Changes in torque-angle profiles of the hamstrings and hamstrings-to-quadriceps ratio following two hamstrings strengthening exercise interventions in female hockey players

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Brief running head: Effects of two strengthening programmes on the torque-angle profiles of the hamstrings.

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ABSTRACT

The aim of this study was to compare the effects of two hamstrings strengthening interventions (nordic hamstrings (NHE) *vs.* eccentric leg curl (ELC)) on the hamstrings torque-angle profiles and functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}) in female hockey players. Female university-level players were randomly allocated to a NHE (n=9, 19.7±1.4 years; 168.4±4.4 cm; 66.2±7.2 kg, 26.0±4.4 %), ELC (n=8, 19.5±1.0 years; 168.1±3.4 cm; 66.7±4.5 kg, 24.8±3.5 %), or control (C) group (n=8, 19.6±1.4 years; 169.9±7.5 cm; 70.7±13.0 kg, 25.9±5.2 %). They performed baseline isokinetic concentric strength tests of the quadriceps (Q_{con}) and eccentric strength of the hamstrings (H_{ecc}) at 120º.s^{-1}, followed by a six-week intervention with exercises (NHE or ELC) performed three times weekly, before post-tests. Analyses of variance with repeated measures were used to assess the effects of knee position angle (from 90° of knee flexion to 10° close to extension), group and time on Q_{con}, H_{ecc} and H_{ecc}:Q_{con}. There were no interactions between independent variables. Significant increases in H_{ecc} and H_{ecc}:Q_{con} were shown after NHE (+29.9% and +27.8%) and ELC (+30.5% and +38.3%) in the non-dominant leg only. Furthermore, significant shifts in the hamstrings eccentric angle of peak torque (APT) towards a longer muscle length were shown in both legs (14.3 to 28.6%). These findings suggest that NHE and ELC both resulted in significant improvements in peak and muscle-length-specific neuromuscular risk factors in the non-dominant (ND) limb, thereby reducing interlimb peak strength asymmetries. Strength and conditioning specialists could therefore use both the NHE and ELC exercises in female hockey players.

Key words: nordic hamstring, eccentric leg curl, asymmetry, angle of peak torque.

INTRODUCTION

Hamstring strain injuries (HSI) are amongst the most commonly reported injuries in team sport players (17,44). The risk of HSI is multifactorial and influenced by both modifiable and non-modifiable factors, with modifiable neuromuscular factors such as strength and strength imbalance of considerable interest (27) to strength and conditioning practitioners. Early studies suggested that excessive agonist-antagonist imbalance represented by low eccentric or concentric hamstring to concentric quadriceps peak torque ratios (H_{con}:Q_{con} and H_{ecc}:Q_{con}), are a risk factor for HSI in soccer and Australian football players (15,32). There is also evidence in rugby and soccer players that greater than 15% inter-limb hamstrings strength imbalance (4,18) is a risk factor for HSI. In addition to peak strength values, it has been suggested that the angle at which peak torque is produced (APT) and force production specifically in greater extension may also be relevant to HSI risk (6,36). Indeed, strains commonly occur at knee extension angles of 0 to 30° (39), yet hamstring eccentric peak torque is typically reported at angles greater than 30° of flexion (9,11).

While not all prospective HSI risk studies have confirmed these neuromuscular factors associations (42-43), there are a number of intervention studies aimed at increasing eccentric hamstring strength or reducing agonist-antagonist and inter-limb imbalance which have been successful in reducing HSI incidence (20,37,44). It has also been proposed that a shift in the angle of eccentric peak torque (APT) of the hamstrings towards longer muscle lengths, usually achieved with eccentric strength training, may partly mediate its protective effect against HSI (11-12). These findings suggest the need for further studies in this area. In particular, it would be interesting to consider all the above-mentioned risk factors in the same study to get a better understanding of some of the specific adaptations associated with various exercise-based interventions.

In practice, training interventions include a variety of exercises (11,32), while in the research context, understanding the specific effects of particular exercises may necessitate implementing single exercise interventions. Indeed, this can help strength and conditioning coaches to select the relevant exercise(s) targeting specific risk factor(s) according to their athlete's neuromuscular profile. One of the most extensively evaluated eccentric exercises in HSI risk reduction interventions is the Nordic Hamstrings (NHE) and large decreases (65-70%) in HSI incidence were observed in soccer players who participated in programs including NHE (20,33). Nonetheless, two specific concerns have been raised about the NHE. Firstly, it is suggested that it may provide a lower stimulus for adaptations in extended knee positions in weaker individuals who cannot maintain control in this position (7,9,26) and secondly, that in individuals with a large hamstring strength asymmetry, the exercise may lead to greater adaptations in the stronger leg, hence increasing inter-limb asymmetry (11,28,40). However, as there is evidence that lower strength adaptations closer to extension (31) or increased asymmetries (11) following interventions based on the NHE, these concerns may not be well founded,

Nonetheless, the eccentric leg curl (ELC) is a potential alternative exercise also commonly performed in injury prevention programs (3,21,24) and 10 weeks of twice weekly eccentric overload leg curl training using the Yo Yo device was associated with a reduction in HSI incidence of 23.7% and a 65% decrease in injury severity in elite soccer players (21). The ELC can also be performed using bodyweight only, using a suspension device, making it**,** like the NHE, an accessible exercise. To our knowledge, however the effects of the ELC performed without external load, on eccentric strength or other HSI risk factors has not been specifically evaluated.

Within this context, the aim of the present study was to compare the effects of the NHE and the suspension ELC bodyweight exercises on a variety of isokinetic hamstring strength measures and indices considered to be associated with HSI risk in female field hockey players. We hypothesized that, compared to the ELC, the NHE would be less effective in promoting improvements in eccentric torque closer to full extension and would lead to larger increases in strength on the dominant (D) limb and increase asymmetries in those with greater asymmetry at baseline.

METHODS

Experimental Approach to the Problem

This study used a single-blinded (examiner) randomized control trial design to compare the chronic effects of two strength exercises on hamstrings injury risk factors. To randomize, subjects were first divided according to playing position and then picked a group from a hat, so that each group comprised of a mixture of playing positions. Testing order was according to entrance into the study. The NHE was chosen based on its common use in strength and conditioning and injury prevention programs for team sport players, while the suspension ELC is a more novel exercise, less studied in the literature, but also performed without external loading. These exercises also differ in that the NHE is a knee-dominant exercise, while the ELC involves both the knee and hip joints. The dependent variables, including peak torque, interlimb peak torque asymmetry and H_{ecc}:Q_{con}, e.g., (10-11) were selected as they are consistently cited in the literature as neuromuscular factors relevant to hamstrings injury risk. Angle of peak torque and torque-angle profiles are less well studied, but they have received recent attention as potential mediators of risk (12,26,38). Each participant attended the laboratory on two separate occasions, to perform baseline and post-intervention measurements, respectively. Tests were performed at the same time of the day to minimize performance variations due to circadian rhythms. Between baseline and post-intervention tests, subjects in the two training groups (NHE and ELC) were requested to perform a specific training program three times weekly for six weeks in addition to their hockey training, while the control (C) group only took part in the weekly hockey training.

Subjects

Participants consisted of 30 university-level female hockey players who were currently without lower limb injury and with no history of a hamstring tear or an ACL injury in the past year. This sample size was determined by an a priori power analysis (G*power 3.0, Dusseldorf University, Germany) based on similar previous studies (10,12). At the time of the study, all subjects trained for two hours, twice a week and competed in British University and College Sport leagues (Premier South division and Midlands division 2A) once a week. They were randomly divided into three groups: A Nordic Hamstrings exercise training group (NHE, n=10), an eccentric leg curl training group (ELC, n=10) and a control group (C, n=10). Five subjects dropped out during the course of the study due to injuries (n=3), or lack of commitment to the training program (n=2), (Figure 1). Therefore, data collected for these subjects was removed, resulting in the following demographic and anthropometric data characteristics: NHE (n=9, age: 19.7±1.4 years; height: 168.4±4.4 cm; body mass: 66.2±7.2 kg, body fat: 26.0±4.4 %), ELC (n=8, age: 19.5±1.0 years; height: 168.1±3.4 cm; body mass: 66.7±4.5 kg, body fat: 24.8±3.5 %), C (n=8, age: 19.6±1.4 years; height: 169.9±7.5 cm; body mass: 70.7±13.0 kg, body fat: 25.9±5.2 %). All procedures were in accordance with, and approved by, the University's Ethical Research Committee standards. Written informed consent to participate in the study was obtained for each participant.

Baseline and post-intervention sessions

These sessions consisted of measuring the eccentric strength of the hamstrings (H_{ecc}) and the concentric strength of the quadriceps (Q_{con}, to calculate H_{ecc}:Q_{con}) for both legs. The leg with the greater H_{ecc} at 30° at baseline was defined as dominant (D), while the contralateral leg was referred as the non-dominant (ND). The angle of 30° was chosen as it has previously been reported as the angle of hamstring eccentric peak torque (10-11). Strength tests were preceded by a 10-min warm-up on a cycle ergometer (Monark 874E, Varberg, Sweden) at an intensity of 100W with four intermittent 6-second sprints at the 6th, 7th, 8th and 9th minutes (min), a warm-up performed in several similar studies (11,16). Strength measurements were performed on an isokinetic dynamometer (Biodex system 2, Shirley, NY, USA). Leg testing order was randomized by having each consecutive subject tested on the opposite leg as the previous one. This was automatically achieved by using the second position (left or right) of the dynamometer for one subject being used as the first for the next subject. Subjects were seated with their hips flexed at approximately 90º. Stabilization straps to the trunk, thigh, and tibia where attached to prevent any extraneous joint movement. The axis of rotation of the dynamometer lever arm was visually aligned with the lateral femoral condyle, and the lower leg was attached to the lever arm of the dynamometer at the level proximal to the malleoli. Subjects familiarized themselves with each contraction type by performing several sub-maximal trials, and then performed five maximal trials for each condition at a velocity of 120°/s. This velocity was chosen to allow safe and reliable measurements of concentric and eccentric strength (38). The range of motion was 0° (full knee extension) to 90°. Players were encouraged to provide maximal effort throughout and requested to keep their ankle in the neutral position (13). Muscle groups and right and left leg conditions were randomized between subjects, but each participant performed the tests in the same order at baseline and post-intervention.

Torque-angle profiles for each Q_{con} and H_{ecc} were extracted using custom algorithms created in Matlab (MathWorks Inc., Natick, MA, USA). Gravity-corrected torque values were quantified as the average of 5 trials, with each trial maintaining the required 120 °/s angular velocity for at least a range of motion (ROM) of 70°, and with each trial reaching a peak torque that is at least 90% of the highest peak torque registered across the 5 trials (2). The five torque-angle profiles were subsequently averaged using a 10-point smoothed average with a 1° resolution. From this averaged torque-angle profile the following variables were then determined for D and ND :

- Absolute torque (N·m) for every 10° throughout the ROM (10° to 90°) for Q_{con} and H_{ecc}.
- Absolute peak torque (N·m); the highest torque produced within the ROM.
- Angle of peak torque; the angle at which absolute peak torque was produced ((APT, º).
- Functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}); the ratio of the eccentric torque of the hamstrings and the concentric torque of the quadriceps, for every 10° throughout the ROM (10° to 90°).
- Peak H_{ecc}:Q_{con}: the highest value for this ratio within the ROM.

Strength exercises

Following baseline testing, subjects in both training groups (NHE and ELC) completed a six week, three times weekly exercise protocol. The exercise protocol was performed twice weekly during hockey practice sessions supervised by the coach, while the other weekly session was performed outside practice sessions (unsupervised) at the team's training facilities. Both exercises involved players working in pairs, with the non-exercising player helping the exercising player to get back into the starting position between repetitions and sets. The difficulty of the exercise was progressed by moving the catch position (where subjects "catch" themselves on the floor using their arms in a push up position) further towards knee extension (NHE, depending on individual progression), and overload was also increased by increments in volume (Table 1).

In the NHE group (Figure 2c and 2d), players started in an upright, kneeling position with hips at full extension and lower legs secured by a partner applying pressure to ensure feet stay in contact with the floor at all time. They were requested to slowly lower their body (over 3 to 4 s) forward towards the floor, while keeping a neutral alignment between trunk and hip joints and using the hamstrings to control the descent. Subjects were encouraged to hold the hamstrings eccentric action for as long as possible, and when they could no longer control the movement, they were instructed to "catch" themselves on the floor using their arms in a push up position. They then passively returned to the start position.

The ELC exercise (Figure 2a and 2b) involved the use of a suspension trainer (TRX training UK). Subjects started in a supine position on the floor, with the suspension trainer attached to a solid structure above them, heels of both legs placed into straps, which were in a vertical position. Strap length was adjusted to subjects' anthropometric characteristics. Subjects were requested to extend their hip to move into a bridge position (hips, trunk and legs aligned at 180º), and were then passively pushed into a flexed position (both hips and knees flexed at 90º) by a partner to avoid a concentric contraction of the hamstrings. The active part of the exercise started with subjects extending their knees and hips in a slow controlled manner (within 3 to 4 s) until legs, hips and trunk were aligned (180º)-constituting one repetition. The previous steps were then repeated (passive flexion with the help of a partner, then controlled extension), without letting the hips touch the floor at any time. Therefore, in both exercises only the eccentric phase was active

Statistical Analyses

Statistical analyses were performed using SPSS statistical software (version 23.0). The parametric nature of the data was checked using the Shapiro-Wilk test. Subsequently, differences in baseline characteristics between groups were assessed with a one-way ANOVA, followed by a Scheffe post-hoc test. A three-way mixed factorial ANOVA with repeated measures was used to assess the effects of angle (10°, 20°, 30°, 40°, 50°, 60°, 70°, 80° and 90°), group (NHE, ELC and C) and time (baseline vs. post-intervention) on absolute torque values for Q_{con}, H_{ecc} and H_{ecc}:Q_{con}. Other dependent variables, including peak torques, peak H:Q ratios and APT were assessed by a two-way ANOVA with repeated measures (time x group). If the ANOVA revealed a significant interaction, Student T-tests for paired samples were performed to determine where differences lay. Effect sizes were calculated using Cohen *d* and interpreted as small (>0.2), medium (>0.5), and large (>0.8), (13). Each dependent variable was presented as mean and standard deviation (Mean±SD), and 95% confidence interval limits for the differences tested (95% CI) were also shown. Finally, in order to determine whether the magnitude of D or ND leg adaptations to either NHE or ELC training was influenced by interlimb asymmetry, the association between asymmetry in PT and APT at baseline and changes (%) in PT and APT, respectively, was checked by a Pearson correlation coefficient. For all these analyses, a p value inferior to 0.05 was considered statistically significant.

RESULTS

There were no significant between group differences in baseline demographic and anthropometric data (P>0.05).

Hamstrings eccentric contractions (H_{ecc})

The ANOVA showed a significant effect of time, and a significant interaction between time and group on the eccentric peak torque of the hamstrings in the ND leg ($p<0.05$, Table 1) but no significant effects on the D leg ($p>0.05$, table 1). Pairwise comparisons in the ND leg revealed significant increases between baseline and post-intervention tests in the ELC group (p=0.003, d=1.02, 95% CI: 7.4 to 23.7) and in the NHE groups (p=0.005, d=0.73, 95% CI: 3.1 to 20.4, Table 1) only.

We observed a significant effect of time on APT in both legs ($p<0.05$, Table 1) and a significant interaction between time and group was observed in the D leg only ($p<0.05$, Table 1). Post-hoc analyses showed significant decreases in APT of the ND in all groups (p=0.009, d=1.26, 95% CI: -9.0 to -1.5), and significant decreases in APT of the D leg for the ELC group (p=0.011, d=0.62, 95% CI: -10.6 to -1.9) and the NHE group (p=0.002, d=0.89, 95% CI: -13.5 to -2.0) only.

Quadriceps concentric contractions (Q_{con})

There was no significant effect of time, group or time x group interaction on the quadriceps concentric PT or APT ($p>0.05$, Table 1).

Functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con})

We found significant effects of time, and a significant interaction between time and group on H_{ecc}:Q_{con} in ND leg only ($P<0.05$, Table 1) but not in the D leg ($p>0.05$, Table 1). Pairwise comparisons in the ND leg showed signicant increases between pre- and post-tests in the ELC group (p=0.005, d=1.31, 95% CI: 0.09 to 0.36) and NHE group only (p=0.037, d=0.83, 95% CI: 0.01 to 0.30).

Torque-angle profiles

The three-way ANOVA examining the torque-angle relationship for H_{ecc} showed significant effects of time (p=0.023, d=1.04, and p=0.001, d=2.28, respectively for the D and ND legs) and angle (p=0.001, d=3.10, and p=0.001, d=2.91, respectively for the D and ND legs). In addition, we found a group x time interaction (p=0.002, d=1.79) in the ND leg only. In this group, pairwise analyses showed a significant increase in Hecc between pre- and post-testing in the ELC group (p=0.009, d=2.69) and NHE group (p=0.003, d=3.46) only (Figure 1).

There was no significant effect of any variable, except angle (p=0.001, d=4.18, and p=0.001, d=4.00, respectively for the D and ND legs) on Q_{con}.

The analysis of H_{ecc}:Q_{con} showed a significant effect of angle in both legs (p=0.001, d=3.65, and p=0.001, d=2.67, respectively in the D and ND leg legs). In addition, there was a significant effect of time (p=0.036, d=1.15) and a significant interaction between time and group (p=0.048, d=1.06) in the ND leg only. Pairwise comparisons in this group revealed a significant increase in H_{ecc}:Q_{con} between pre- and post-intervention in the ELC (p=0.044, d=1.03) and NHE (p=0.043, d=1.03) groups only (Figure 2).

Correlations

We found a significant negative correlation between PT asymmetry at baseline and PT change between pre- and post-intervention in the D leg for the ELC group (r=-0.768, p=0.026). In addition, we observed a significant positive correlation between PT asymmetry at baseline and PT change between pre- and post-intervention in the ND leg for the NHE group (r=0.907, p=0.002). A significant positive correlation was also shown between between APT asymmetry at baseline and APT change between pre- and post-intervention in the ND leg for the NHE group (r=0.822, p=0.012). Finally, we observed a significant positive correlation between between APT asymmetry at baseline and PT change between pre- and post-intervention in the ND leg for the NHE group (r=0.869, p=0.005).

DISCUSSION

While in practice preventive interventions usually integrate various exercises within a program, we compared the NHE and ELC in separate single exercise strength training interventions to isolate adaptations in PT, APT and asymmetry associated with each exercise. We hypothesized that, compared to the ELC, the NHE would be less effective in promoting improvements in eccentric torque closer to full extension and would lead to larger increases in strength on the dominant limb and increase asymmetries in those with greater asymmetry at baseline. We found that the NHE and ELC resulted in similar significant increases in PT in the ND leg only, and significant shift in the hamstrings eccentric APT towards a longer muscle length in both legs. In addition, both exercises reduced asymmetry in PT and APT. Therefore both of our hypotheses were rejected.

Peak torque (PT) changes

Significant increases were noted following both exercise interventions in the ND leg only (from 29.9 to 30.4%). The greater gains observed in the ND leg following the NHE are in line with the results of Mendiguchia et al. (28) in healthy individuals. However, PT gains following strength trainingprograms including or solely using the NHE show contrasting results, with no significant increase in eccentric peak torque reported after four week interventions in recreational athletes and soccer players (9,11), while significant improvements of up to 21% were observed over the same duration in another study in soccer players (22). The contrasting results between our findings and those from the two above-mentioned studies could be due to sport speciality (hockey *vs.* soccer) or gender, but the paucity of literature on specific hamstring strengthening in hockey players (34) prevents us from making a direct comparison with previous work. Regarding gender, previous literature suggests that the NHE may not be as beneficial in females compared to males, due to weaker muscles and lack of muscle control during the last phase of the exercise (24). However, the positive adaptations reported after the NHE in females in the present study do not support this concept, highlighting the need for further studies in this area. Interestingly, Matthews et al. (26) also found significant inprovements in the hamstrings eccentric PT measured in a fatigued state following an assisted NHE training intervention. These results, together with our findings on the NHE and ELC, suggest that significant peak eccentric strength improvements can be achieved with either of these bodyweight only conditioning exercises. Therefore, strength and conditioning coaches aiming at improving peak strength could use both of these exercises to increase variety in their programs.

Associations between asymmetry and adaptations

We found a significant positive correlation between baseline interlimb PT asymmetry and increase ND leg PT following the NHE exercise. Participants with greater asymmetry at baseline had a greater increase in PT in the weaker ND leg, therefore contrary to concerns that the NHE may magnify strength asymmetries, it appears to reduce them. Similarly, there was a significant negative correlation between baseline interlimb PT asymmetry and change in PT in the D leg following the ELC exercise, whereby the increase in PT in the D leg after ELC was lower in participants with greater baseline asymmetry. These findings may be somewhat counterintuitive and appear to contradict observations in athletes in whom asymmetry is caused by previous injury. Bourne et al. (3) observed that in athletes with prior hamstring injuries, activation was lower in the previously injured/weaker limb during the NHE, while a pattern of offloading of the previously injured limb was described by Roos et al (35) during the squat exercise in individuals with prior anterior cruciate ligament reconstruction – both observations suggesting that in those individuals, performing these bilateral exercises could exacerbate their asymmetries

Potentially, the pattern of gains in the ND leg could be relate to the degree of PT asymmetry in the present sample, which appears to be higher than in other sports (17.6% *vs.* 9.0% in female soccer players of a similar level, (16)).

Field hockey is an asymmetrical sport, since all players hold the stick and strike the ball with their right arm and left leg dominance has previously been reported in female field hockey players, with significantly greater lean mass and bone mineral density observed in the left compared to the right side in the female Polish national team (23). The association between interlimb asymmetry and injury risk has to our knowledge not been examined in hockey players, however, an interlimb eccentric peak torque asymmetry greater than 15% was associated with elevated risk of HSI in a cohort of professional male soccer players (18). Furthermore, Bourne et al. (5) reported 2.4 and 3.4 fold higher risk of HSI in Rugby Union players with a greater than 15% and 20% eccentric peak force asymmetry during the NHE, respectively. However, using the same NHE strength assessment, Timmins et al. (41) found no relationship between asymmetry and prospective HSI risk in soccer players, suggesting that the relative importance of absolute eccentric strength and asymmetries thereof, are not clear cut and may vary by sport and other factors. To our knowledge, the present study is the first to report strength asymmetry in female hockey players. Nonetheless, at baseline, four players in the ELC group and four players in the NHE group showed asymmetry values greater than 15%, while after intervention only one of the four original players in the ELC group and two of the four original players in the NHE group maintained a high magnitude of asymmetry post intervention. These results indicate that, in female hockey players without a recent history of injury but with relatively large asymmetries, both exercises can improve peak eccentric strength in weaker limb and reduce asymmetry, while also promoting beneficial shifts in APT in both limbs.

Angle of peak torque (APT) and angle-specific torque

Significant shifts of up to 42% in the APT in the direction of longer muscle lengths have been reported after various types of hamstrings strengthening interventions (8,11,26). However, these studies differ from the present in terms of population (mostly male subjects, either sedentary or soccer, rugby or Australian football players), and length of intervention (from three to four weeks). We observed significant decreases (i.e. towards longer muscle lengths) in APT ranging from 14.3% to 28.6% (with moderate to large effect sizes), with no difference between exercise types on the D and ND sides. These values are very close to those reported by Clark et al. (10), who showed decreases in APT from 16.3% to 23.4% in Australian footballers following a four-week NHE exercise intervention. The slightly larger effects observed in the present study could be due to our longer intervention period (7), as well as the relatively low level of strength of our players at baseline (25).

The observed shift of APT towards longer muscle lengths may be particularly useful in hockey players because the position repeatedly adopted in hockey tends to put this muscle group in a lengthened position at the hip, suggesting that both exercises could be valuable conditioning exercises appropriate to the biomechanics of this sport. Furthermore, we found that both the ELC and the NHE led to increased hamstrings eccentric torque near full knee extension i.e. at 10º, suggesting that concerns that the NHE may not be effective at promoting adaptations at long lengths due to lack of muscle control during the last phase of the exercise (26), may not be warranted - contrary to our first hypothesis. A similar observation was made by Clark et al. (11) highlighting that the leg with the APT closer to extension (i.e. represented by a smaller value in the present study) had a larger shift in APT following the NHE than the ELC. Indeed, the NHE decreased APT asymmetry, while an increase in APT asymmetry was observed following the ELC (from 14.3% at baseline to 20.0% post-intervention in favor of the ND leg). This suggests that, of the two exercises the NHE might be more appropriate in athletes for whom asymmetry is a concern. Our results differ from those of Clark et al. (11), who observed an increase in APT asymmetry from 23.3% at baseline to 29.8% following a four-week NHE intervention. The increased asymmetry in APT after ELC could be due to various factors linked to the technique adopted by our subjects. However, since the legs were in separate straps and therefore somewhat independent, it seems unlikely that an over-dependence on control with the leg with the APT closest to extension attenuated adaptations in the other leg, suggested previously as an explanation for asymmetrical APT adaptations to NHE training (11,28). Further studies including video analysis are necessary to clarify these discrepancies. Nevertheless, these results suggest that the NHE may be a better exercise for players with a large APT asymmetry.

H:Q ratio

While the exercise interventions leading to 8.5% to 38.3% increases in H_{ecc}:Q_{con} across legs, these changes were only significant after ELC and NHE exercises in the ND leg. Our results conflict with those from Brughelli et al. (10) who showed no significant effect of four weeks of NHE on the H_{ecc}:Q_{con} of professional soccer players. In contrast, other studies found significant improvements in H_{ecc}:Q_{con} following eccentric strengthening in male and female soccer players (19,29). As mentioned before, these contrasting results may be due to the lower baseline strength levels in the subjects tested in these previous studies, with a lower strength at baseline likely to result in greater gains (25). A higher hamstring to quadriceps strength ratio may be protective against ACL injury (30), suggesting that this improved ratio following the NHE may have be beneficial in terms of ACL injury risk reduction in female hockey players, at least in their D limb. While the impact of NHE alone has not been assessed in a prospective study of ACL risk, as one of the few strength exercises within the FIFA 11^{+} warm up program, it is reasonable to assume that it may have contributed to the reduced incidence of ACL injury observed in female athletes following participation in the program (1).

The main limitation of the present study is the lack of control for one of the weekly training sessions. In addition, the two exercises evaluated are performed at different hip angles (fixed at 180º during the NHE and from 90º to 180º during the ELC), while strength was conducted seated with a fixed position of 90º of hip flexion. This testing position was chosen to allow comparisons with previous studies using this configuration in isokinetic strength assessments (10-11).

PRACTICAL APPLICATIONS

The present study showed that in healthy hockey players with substantial interlimb strength asymmetries both the NHE and the ELC, two easy to implement bilateral eccentric hamstrings exercises resulted in significant improvements in peak and muscle length specific neuromuscular risk factors in the weaker limb, thereby reducing interlimb strength asymmetries. Therefore, both exercises appear to have a place in HSI and possibly ACL risk reduction programs and could be used by strength and conditioning coaches. Further research should focus on the independent and mixed effects of bilateral and unilateral strengthening exercises in athletes with and without substantial asymmetries.

REFERENCES

1. Barengo, NC, Meneses-Echávez, JF, Ramírez-Vélez, R, Cohen, DD, Tovar, G, and Enrique Correa Bautista, J. The impact of the fifa 11+ training program on injury prevention in football players: A systematic review. *Int J Environ Res Public Health* 11: 11986–12000, 2014.
2. Bossuyt, FM, Garcia-Pinillos, F, Raja Azidin, RMF, Vanrenterghem, J, and Robinson, MA. The utility of a high-intensity exercise protocol to prospectively assess ACL injury risk. *Int J Sports Med* 37: 125–133, 2016.
3. Bourne, MN, Opar, DA, Williams, MD, Al Najjar, A, and Shield, AJ. Muscle activation patterns in the nordic hamstring exercise: impact of prior strain injury. *Scand J Med Sci Sports* 26: 666–674, 2016.
4. Bourne, MN, Opar, DA, Williams, MD, and Shield, AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. *Am J Sports Med* 43: 2663–2670, 2015.
5. Bourne, MN, Opar, DA, Williams, MD, and Shield, AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union. *Am J Sports Med* 43: 2663–2670, 2015.
6. Brockett CL, Morgan DL, Proske U. Predicting hamstring strain injury in elite athletes. *Med Sci Sports Exerc*. 36(3):379-387, 2004.
7. Brughelli, M and Cronin, J. Altering the length-tension relationship with eccentric exercise : implications for performance and injury. *Sports Med* 37: 807–826, 2007.
8. Brughelli, M, Cronin, J, and Nosaka, K. Muscle architecture and optimum angle of the knee flexors and extensors: a comparison between cyclists and Australian rules football players. *J strength Cond Res* 24: 717–721, 2010.

9. Brughelli, M, Mendiguchia, J, Nosaka, K, Idoate, F, Arcos, AL, and Cronin, J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport* 11: 50–55, 2010.

10. Brughelli, M, Mendiguchia, J, Nosaka, K, Idoate, F, Arcos, AL, and Cronin, J. Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players. *Phys Ther Sport* 11: 50–55, 2010.

11. Clark, R, Bryant, A, Culgan, JP, and Hartley, B. The effects of eccentric hamstring strength training on dynamic jumping performance and isokinetic strength parameters: a pilot study on the implications for the prevention of hamstring injuries. *Phys Ther Sport* 6: 67–73, 2005.

12. Cohen, DD, Zhao, B, Okwera, B, Matthews, MJ, and Delextrat, A. Angle-specific eccentric hamstring fatigue after simulated soccer. *Int J Sports Physiol Perform* 10: 325–331, 2015.

13. Cohen, J. *Statistical power analysis for the behavioral sciences* (2nd Edition). Hillsdale, NJ: Lawrence Earlbaum, 1988.

14. Croce, R V, Miller, JP, and St Pierre, P. Effect of ankle position fixation on peak torque and electromyographic activity of the knee flexors and extensors. *Electromyogr Clin Neurophysiol* 40: 365–373, 2000.

15. Croisier, J-L, Ganteaume, S, Binet, J, Genty, M, and Ferret, J-M. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am J Sports Med* 36: 1469–1475, 2008.

16. Delextrat, A, Baker, J, Cohen, DD, and Clarke, ND. Effect of a simulated soccer match on the functional hamstrings-to-quadriceps ratio in amateur female players. *Scand J Med Sci Sport* 23: 478–486, 2013.

17. Dick, R, Hootman, JM, Agel, J, Vela, L, Marshall, SW, and Messina, R. Descriptive epidemiology of collegiate women's field hockey injuries: national collegiate athletic association injury surveillance system, 1988-1989 through 2002-2003. *J Athl Train* 42: 211–220, 2007.

18. Fousekis, K, Tsepis, E, Poulmedis, P, Athanasopoulos, S, and Vagenas, G. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. *Br J Sports Med* 45: 709–714, 2011.

19. Holcomb, WR, Rubley, MD, Lee, HJ, and Guadagnoli, MA. Effect of hamstring-emphasized resistance training on hamstring:quadriceps strength ratios. *J strength Cond Res* 21: 41–47, 2007.

20. van der Horst, N, Smits, D-W, Petersen, J, Goedhart, EA, and Backx, FJG. The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players. *Am J Sports Med* 43: 1316–1323, 2015.

21. de Hoyo, M, Pozzo, M, Sanudo, B, Carrasco, L, Gonzalo-Skok, O, Dominguez-Cobo, S, et al. Effects of a 10-week in-season eccentric overload training program on muscle injury prevention and performance in junior elite soccer players. *Int J Sport Physiol Perform* 46–52, 2014.

22. Iga, J, Fruer, CS, Deighan, M, Croix, MDS, and James, DVB. "Nordic" hamstrings exercise - engagement characteristics and training responses. *Int J Sports Med* 33: 1000–1004, 2012.

23. Krzykała, M., & Leszczyński, P. (2015). Asymmetry in body composition in female hockey players. *Homo: Internationale Zeitschrift fur die Vergleichende Forschung am Menschen, 66(4)*, 379-386.

24. Malliaropoulos, N, Mendiguchia, J, Pehlivanidis, H, Papadopoulou, S, Valle, X, Malliaras, P, et al. Hamstring exercises for track and field athletes: injury and

exercise biomechanics, and possible implications for exercise selection and primary prevention. *Br J Sports Med* 46: 846–851, 2012.

25. Mangine, GT, Gonzalez, AM, Townsend, JR, Wells, AJ, Beyer, KS, Miramonti, AA, et al. Influence of baseline muscle strength and size measures on training adaptations in resistance-trained men. *Int J Exerc Sci* 11: 198–213, 2018.

26. Matthews, MJ, Heron, K, Todd, S, Tomlinson, A, Jones, P, Delextrat, A, et al. Strength and endurance training reduces the loss of eccentric hamstring torque observed after soccer specific fatigue. *Phys Ther Sport* 25, 2017.

27. Mendiguchia, J, Alentorn-Geli, E, and Brughelli, M. Hamstring strain injuries: are we heading in the right direction? *Br J Sports Med* 46: 81–85, 2012.

28. Mendiguchia, J, Arcos, AL, Garrues, MA, Myer, GD, Yanci, J, and Idoate, F. The use of MRI to evaluate posterior thigh muscle activity and damage during Nordic hamstring exercise. *J Strength Cond Res* 27: 3426–3435, 2013.

29. Mjølsnes, R, Arnason, A, Østhagen, T, Raastad, T, and Bahr, R. A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. 311–317, 2004.

30. Myer, GD, Ford, KR, Barber Foss, KD, Liu, C, Nick, TG, and Hewett, TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med Off J Can Acad Sport Med* 19: 3–8, 2009.

31. Naclerio, F, Faigenbaum, AD, Larumbe, E, Goss-Sampson, M, Perez-Bilbao, T, Jimenez, A, et al. Effects of a low volume injury prevention program on the hamstring torque angle relationship. *Res Sport Med* 21: 253–263, 2013.

32. Orchard, J, Marsden, J, Lord, S, and Garlick, D. Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers. *Am J Sports Med* 25: 81–85, 1997.

33. Petersen, J, Thorborg, K, Nielsen, MB, Budtz-Jørgensen, E, and Hölmich, P. Preventive effect of eccentric training on acute hamstring injuries in men's soccer. *Am J Sports Med* 39: 2296–2303, 2011.

34. Podgórski, T and Pawlak, M. A half century of scientific research in field hockey. *Hum Mov* 12, 2011.

35. Roos, PE, Button, K, and van Deursen, RWM. Motor control strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: an observational study. *J Neuroeng Rehabil* 11: 19, 2014.

36. Ruas CV, Pinto RS, Haff GG, Lima CD, Pinto MD, Brown LE. Alternative methods of determining hamstrings-to-quadriceps ratios: a comprehensive review. *Sports Med Open*. 5(1): 11, 2019.

37. Schache A. Eccentric hamstring muscle training can prevent hamstring injuries in soccer players. *J Physiother*.58(1): 58, 2012.

38. Small, K, McNaughton, L, Greig, M, and Lovell, R. The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *J Sci Med Sport* 13: 120–125, 2010.

39. De Ste Croix, M, ElNagar, YO, Iga, J, Ayala, F, and James, D. The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio. *Knee* 24: 745–750, 2017.

40. Taberner, M, O'Keefe, J, and Cohen, DD. The sliding leg curl. *Strength Cond J* 38: 117–121, 2016.

41. Timmins, RG, Bourne, MN, Shield, AJ, Williams, MD, Lorenzen, C, and Opar, DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. *Br J Sports Med* 50: 1524–1535, 2016.

42. van Dyk N, Bahr R, Burnett AF, Whiteley R, Bakken A, Mosler A, Farooq A, Witvrouw E. A comprehensive strength testing protocol offers no clinical value in predicting risk of hamstring injury: a prospective cohort study of 413 professional football players. *Br J Sports Med*. 51(23):1695-1702, 2017.

43. van Dyk N, Bahr R, Whiteley R, Tol JL, Kumar BD, Hamilton B, Farooq A, Witvrouw E. Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: A 4-Year Cohort Study. *Am J Sports Med*. 44(7):1789-1795, 2016.

44. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. *Br J Sports Med*. 2019 Feb 26. pii: bjsports-2018-100045

45. Woods, C, Hawkins, RD, Maltby, S, Hulse, M, Thomas, A, and Hodson, A. The football association medical research programme: an audit of injuries in professional football--analysis of hamstring injuries. *Br J Sports Med* 38: 36–41, 2004.

Table and Figure captions

Table 1. Training sets and repetitions during the 6-week training intervention in the eccentric leg curl (ELC) and nordic hamstrings (NHE) groups.

Table 2. Effect of eccentric leg curl (ELC), nordic hamstrings (NHE) and no intervention (C: control) on the eccentric peak torque (PT) of the hamstrings (H_{ecc}), concentric peak torque of the quadriceps (Q_{con}), the angles at which PT was produced (APT) and the functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}) in the dominant (D) and non-dominant (ND) leg of female field hockey players (ηP^{2}partial eta squared). Values are presented as mean (SD).

*: significant effect of time, group or interaction, $p<0.05$.

Figure 1. Study flow chart (CONSORT).

Figure 2. Photos of the eccentric leg curl (ELC, 2a and 2b) and nordic hamtring (NHE. 2c and 2d) exercises at their start and end.

Figure 3. Effects of time (full line: baseline; dotted line: post-intervention), knee angle (10 being close to extension and 90 knee flexed at 90) and group (eccentric leg curl: ELC; nordic hamstrings: NHE and control: C) on the eccentric torque of the hamstrings (H_{ecc}) in the dominant (D) and non-dominant (ND) legs of female field hockey players.

*: significant difference between pre- and post-intervention, $p<0.05$.

Figure 4. Effects of time (full line: baseline; dotted line: post-intervention), knee angle (10 being close to extension and 90 knee flexed at 90) and group (eccentric leg curl: ELC; nordic hamstrings: NHE and control: C) on the functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}) in the dominant (D) and non-dominant (ND) legs of female field hockey players.

*: significant difference between pre- and post-intervention, $p<0.05$.

Table 1.

	Session 1	Session 2	Session 3
Week 1	2 sets of 6 repetitions	2 sets of 6 repetitions	2 sets of 7 repetitions
Week 2	2 sets of 7 repetitions	2 sets of 8 repetitions	2 sets of 8 repetitions
Week 3	2 sets of 9 repetitions	2 sets of 9 repetitions	3 sets of 7 repetitions
Week 4	3 sets of 7 repetitions	3 sets of 8 repetitions	3 sets of 8 repetitions
Week 5	3 sets of 9 repetitions	3 sets of 9 repetitions	3 sets of 10 repetitions
Week 6	3 sets of 10 repetitions	3 sets of 7 repetitions	3 sets of 7 repetitions

NHE, depending on individual progression

Table 2

Table 2. Effect of eccentric leg curl (ELC), nordic hamstrings (NHE) and no intervention (C: control) on the eccentric peak torque (PT) of the hamstrings (H_{ecc}), concentric peak torque of the quadriceps (Q_{con}), the angles at which PT was produced (APT) and the functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}) in the dominant (D) and non-dominant (ND) leg of female field hockey players (ηP^2partial eta squared). Values are presented as mean (SD).

		C	ELC	NHE	p value and effect size
Hecc					
PT D	Pre Post	60.4(14.8) 57.7(17.2)	60.9(18.8) 65.2(16.4)	55.4(15.8) 62.2(19.4)	Time: p=0.153, ηP^2: 0.091 Group: p=0.847, ηP^2: 0.015 Interaction: p=0.132, ηP^2: 0.168
PT ND	Pre Post	52.0(14.1) 50.0(12.5)	50.9(13.3) 66.4(16.9)*	43.2(18.4) 56.1(16.9)*	**Time: p=0.001, ηP^2: 0.591** Group: p=0.447, ηP^2: 0.074 **Interaction: p=0.001, ηP^2: 0.534**
APT D	Pre Post	30.0(15.1) 35.0(7.6)	30.0(10.7) 23.8(9.2)*	36.7(10.4) 27.8(9.7)*	Time: p=0.066, ηP^2: 0.145 Group: p=0.430, ηP^2: 0.074 **Interaction: p=0.009, ηP^2: 0.349**
APT ND	Pre Post	36.3(7.5) 32.5(13.9)*	35.0(7.6) 30.0(7.6)*	32.5(7.1) 25.6(8.2)*	**Time: p=0.009, ηP^2: 0.285** Group: p=0.399, ηP^2: 0.084 Interaction: p=0.778, ηP^2: 0.024
Qcon					
PT D	Pre Post	91.0(15.9) 90.8(14.9)	86.0(7.6) 84.5(12.0)	86.2(16.7) 84.2(14.9)	Time: p=0.500, ηP^2: 0.021 Group: p=0.912, ηP^2: 0.008 Interaction: p=0.622, ηP^2: 0.042
PT ND	Pre Post	92.1(13.9) 90.4(13.1)	84.6(11.7) 82.3(17.6)	80.3(16.5) 80.4(12.5)	Time: p=0.396, ηP^2: 0.035 Group: p=0.292, ηP^2: 0.111 Interaction: p=0.794, ηP^2: 0.022
APT D	Pre Post	65.7(8.3) 63.7(11.7)	60.7(7.0) 60.4(14.0)	62.9(10.0) 62.4(9.7)	Time: p=0.731, ηP^2: 0.006 Group: p=0.647, ηP^2: 0.043 Interaction: p=0.959, ηP^2: 0.004
APT ND	Pre Post	63.3(9.2) 63.1(7.0)	60.1(8.5) 60.1(16.0)	65.8(11.9) 63.4(8.7)	Time: p=0.771, ηP^2: 0.005 Group: p=0.586, ηP^2: 0.055 Interaction: p=0.926, ηP^2: 0.008
H_{ecc}:Q_{con}					
PEAK ND	Pre Post	0.57(0.13) 0.55(0.10)	0.60(0.13) 0.83(0.21)*	0.54(0.19) 0.69(0.17)*	**Time: p=0.001, ηP^2: 0.468** Group: p=0.114, ηP^2: 0.187 **Interaction: p=0.007, ηP^2: 0.374**
PEAK D	Pre Post	0.66(0.09) 0.63(0.13)	0.71(0.20) 0.77(0.16)	0.66(0.20) 0.75(0.25)	Time: p=0.127, ηP^2: 0.102 Group: p=0.513, ηP^2: 0.059 Interaction: p=0.161, ηP^2: 0.153

***: significant time, group or interaction, P<0.05.**

Figure 1

Figure 1.

CONSORT Flow Diagram

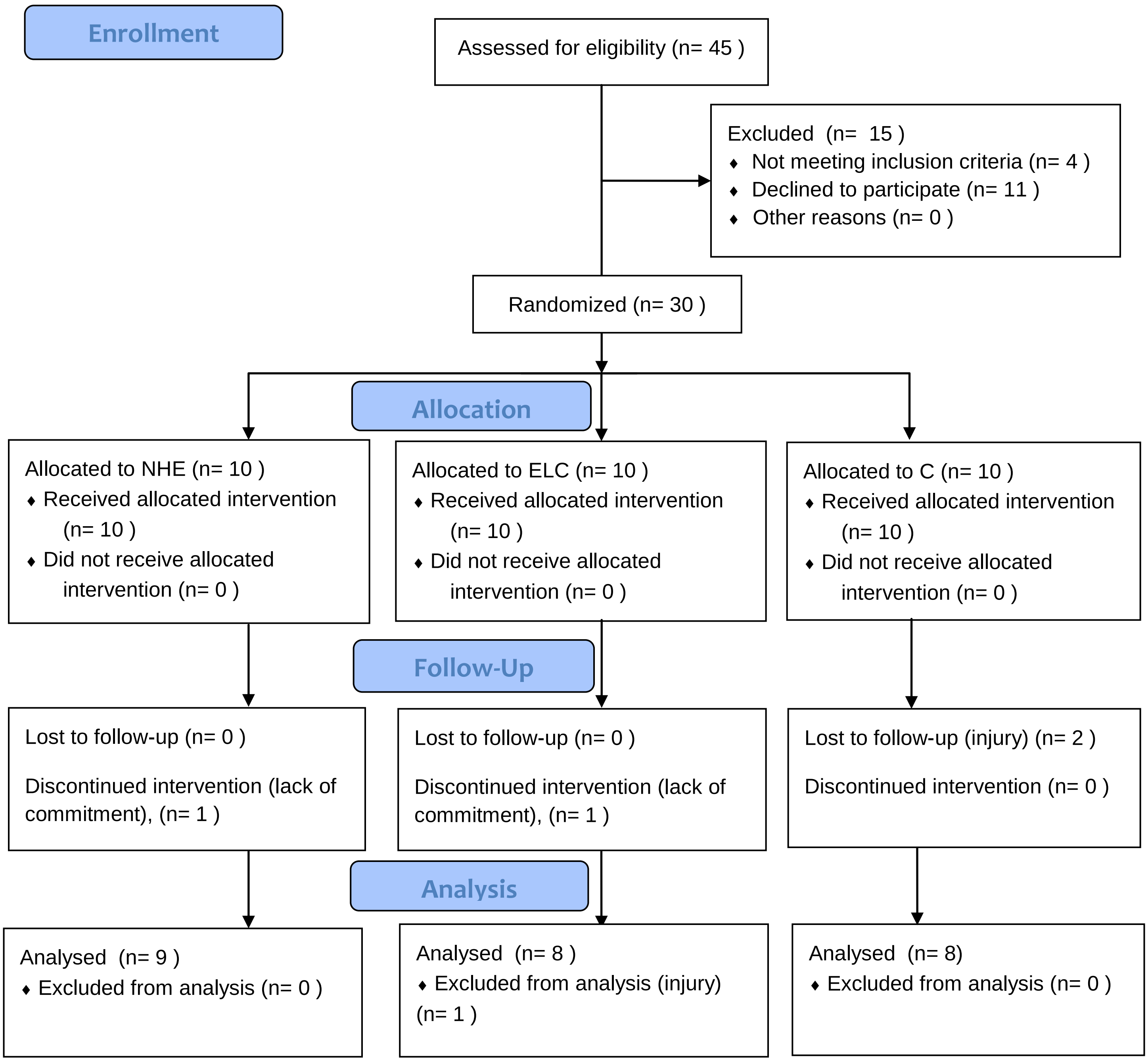


Figure 2

Figure 2

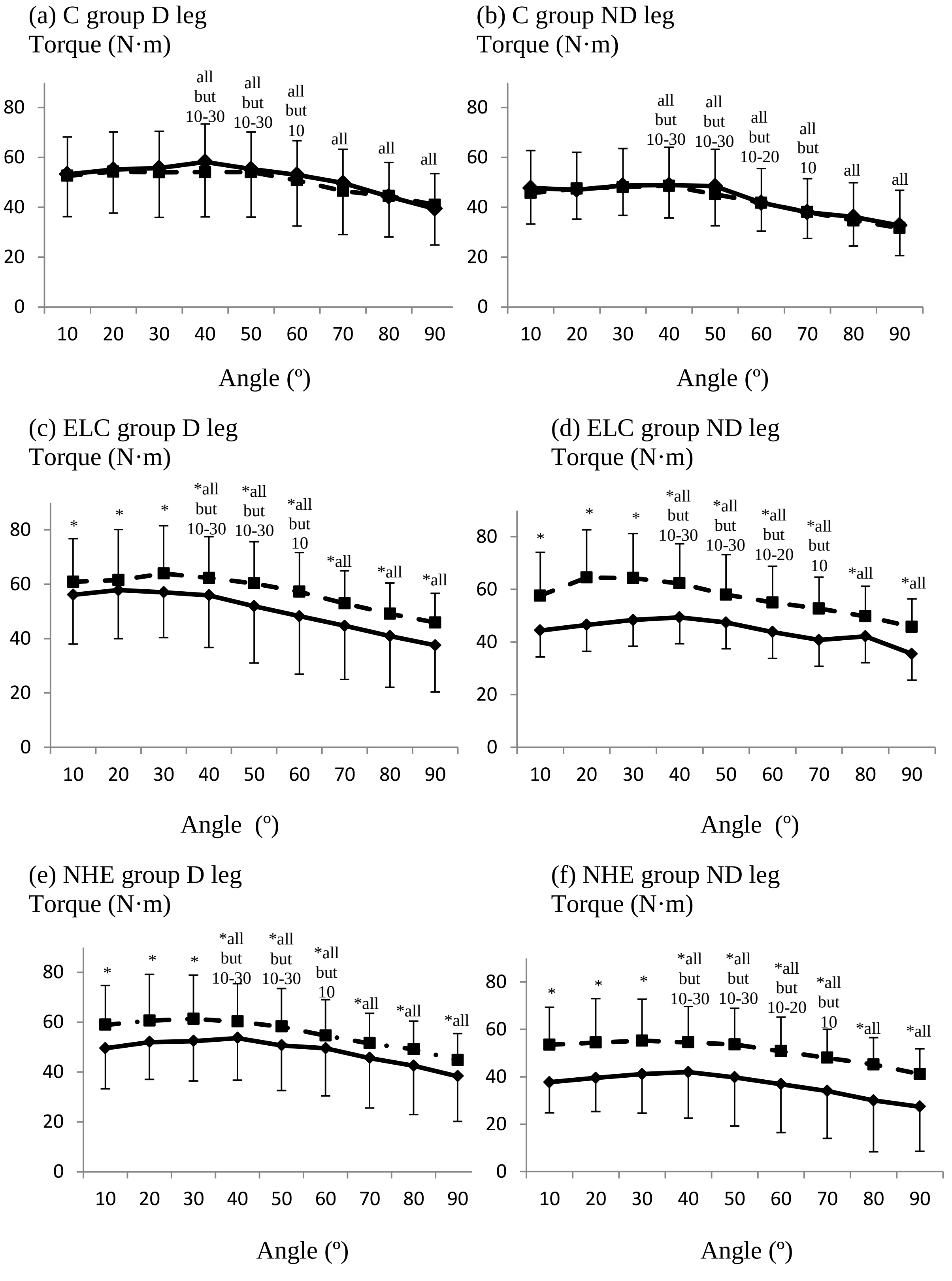
2a

2b

2c

2d

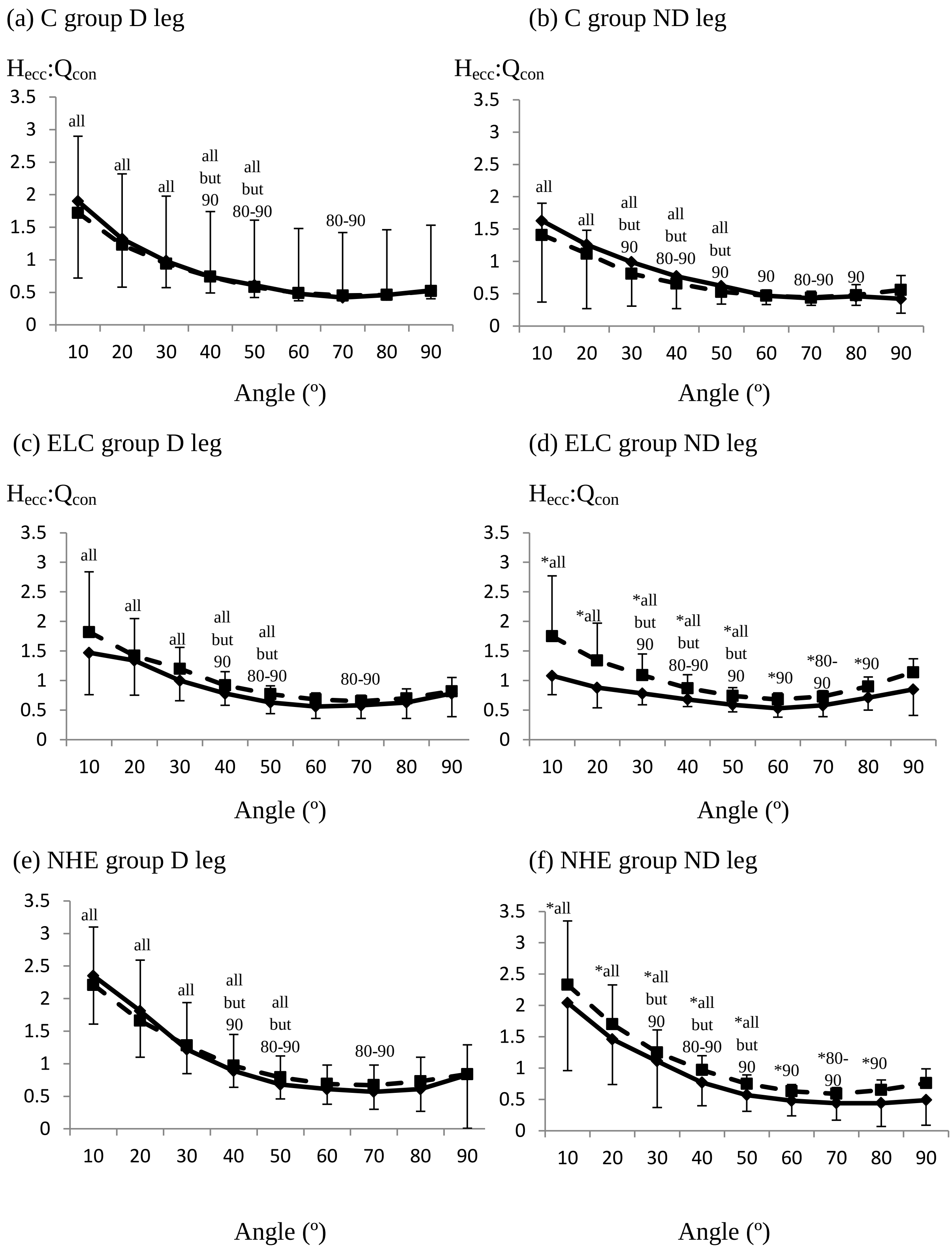
Figure 3. Effects of time (full line: baseline; dotted line: post-intervention), knee angle (10 being close to extension and 90 knee flexed at 90) and group (eccentric leg curl: ELC; nordic hamstrings: NHE; control: C) on the eccentric torque of the hamstrings (H_{ecc}) in the dominant (D) and non-dominant (ND) legs of female field hockey players.



*: significant difference between pre- and post-intervention, p<0.05.

Figure 4

Figure 4. Figure 1. Effects of time (full line: baseline; dotted line: post-intervention), knee angle (10 being close to extension and 90 knee flexed at 90) and group (eccentric leg curl: ELC; nordic hamstrings: NHE; control: C) on the functional hamstrings-to-quadriceps ratio (H_{ecc}:Q_{con}) in the dominant (D) and non-dominant (ND) legs of female field hockey players.



*: significant difference between pre- and post-intervention, p<0.05.