changes in muscle architecture and morphology, and also increased hamstring flexibility in amateur soccer players. As eccentric hamstring strength and flexibility are modifiable risk factors, we would strongly recommend that coaches administer this exercise in field-training sessions to lower the risk of hamstring injury strains. Although we did not see any differences between PRE and POST groups in the chronic intervention
study, we would recommend that the NHE’s be performed at the end of training given our results from the first study.

**Background**

Epidemiological studies have consistently shown hamstring injury strains to have a high prevalence rate in many sports, such as running (11%; 17), Australian Rules Football (16-23%; 22,23,35) and soccer (12-15%; 9,10,11,30,37). Unfortunately, hamstring strain injuries are also considered to be one of the most prevalent factors that determines missed playing or training time in athletes. For example, the English FA revealed that 2,378 professional players missed a total of 13,116 days and 2,029 competitive matches over two soccer seasons, due solely to hamstring injuries (37).

Hamstring injury is predominantly sustained through non-contact mechanisms (91%), with 57% incurred whilst running (37). The most commonly suggested aetiological risk factors for hamstring strain injury are: insufficient flexibility (33,36), inadequate warm-up (7,29), muscle weakness (6,22), strength imbalance between quadriceps and hamstring muscles (6,22), fatigue (18,26,27) and previous injury (24,35). Although injury may occur due to a single factor, it is more likely to be the result of an interaction between multiple risk factors (12).

Eccentric muscular strength deficiency has been the primary focus of hamstring injury research (26,31), particularly as fatigued muscles are more susceptible to strain whilst eccentrically contracting (18). Therefore intervention studies have incorporated the Nordic Hamstring Curl Exercise in an attempt to reduce incidence rates (2,21). This exercise requires the athlete to resist the forward falling motion by eccentrically activating the hamstring muscles (see Figure 1). This particular exercise is acceptable to practitioners because it is simple to administer in field-environments without the need for specialised training equipment. Furthermore, previous research has shown that this exercise increases eccentric hamstring strength (21,31), reduces strength imbalance between the hamstrings and the quadriceps (31) and ultimately reduces the injury prevalence (1,25).

Almost half (47%) of all hamstring strains occur during the last third of the first and second halves of soccer matches (37), suggesting fatigue as a potential predisposing factor to injury. Interestingly, when the Nordic exercises were used as a preventative strategy, hamstring injury incidence rates were not reduced during soccer matches per se (1). Furthermore, we have previously observed no improvement in resting eccentric muscle strength after a programme of Nordic exercises was administered during the ‘cool-down’ of soccer training sessions (31). We suggest two factors that may explain the equivocal findings on the Nordic hamstring exercise and hamstring
strain injury prevention; 1) individual compliance to the exercise task; and 2) performing the exercises in either a fatigued or non-fatigued state.

Firstly, we hypothesise that since the magnitude of resistance to the forward-falling motion, together with the range over which it is applied, are determined by individual, there may be considerable variability in muscle recruitment strategies. Hence the training stimulus may differ both between and within individual training sessions, which may impact on the efficacy of the injury prevention strategy. Therefore, research is required to determine the acute neuromuscular and performance responses to Nordic exercises.

With regards to the timing of the intervention, we previously hypothesised that by implementing a Nordic hamstring programme in a non-fatigued state, any strength gains may not be maintained during the latter stages of matches (31) when players are at greatest risk of injury (37). Strength training injury prevention programmes are typically conducted in a non-fatigued state (1,2,21). Indeed, the FIFA 11+ injury prevention program developed by FIFA was specifically designed to coincide with the warm-up before soccer training sessions, and the efficacy of this programme remains equivocal (4,14). It could be hypothesised that performing strengthening exercises in a fatigued state may help improve and/or maintain strength in a fatigued state. This is supported by other research from our laboratory, showing increased motor unit recruitment when training in a fatigued state (20), which is thought to be crucial for facilitating maximal strength development (15).

To this end we previously investigated the effect of timing of a hamstring strain prevention program upon markers of hamstring injury risk in soccer players (31). We administered prevention programs either before (i.e. during warm-up) or after (during cool-down) soccer training. Both groups incorporated a programme of eccentric hamstring strengthening exercises (21) into bi-weekly soccer training sessions over the 8-week intervention period. The findings indicated that the timing of the strengthening exercises during training sessions affects the temporal pattern of strength gains during simulated soccer match-play. Following the intervention period, players performing the hamstring exercises during the warm-up of training had significantly increased resting eccentric hamstring muscle strength and a reduced hamstring to quadriceps strength imbalance (Figure 2). Conversely, players performing the exercise during the cool-down demonstrated better-maintained eccentric hamstring strength and reduced agonist-antagonist strength imbalance during simulated soccer match-play (Figure 2).

Figure 2: Changes in eccentric hamstring peak torque (A) and functional eccentric
Hamstring:concentric quadriceps ratio (B) between pre- and post- soccer match simulation for cool-down and warm-up groups. Reproduced from Small et al. (31).

Therefore, the fatigued training strategy was shown to reduce the negative effects of fatigue on markers of hamstring injury risk at the ends of each half of simulated soccer match-play. This may suggest reduced risk incurring hamstring strains at the times of highest susceptibility to injury during matches (37). In support of this hypothesis, research has shown reduced injury rates in team-sports players performing generalised injury prevention programmes at the end of their training sessions (34).

However, our original study was limited to muscle strength measures, thus the effects of a Nordic exercise program on other hamstring strain injury factors such as flexibility and passive stiffness are still unknown. Moreover, to date the potential mechanisms that underpin the effect of timing on muscular injury risk factors have not been elucidated. Hence additional study is warranted to examine muscular adaptations following fatigued strength training. This could provide vital knowledge for better understanding fundamental concepts to consider when designing future injury prevention programmes in team-sports.

Objectives

The aim of this research program was to examine the acute and chronic effects of timing of a hamstring strain prevention exercise, upon markers of hamstring injury risk in soccer players. We therefore have two distinct research objectives:

Research Objectives:
1. Examine the acute neuromuscular and performance responses to the Nordic hamstring exercises, in both fatigued and non-fatigued conditions
2. Examine the effects of performing a Nordic injury prevention program, in either a fatigued or non-fatigued state, upon hamstring strain injury risk factors
Methods

Because our study has two distinct research questions, the specific methodologies, results and discussion for each objective will be presented separately. Firstly, we will provide details of the general procedures common to both objectives, thereafter specific experimental details will be presented.

General Methods

Participants

Amateur male soccer players aged between 18 and 35 years were recruited for this research program. The players routinely participated in two training sessions and one competitive match per in-season week. This cohort was chosen due to the fact that NHE intervention was implemented as part of the FIFA 11+ injury prevention program to reduce hamstring muscle strain injuries for amateur players whom may not have access to the necessary equipment and/or the expertise required for eccentric strength training of the hamstring muscle groups (38). Players were free from any musculoskeletal injury and had been so for the preceding 6 months. The procedures for the studies were approved by the local human ethics committee of the University of Western Sydney (H9840) and conformed to the Declaration of Helsinki. Players provided written and verbal consent to participate in the research program.

Players attended the laboratory in a 2-hour post-prandial state, having been instructed to ingest 500 ml of water in the hour prior to arrival. In the preceding 24 hours, a food and fluid intake diary was completed so that it could be replicated for subsequent trials. Fluid intake during laboratory trials was permitted *ad libitum* and recorded during the first experimental visit, and replicated in subsequent trials. Players did not undertake any strenuous or unaccustomed exercise in the 24-hours before trials, and were restricted from alcohol and caffeine ingestion during this time. Repeated trials were scheduled for the same time of day to negate the influence of diurnal variation upon outcome measures (28).

Motor Unit Recruitment

Electromyographic signals were recorded using pairs of AG/AgCl surface electrodes applied to the bicep femoris (BF) and medial hamstring (MH; semitendinosus and semimembranosus) muscles, placed according to previous recommendations (5; see Figure 3). A ground electrode was placed on the most prominent bony aspect of the tibia. EMG signals were recorded at 2000Hz using an analog to digital converter (Powerlab 16/35, ADI instruments, Australia; 16-bit analog to digital conversion), amplified (ML138 Octal Bio Amp, ADI instruments, Australia) and band pass filtered (between 10 and 500 Hz). EMG signals were subsequently rectified and smoothed using a root mean square (RMS) calculation with a 200 ms sliding window to determine the amplitude (mV).
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Hamstring Strength

The KinCom isokinetic dynamometer (Chattanooga, Kin-Com 125 Version 5.32) was used to determine concentric and eccentric strength of the knee flexors at 30°·s⁻¹. Maximal contractions were performed in the right leg of all participants using a cuff applied 2 cm superior to the lateral malleolus. Participants were restrained via straps beneath and above the gluteal muscles to isolate knee flexor muscle activity. Gravity-corrected peak torque was recorded via a strain gauge located in the lever arm of the dynamometer, the pivot arm of which was aligned to the lateral femoral epicondyle (see Figure 4). Torque signals were recorded at 2000Hz using an analog to digital converter (Powerlab 16/35, ADI instruments, Australia; 16-bit analog to digital conversion) and smoothed over 50ms by a digital low pass filter cut off at 50Hz. Maximal force was defined as the greatest torque value recorded during three maximal voluntary eccentric and concentric contractions, which were interceded by 10s rest. Participants were instructed to contract their hamstrings “as fast and as forcefully as possible” throughout the full range of motion, with verbal encouragement provided by two investigators throughout.

Figure 3. Bicep femoris and medial hamstring surface electrode placement.

Figure 4. Isokinetic Dynamometer configuration for hamstring peak torque determination.
Nordic Hamstring Exercises

The eccentric hamstring strengthening exercises were performed with the assistance of a partner as depicted in Figure 1. With the trainee in an upright kneeling position, the partner applied pressure superior to the lateral malleoli to provide stability and to isolate the hamstring muscles. Players were instructed to “lock their hips out” to prevent hip-flexion during the task. Trainee’s then slowly moved the trunk forward and were instructed to control the forward-falling motion by engaging their hamstring muscles for as much of the descent phase as possible. The player then allowed their chest to contact the exercise mat in a prone position, and then pushed forcefully back with the hands to ascend to the starting position with minimal concentric hamstring muscle activity. A metronome was used to control the descent phase as close to 30°·s⁻¹ as possible, with 6-sec rest permitted between subsequent repetitions within a set.

Statistics

Data are presented as mean ± SD unless otherwise stated. Group based differences were assessed using magnitude-based inferences. A priori we determined the minimum practically important difference as 0.2 between-subjects. Using a customized spreadsheet [39], the magnitude of the effect statistic was classified as small, moderate or large via standardized thresholds (0.2, 0.6, and 1.2, respectively) established from the between-subject SD. Mechanistic inferences were determined from the disposition of the 90% confidence interval for the mean difference to these standardized thresholds. Where the difference in percentage distance covered was ≥ 5% in both a substantially positive and negative sense, the true effect was classified as unclear. In the event that a clear interpretation was possible, the following probabilistic terms were adopted: < 0.5 %, most unlikely; 0.5–5 %, very unlikely; 5–25 %, unlikely; 25–75 %, possibly; 75–95 %, likely; 95–99.5 %, very likely; > 99.5: most likely [40].
Study 1: Acute neuromuscular and performance responses to Nordic Hamstring Exercises completed before or after training

Specific Methods

The aim of this first study was to determine the acute neuromuscular performance response to a bout of NHE performed either before or after a simulated soccer training session. 8 amateur players attended the laboratory on two occasions separated by a week. Upon arrival the skin surfaces were prepared for surface EMG (sEMG) measurement of hamstring muscle activation (see details above).

Players then performed a standardized 15-min soccer-specific warm-up routine that consisted of multi-directional running drills and dynamic flexibility actions. Thereafter, priming contractions were performed on the dynamometer to prepare for maximal voluntary contractions (MVC). Three eccentric and concentric hamstring contractions (see details above) were performed at 50% of the players’ self-determined maximum, followed by one 75% effort for each contraction-type. After 60-sec rest players then performed maximal voluntary contractions as described earlier.

Players performed four 15-min bouts of SAFT₉₀; a standardized laboratory exercise protocol designed to mimic the intermittent and multi-directional nature of running in soccer match-play. SAFT₉₀ has been shown to elicit both the internal physiological response, and external loading demands of soccer (16). SAFT₉₀ incorporates varying multi-lateral movements and running velocities are prescribed by an audio CD, which is fixed to ensure that the absolute workload of the players is standardized between repeated trials. During each 15-min SAFT₉₀ segment, the players average 10m sprint times (3m rolling start) was determined using light gates from 3 sprints at standardized time-points. SAFT₉₀ bouts were separated by 4-min rest intervals, during which MVC was measured.

In a counter-balanced fashion, players performed a program of NHE (6 sets of 5 repetitions) either before or after the simulated soccer-training session. 60-s rest was afforded between sets, and the sEMG and knee flexion angle were determined throughout each set. Peak torque assessments with sEMG recordings were administered before and after the NHE program.

Results

The average and peak heart rate response during the SAFT₉₀ bouts was 158 ± 19 and 178 ± 13 beats·min⁻¹, respectively. sEMG during NHE was not different between trials. A greater fatiguing effect was observed in eccentric hamstring strength when the NHE program was administered before training (15.6%; 90% confidence intervals [CI]: 11.0 to 20.3%; likely moderate effect). The concentric hamstring fatigue response to NHE was not different between PRE and POST trials. Performing NHE prior to simulated soccer training maintained baseline sprinting performance, which was lower in the post-trial during the 2nd and 3rd bout of SAFT₉₀ (see Table 1).
Table 1. Between trial differences in sprint performance (s) during simulated soccer training.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th>Difference (% mean; 90% CI)</th>
<th>Qualitative Inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAFT15</td>
<td>1.63 ± 0.03</td>
<td>1.62 ± 0.06</td>
<td>-0.3; -2.9 to 2.3</td>
<td>Unclear</td>
</tr>
<tr>
<td>SAFT30</td>
<td>1.61 ± 0.08</td>
<td>1.64 ± 0.07</td>
<td>2.2; -0.1 to 4.4</td>
<td>Likely small</td>
</tr>
<tr>
<td>SAFT45</td>
<td>1.62 ± 0.08</td>
<td>1.67 ± 0.08</td>
<td>3.0; -1.4 to 7.7</td>
<td>Unclear</td>
</tr>
<tr>
<td>SAFT60</td>
<td>1.62 ± 0.08</td>
<td>1.66 ± 0.07</td>
<td>2.8; 0.5 to 5.1</td>
<td>Possibly moderate</td>
</tr>
</tbody>
</table>

In contrast, eccentric hamstring peak torque was reduced when the NHE program was administered prior to simulated training (see Table 2). Concentric hamstring peak torque was also transiently reduced (possibly small effects, data not shown) for the first 30 min of SAFT90 after NHE’s.

Table 2. Between trial differences in eccentric peak torque (Nm) before and during simulated soccer training.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th>Difference (% mean; 90% CI)</th>
<th>Qualitative Inference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>105.3 ± 24.5</td>
<td>104.6 ± 20.2</td>
<td>-0.1; -7.1 to 7.5</td>
<td>Unclear</td>
</tr>
<tr>
<td>SAFT15</td>
<td>86.8 ± 26.3</td>
<td>97.8 ± 14.8</td>
<td>16.2; -3.6 to 40.2</td>
<td>Possibly moderate</td>
</tr>
<tr>
<td>SAFT30</td>
<td>88.2 ± 29.0</td>
<td>97.4 ± 11.5</td>
<td>15.6; -4.0 to 39.3</td>
<td>Possibly moderate</td>
</tr>
<tr>
<td>SAFT45</td>
<td>89.1 ± 25.1</td>
<td>103.9 ± 13.5</td>
<td>20.1; 0.8 to 43.1</td>
<td>Possibly moderate</td>
</tr>
<tr>
<td>SAFT60</td>
<td>90.3 ± 27.6</td>
<td>92.9 ± 8.0</td>
<td>6.9; -16.3 to 36.6</td>
<td>Unclear</td>
</tr>
</tbody>
</table>

Discussion

To our knowledge, this is the first study to examine the acute performance responses to a program of Nordic Hamstring exercises. This is also the first attempt to determine the impact of the program scheduling in relation to the training session. The major findings in this study were as follows: 1) Eccentric hamstring fatigue was stronger when the NHE were performed before training; 2) NHE before training decreased eccentric hamstring force during simulated soccer training; 3) NHE prior to soccer training maintained baseline sprint performance.

The greater eccentric hamstring fatiguing response to the Nordic program delivered before the simulated training session may be caused by the order effect of the exercises and the degree of engagement during the decent phase of the NHE. Here, we observed no between group differences in motor unit recruitment either during the MVC or the NHE, suggesting that there was no difference in the players’ engagement characteristics during the exercises. The reduced fatiguing effect to the NHE program performed at the end of the training session is therefore most likely a consequence of the reduced strength incurred from 60-mins of intermittent and multi-directional running. The 11-13% reduction in eccentric peak knee extensor torque is commensurate with the declines observed using the SAFT90 protocol in previous research (16,32), considering the differences in task duration and isokinetic speed. Hence the a priori eccentric load placed on the hamstrings during the rapid acceleration and deceleration phases of the SAFT protocol lessened the eccentric training stimulus when NHE were performed after training.

The greater fatiguing effect of the NHE on eccentric hamstring function in PRE persisted throughout the first 45-mins of the soccer training session. In contrast, we did not observe a decline in eccentric hamstring peak torque in the POST trial until 60 mins of the exercise protocol was completed. Previous studies have shown...
eccentric hamstring strength to decline in the latter stages of each half (16,32,42), which may be attributed to the different nature and speed of the hamstring contractions administered in this field of research. Nonetheless, the reduced eccentric hamstring strength in PRE that persisted during training may render the player more susceptible to hamstring injury, since fatigue (18,26,27) and weakness (6,22) are considered as risk-factors for non-contact muscle strains.

A unique and somewhat surprising finding of the current study was the maintained sprint performance throughout the simulated training session in PRE, versus the decline over time in POST. Whilst speculative, the improved sprint performance during training in PRE versus POST might be caused by the reduced antagonistic function of the hamstrings during the deceleration phase of the knee extension during sprinting or directional changes. Further research is required to confirm or refute this observation, and to determine the mechanistic basis for the maintained sprint performance in PRE.

In summary, performing Nordic Hamstring exercises as part of the warm-up for subsequent soccer training induces a strong training stimulus that reduces the eccentric strength of the hamstring muscles for the remainder of the session. Whilst sprint performance was maintained by performing the exercises in the warm-up, it may be caused by the impaired function of the hamstring muscles and thus render the player more susceptible to non-contact strains. Accordingly, we would recommend that Nordic Hamstring Exercises be conducted at the end of field-training sessions, rather than as part of the warm up as prescribed in the FIFA 11+ injury prevention program. Although the FIFA 11+ has been demonstrated as an effective warm-up modality (43), its acute impact upon hamstring muscle function was not examined.
Study 2: Hamstring Injury Prevention in Soccer: Before or after training?

Specific Methods

The aim of this study was to examine the impact of undertaking a chronic NHE program in either a fatigued or non-fatigued state upon hamstring injury risk factors. 42 amateur players were recruited for this study, however data from 31 players was available for analysis due to injury (n=3) and withdrawal (n=8). The players represented 3 amateur teams who undertook two field-based training sessions and one competitive fixture each week during the in-season phase. The trial was administered during the in-season period to attenuate the influence of other training or detraining adaptations. Players were randomly allocated into one of three experimental cohorts; a control group (CON), a NHE program administered either before (PRE) or after (POST) the bi-weekly field-training sessions. Randomization was performed within each squad to limit the influence of training status and load, which may have existed between different teams. Between-group contamination was minimized by single-blinding the players’ to the aims of the study. Research assistants delivered the exercise programs and monitored adherence.

**Table 3. Baseline characteristics of players in each training group**

<table>
<thead>
<tr>
<th></th>
<th>PRE (n=10)</th>
<th>POST (n=11)</th>
<th>CON (n=11)</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>24 ± 7</td>
<td>22 ± 4</td>
<td>24 ± 5</td>
</tr>
<tr>
<td>Stature (m)</td>
<td>1.80 ± 0.06</td>
<td>1.78 ± 0.05</td>
<td>1.79 ± 0.06</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>74.4 ± 11.3</td>
<td>79.3 ± 11.7</td>
<td>80.4 ± 14.9</td>
</tr>
</tbody>
</table>

PRE and POST groups undertook the same 12-week intervention program, outlined in **Table 4**, which consisted of the NHE outlined above. The total volume of NHE repetitions administered in this study was based upon existing research (21,25), though we increased the volume in each session due to the reduced training frequency in our cohort. PRE was administered after the warm-up of each field-session, and players in POST performed the routine at the end of training. The CON group performed core stability exercises (static bench and sideways bench), which were prescribed and periodized according to the FIFA 11+ routine, and delivered before and after training on alternative training sessions to mask the study aims. These core exercises have been shown to have little effect on hamstring motor unit recruitment (41).
The outcome measures in this study were eccentric and concentric strength, passive tissue stiffness, and extensibility of the hamstring muscle group, together with muscle thickness and pennation angle of the BF. Players attended the laboratory within 7 days of commencement and cessation of the 12-week program to determine changes in the outcome measures.

Hamstring Muscle Architecture

A sagittal view of the biceps femoris was collected via ultrasound whilst players lay supine with the knee of their dominant leg positioned at 45°. A 7.5 MHz linear array transducer (Chison 8300 Digital Ultrasound System, China) was applied to the lateral posterior portion of the BF to determine muscle thickness and pennation angle. Muscle thickness was recorded as the average perpendicular distance between the deep and superficial aponeurosis, as recorded at 3 points distributed evenly across the field of view. Pennation angle was determined as the mean angle of three muscle fascicles relative to their insertion at the deep aponeurosis (see Figure 5). Three images were collected during each laboratory visit and the average values recorded for both muscle thickness and pennation angle were used for subsequent analysis.

Figure 5. An ultrasound image of the biceps femoris. The line (AB) represents the superficial aponeurosis. The line (CD) represents the deep aponeurosis. Pennation Angle was determined as the line of best fit placed along a fascicle relative to the deep aponeurosis. Reproduced from (55).
Instrumented straight leg raise (iSLR)

The instrumented straight leg raise (iSLR) test was used for measurement of maximum leg excursion angle (\(\text{leg}^{\circ}_{\text{max}}\)), maximal stiffness (\(\text{Me}_{\text{max}}\)), and passive stiffness using the KinCom isokinetic dynamometer (Chattanooga, Kin-Com 125 Version 5.32). Participants lay supine with straps across the trunk, hips, and opposite thigh to isolate the movement to the fully extended left-leg. Following familiarization with the experimental set-up and preliminary movement through a partial range of motion, the hip was passively flexed through the players self-determined maximum range of motion by the dynamometer at a movement velocity of 5° per second (see Figure 6). The iSLR protocol has good reproducibility (ICC \(r=0.94\)) and has been shown to be more sensitive to training related changes than manual straight leg raise methods (13). Hamstring extensibility was defined as the maximum angle of the leg (\(\text{leg}^{\circ}_{\text{max}}\)) in the horizontal plane determined as the angular position of the lever arm of the KinCom relative to the initial starting position (leg fully extended in line with the trunk 0°). \(\text{leg}^{\circ}_{\text{max}}\) has been identified in the literature as a reliable measure of hamstring extensibility (19).

![Figure 6. Instrumented straight leg raise (iSLR) configuration](image)

Hamstring stiffness was determined during the iSLR from the active torque required to lift the left-leg throughout the range of motion. Passive torque of the limb was measured \textit{a priori} and deducted from absolute torque values for each data point during leg raising. The remaining value provides a measure of the resistance to deformation of the leg independent of individual leg weight. Peak stiffness of the muscle was defined as the peak torque calculated during leg excursion, whereas passive tissue stiffness was recorded as the torque-angle slope (Nm°\(^{-1}\)) through the common range of motion (20-50°). Analysis through the common range of motion allows comparison of passive tissue stiffness between participants independent of total hamstring extensibility. Maximum leg excursion angle (\(\text{leg}^{\circ}_{\text{max}}\)), maximal stiffness (\(\text{Me}_{\text{max}}\)), and passive stiffness were taken from the average of three repeated iSLR trials separated by 60-s rest.
Results

Performing the NHE derived likely small peak torque increases in both PRE (+12.5%; 90% confidence intervals [CI]: 2.8 to 23.1%) and POST groups (+8.2; CI: -2.2 to 19.8%), relative to CON. There were also likely small increases in muscle thickness (PRE: +6.0% [CI: 0.7 to 11.5%]; POST: 5.7% [CI: 2.6 to 8.8%]), and most-likely moderate increases pennation angle (PRE: +23.3% [CI: 15.6 to 31.5%]; POST: 17.5% [CI: 9.5 to 26.1%]) in the PRE and POST groups versus CON. Between-group differences in sEMG changes were unclear. Only pennation angle was different between treatment groups, with a likely greater (small) increase in PRE versus POST (+4.8; CI: -0.1 to 9.3%).

The POST group had likely small increases in leg⁠^max (+9.2%; CI: 2.2 to 16.6%), with possibly small increases for PRE (+4.5%; CI: -2.2 to 11.7%), versus CON. The changes in leg⁠^max were possibly greater (small) in POST than PRE (+4.4%; CI: -3.1 to 12.6%). POST also yielded possibly small increases in Me⁠^max in comparison to both CON (+16.2%; CI: -3.6 to 40.1%) and PRE (+14.9%; CI: -4.7 to 38.7%). Passive tissue stiffness was decreased in PRE versus both CON (very likely moderate effect; -25%; CI: -7.9 to -39.0%) and POST (likely small effect; -26.8%; CI: 7.5 to -73.7%).

Discussion

The aim of this study was to examine the effects of a NHE program upon hamstring strain injury risk factors. We also examined if performing the program either before (non-fatigued) or after (fatigued) bi-weekly field-based training sessions influenced neuromuscular, architecture and morphological adaptations. The key findings of this study were as follows: 1) The NHE program improved eccentric hamstring peak torque and Bicep Femoris muscle thickness; 2) hamstring extensibility was increased in both NHE groups, with greater increases observed in the POST group; 3) Bicep Femoris pennation angle increased in both training groups, but the effect was greater in PRE.

Deficiencies in eccentric hamstring strength are a commonly cited risk factor for hamstring muscle strain injuries (6,35,47,48). Thus, injury prevention programs have included eccentric strength training exercises for the prevention of hamstring muscle strain injuries (1,25,45). Furthermore, the NHE has shown to be an effective exercise for the development of eccentric hamstring strength (21,31,46) and reducing hamstring injury rates (1,25,45). The findings of the present study, support previous research showing increases eccentric strength following an intervention using the NHE (21,31,46). We observed 12.4% and 8.5% increases peak eccentric strength for the PRE and POST groups, respectively, when compared to the control group (-0.2%). These findings are somewhat similar to previous research by Small et al. (31), who observed an increase of 6.7% in peak eccentric hamstring strength when the NHE was performed during the warm-up of soccer training sessions. However, in contrast to the present study’s findings, Small et al. (31) observed no changes in baseline eccentric strength, when the NHE was performed during the cool-down of training sessions.

Furthermore, several other studies examining the NHE strength training intervention have also reported somewhat similar increases in peak eccentric strength to those found in the present study. Iga et al. (46) observed increases of 14.8% and 20.2% in eccentric strength for the respective dominant and non-dominant limbs. Mjolsnes et al. (21) observed an 11% increase in strength. However, we would urge caution in comparing the magnitude of strength changes between studies because of the

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differences in isokinetic dynamometer protocols (i.e. position and dynamometer velocity) and the volume and periodization of NHE intervention programs.

The current NHE training prescription as recommended by FIFA 11+ is one set of three to five repetitions for beginners, 7-10 repetitions for intermediates and 12-15 repetitions for advanced individuals (49). Yet, the total volume prescribed (number of repetitions performed) in the studies examining the effect of NHE is much greater than these current recommendations. Additionally, a large variation in the total volume prescribed in each of the previous studies is evident. Iga et al. (46) implemented a four-week strength training intervention period that consisted of 154 repetitions. Mjolsnes et al. (21) utilised a 10-week strength training intervention comprising of 826 repetitions. While Small et al. (31) administered an eight-week intervention comprising of 610 repetitions. The present study prescribed a total of 684 repetitions over a 12-week intervention period. However, due a lack of compliance in the study, the average number of repetitions performed was 242 and 320 for the PRE and POST groups, respectively. Whilst there are clear differences between the volumes performed in each study, the increases in peak eccentric torque are somewhat homogenous. Therefore, despite the poor compliance rate of players’ in the current study, performing NHE exercises had improvements in strength and potentially rendered the players’ less susceptible to non-contact hamstring strains during training and matches. We would therefore recommend that amateur players perform this partner exercise as part of their routine field-training sessions.

We hypothesized that performing the NHE program in a fatigued state after a training session would optimize the strength adaptations. Previous research has shown an increased motor unit recruitment when training in a fatigued state (20), which is thought to be crucial for facilitating maximal strength development (15), particularly in the early stages of a strength-training program (44). Contrary to our hypothesis, we did not observe any between group differences in the eccentric hamstring strength gains when performing the NHE program before or after soccer training. Moreover, we observed no changes in peak sEMG during maximal voluntary eccentric contractions as a result of the training regimens. Maximal sEMG changes following strength training typically indicate the degree of change in the magnitude and size of motor units recruited as well as the firing rate of these motor units (51). However, previous research has also observed strength training adaptations were not accompanied by sEMG increases when concurrent training interventions were administered (50). The lack of sEMG changes in our POST group might also be explained by the neural inhibition identified following exhaustive aerobic (52) and soccer specific (42) exercise. However, changes in sEMG signals are unable to measure motor unit synchronisation, activation of synergists and antagonists and therefore cannot be considered to reflect the totality of complex neural adaptations (44). Accordingly we would advocate further research to examine the specific neural responses and adaptations to injury prevention exercises performed before and after field-sessions in team sports.

This is the first study to examine the mechanisms that underpin eccentric hamstring strength gains to a NHE program. Although we did not observe the expected neural adaptations to the program, Bicep Femoris thickness was increased in both NHE groups. The increased muscle thickness was accompanied by an increase in the angle of pennation in PRE and POST groups. Our data supports previous research that has also observed structural changes such as hypertrophy and an increase in muscle fascicle pennation angle with eccentric strength training-induced improvements in muscle force generating capacity (56). A greater angle of pennation increases the physiological cross-sectional area of the muscle, which is
generally acknowledged to represent a greater number of acto-myosin cross bridges activated in parallel, thus enhancing the contractile force generating capacity (56). Therefore, the present results suggest that the increases in eccentric strength we observed reflects a change in the muscles architectural and morphological properties as opposed to an improvement in neural factors. Whilst pennation angle changes were greater in the PRE group, the between group differences in muscle thickness and strength gains were unclear.

Flexibility is also considered as a major risk factor in hamstring strain injuries (33,36), with reduced extensibility associated with injury likelihood (36). In the current study, players who were allocated to the NHE groups demonstrated increases in hamstring extensibility as determined by the maximum leg excursion angle tolerated during passive hip flexion. Extensibility increased by 6-9° in both NHE groups, but improvements were greater in POST versus PRE. Correspondingly, increases in the maximal passive torque that could be tolerated were only observed in the POST group. Whilst this data would support the notion of undertaking the NHE after field-based training sessions, we cannot discount that volitional stretch tolerance is a primary determinant of extensibility measurements. Therefore the ability of the POST group to tolerate higher passive torques might merely represent between group disparities in the players’ perceptions of hamstring pain. Indeed, decreases in passive stiffness during the common range of motion were only identified in the PRE group. These reductions are indicative of a reduced resistance to muscle elongation that reflect changes in the mechanical components of muscle function (19,53).

Whilst the mechanistic nature of extensibility changes in PRE and POST groups were somewhat paradoxical, the increased hamstring extensibility derived from the NHE program further demonstrates the appeal of this exercise in reducing the injury risk factors associated with hamstring injury strains. This assertion is supported by research in Rugby, which identified that players’ performing the NHE in combination with a passive stretching program had a reduced incidence and severity of hamstring injuries (54).

Conclusions and Recommendations

In summary, the current study supports previous research that has identified improvements in eccentric hamstring strength and flexibility following a program of Nordic hamstring exercises. As eccentric hamstring strength and flexibility are considered modifiable risk factors to hamstring injury, improvements in these attributes with a program of Nordic hamstring exercises have been shown to reduce the incidence and severity of hamstring injury strains (1,25,45,54). For this first time, this study has identified the mechanism of adaptation to a chronic NHE training regime. Strength adaptations were primarily derived from hypertrophy and increases in muscle pennation angle, rather than optimized neural functioning. Whilst subtle mechanistic differences were apparent between performing the program before or after bi-weekly field training sessions, holistically speaking there were unclear differences in the training adaptations. Therefore, we would recommend that amateur players undertake Nordic hamstring exercises on a bi-weekly basis to reduce their risk of hamstring injury strain. Although we observed no differences between the PRE and POST groups in the current study, we would recommend that the exercises be performed after the field-training sessions, given the fatiguing nature of exercise, which, if performed prior to training, may increase the likelihood of injury during the subsequent training session.
Project Limitations

The main limitation to this research program was the comparatively poor adherence rates of the players’ to bi-weekly field-based training sessions, and thus to the program of Nordic hamstring exercises that we administered. The compliance rate for this training study was 36.9 ± 11.1% (243 ± 82 repetitions) and 43.0 ± 21.1% (320 ± 108 repetitions) of the 23 scheduled sessions during the 12-week intervention for the PRE and POST groups, respectively. Whilst this compliance rate was much lower than anticipated, and was higher in the POST group, we observed no relationship between the volume of repetitions performed and the changes in peak strength. Nonetheless, the low compliance rates potentially masked any between group differences in the adaptations to training, together with their mechanistic underpinnings. Accordingly we would recommend that further research is undertaken in a more controlled laboratory context to determine the effects intervention timing, relative to training sessions, upon adaptations to injury prevention routines, and in particular the Nordic hamstring exercise given the high incidence rate of hamstring injuries in professional and amateur cohorts. Whilst we could not determine between-group differences in this study, the improvements in both eccentric hamstring strength and flexibility derived from low compliance rates suggests that players can modify these injury risk factors with a relatively low volume of Nordic hamstring lowers. Therefore we would strongly recommend that coaches incorporate these exercises during either the warm-up, or preferably during the cool-down of field training sessions.

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Research Dissemination

The following abstracts have been accepted for presentation at International conferences:


In addition to the two studies that have been documented in this report, the data collected during this research program has enabled us to answer other research questions that are related to this topic area. Therefore we anticipate the following published journal articles will be derived as a consequence of this research grant:


Upon completion of this final report, the investigators will begin dialogue with Football New South Wales, the Macarthur District Soccer Football Association, and Football South Coast to identify avenues of dissemination to Soccer coaches and players’ in the state. We hope to share the knowledge generated as a consequence of this research program via websites, newsletters, posters and talks.
References


