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Effects of evidence-based prevention training on neuromuscular and biomechanical risk factors for ACL injury in adolescent female athletes: a randomised controlled trial

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ABSTRACT

Background Adolescent female football and handball players are among the athletes with the highest risk of sustaining anterior cruciate ligament (ACL) injuries.
Aim This study evaluated the effects of evidence-based lower extremity injury prevention training on neuromuscular and biomechanical risk factors for non-contact ACL injury.
Methods 40 adolescent female football and handball players (15–16 years) were randomly allocated to a control group (CON, n=20) or neuromuscular training group (NMT, n=20). The NMT group performed an injury prevention programme as a warm-up before their usual training 3 times weekly for 12 weeks. The CON group completed their regular warm-up exercise programme before training. Players were tested while performing a side cutting movement at baseline and 12-week follow-up, using surface electromyography (EMG) and three-dimensional movement analysis. We calculated: (1) EMG amplitude from vastus lateralis (VL), semitendinosus (ST) and biceps femoris 10 ms prior to initial contact (IC) normalised to peak EMG amplitude recorded during maximal voluntary isometric contraction and (2) VL-ST EMG preactivity difference during the 10 ms prior to foot contact (primary outcome). We measured maximal knee joint valgus moment and knee valgus angle at IC.
Results There was a difference between groups at follow-up in VL-ST preactivity (43% between-group difference; 95% CI 32% to 55%). No between-group differences were observed for kinematic and kinetic variables.
Conclusions A 12-week injury prevention programme in addition to training and match play in adolescent females altered the pattern of agonist-antagonist muscle preactivity during side cutting. This may represent a more ACL-protective motor strategy.

The high incidence of anterior cruciate ligament (ACL) injuries[1] is a major health concern among adolescent females who play sports such as football and handball.[2,3] Of concern, the past decade has seen no decrease in the incidence of ACL rupture among female collegiate athletes who participate in high-risk sports.[4,5] ACL injury is often associated with subsequent limitation of activity, and thus is a major public health issue.[6]

Research on ACL injury prevention has focused on identifying risk factors for ACL injury, including neuromuscular and biomechanical factors.[7] Most ACL injuries occur in non-contact situations when the player performs rapid side cutting movements.[8–10] We have previously found increased risk of non-contact ACL injury among female athletes displaying a combination of reduced electromyography (EMG) preactivity in the medial hamstring muscle (semitendinosus (ST)) along with increased EMG preactivity of the quadriceps muscle (vastus lateralis (VL)) during side cutting, consequently leading to an elevated *VL-ST EMG preactivity difference*.[11] Hewett *et al*[12] reported that excessive knee joint valgus angle and high valgus moments during a drop jump were the primary predictors of non-contact ACL injury risk. Taken together, these findings suggest that motor control patterns may be predictors of non-contact ACL injury.

We conducted a randomised controlled trial among adolescent female football and handball players enrolled in Danish Sports College education, to investigate the neuromuscular and biomechanical effects of a structured warm-up exercise programme used to prevent acute injuries of the lower limb. We hypothesised that 12 weeks of prophylactic training—previously shown to decrease the incidence of acute knee and ankle injuries[13]—would decrease the magnitude of differential VL-ST preactivity from baseline to follow-up during a standardised side cutting movement, compared with usual training (control, CON). Second, it was hypothesised that prophylactic training would lead to a decrease in the knee joint valgus moment and angle compared with CON.[12]

MATERIALS AND METHODS

Study design and participants

We performed a randomised controlled trial in a single football and handball Sports College in Copenhagen, Denmark. All female athletes attending the Sports College (school year: 2010–2011) were assessed for eligibility. The inclusion criterion was: full time student at the Sports College. The exclusion criterion was: musculoskeletal injury causing absence from Sports College training at baseline (January 2011). Using concealed randomisation (more details given below), the study participants were assigned to receive prophylactic neuromuscular training (NMT) or serve as CON. In accordance with The Declaration of Helsinki, and approved by The Committees on Biomedical

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Research Ethics of the Capital Region of Denmark (H-2-2010-091), all participants and parents were informed about the purpose and content of the project, and all parents gave their written informed consent for their child to participate in the study.

Intervention procedures

The intervention is described according to the Template for Intervention Description and Replication (TIDieR) checklist and guide.[14] The NMT programme used in this study was developed by the medical staff from Oslo Sports Trauma Research Centre and coaching staff from the Norwegian Handball Federation,[13] and it halved the incidence of acute ankle and knee injuries in young handball players.[13]

Neuromuscular programme details

The NMT programme included exercises that involved wobble boards (disc diameter 38 cm; Norpro, Notodden, Norway, 2000), balance mats (40×50 cm^2, 7 cm thick; Alusuisse Airex, Sins, Switzerland, 2000) and balls (football and handball). Prior to the intervention, the Sports College received an exercise book, 10 wobble boards and 10 balance mats.

The programme included levels of progressively increasing difficulty. The main focus of the exercises was to improve body awareness and motor control at the hip, knees and ankles during standing, running, side cutting, jumping and landing tasks (for exercise details and exercise progression, see: http://www.klokavskade.no/no/Skadefri/Handball2/OEO).

Implementation of the intervention

Players were encouraged to be highly focused and conscious of the quality of their movements, and there was an emphasis given to core stability and the position of the hip and knee in relation to the foot (aligned knee over toe position). Players were also encouraged to watch each other closely and to provide feedback to each other during all exercise sessions.

The training programme was performed at the Sports College's own indoor facilities. Each training session included three exercises and the players were instructed to spend 4–5 min on each exercise station giving a total session duration of approximately 15 min. Prior to implementation of the training programme, the involved sports teachers at the Sports College were familiarised with the programme during a 2 h seminar, where they received theoretical and practical training on how to coach and implement the programme. Every second week, a member of the research team attended the Sports College to ensure accurate progression and instruction of the programme exercises. Intervention activities were initiated within 1 week after randomisation. The training was implemented three times per week and supervised throughout the intervention period (12 weeks). The sports teachers registered player attendance and completion of training, and reasons for not attending training. Participants completed on average 32±8 training bouts during the 12-week intervention period.

The CON group completed their regular warm-up programme and training during the intervention period. To avoid exercise contamination between groups, the NMT group was separated from the CON group when performing the NMT sessions.

Outcomes

The primary outcome was neuromuscular preactivity of the quadriceps (VL) minus hamstring (ST) muscles preactivity during a standardised side cutting movement, measured using EMG.

The secondary outcome variables were:

1. ST, VL and biceps femoris (BF) muscle preactivity during side cutting, measured using EMG;
2. Knee joint valgus angle at initial contact (IC) and maximal valgus moment measured with three-dimensional (3D) movement analysis;
3. Hamstrings muscle strength measured with hand-held dynamometry.

An exploratory analysis was performed to examine the potential between-group differences in the number of acute time-loss lower extremity injuries at follow-up. An acute time-loss injury was defined as an injury caused by a single identifiable event that resulted in a player not being able to participate in future training or matches.[15] Acute time-loss injuries were registered by the sport teachers at the Sports College and diagnosed by the physical therapist or the study physician.

Test protocol

Side cutting manoeuvre

All participants were tested during a standardised side cutting movement performed in a 3D biomechanics laboratory (Copenhagen University Hospital at Hvidovre, Denmark). During match play, side cutting is typically performed when the time for decision-making in terms of posture control is highly limited. We have previously demonstrated high test-retest reproducibility for the magnitude and timing of lower limb EMG activity during such side cutting tasks,[16] indicating that in well-trained football and handball players, this movement is characterised by a consistent and highly reproducible motor programme. In support of this notion, the neuromuscular characteristics of the side cutting manoeuvre appear to remain unchanged during a regular season of training and match play in adult female football and handball players.[16] The standardised side cutting movement was performed with instructions to the participants to perform the movement as fast and forcefully as possible, to best simulate the conditions of match play.[11 16] An 8 camera Vicon 612 system (Oxford, England), and an AMTI force plate (Massachusetts, USA) were used to evaluate the side cutting movement with a procedure previously described.[17] The knee joint valgus angle at IC as well as maximal knee joint valgus moment during the side cutting movement was calculated for the preferred push-off leg, using the Vicon Plug-in-Gait software module.

Neuromuscular activity

During the side cutting movement, neuromuscular activity was recorded (1000 Hz) in the quadriceps femoris muscle (musculus VT) and medial/lateral hamstring muscles (musculus ST and musculus BF) of the preferred push-off leg using bipolar surface EMG electrodes[18–21] (MyoMonitor IV, Delsys, Boston, Massachusetts, USA). The raw EMG signals were analogue-to-digitally converted and amplified by a factor of 1000, with a common mode rejection rate of >80 dB, bandpass filtered 20–450 Hz, and transmitted wirelessly to a receiver before digital-analogue conversion. EMG data were synchronised with camera and force plate data.

During later offline analysis, all EMG signals were high-pass filtered using a fourth order zero-lag Butterworth filter with a 20 Hz cut-off frequency, and subsequently smoothed by a symmetrical moving root-mean-square filter with a 30 ms time epoch.[11 20] The mean filtered EMG amplitude was calculated for each muscle in the 10 ms time interval prior to IC,[11 16] registered by a floor-embedded force plate. Subsequently, all EMG values were normalised to the peak EMG amplitude recorded (and identically filtered) during a maximal voluntary contraction (MVC). The average of three side cutting trials was calculated for each player.

Maximal voluntary isometric strength

Maximal voluntary isometric knee flexor strength was measured with a portable hand-held dynamometer (PowerTrack II Commander, JTECH Medical, Salt Lake City, Utah, USA) for the preferred push-off leg, as described by Askling *et al*.[22] The participant was lying prone on an examination table with the knee fixed at 10° knee flexion. The dynamometer was fixed by a belt to the handlebar of a glass suction cup placed on the floor.[22] This procedure has been established as reliable for assessing knee flexion strength (ICC 0.84–0.98).[22 23] Three maximal isometric knee flexor contractions were performed and the highest filtered peak EMG amplitude (EMGmax) was used for later EMG normalisation. The maximal MVC force generated by the hamstring muscles was also recorded.

Maximal peak EMG amplitude (EMGmax) was measured for the knee extensors with the participant seated on an examination table and the leg fixed with an external strap at 60° knee flexion. Three maximal isometric knee extensor contractions were performed and the highest filtered peak EMG amplitude was recorded for later EMG normalisation. The dynamometer had an upper measuring range of 550 N.

Randomisation and blinding

We used computer-generated random numbers for randomisation stratified for sports (ie, football and handball). It was not possible to blind the researchers or participants during testing, but the researcher performing the statistics was blinded to group allocation. Furthermore, the physical therapist and physician diagnosing the acute injuries were blind to group allocation.

Sample size

For the primary outcome, a priori power calculation showed that a minimum of 17 participants in each group were required to detect a between-group difference of 15% of EMGmax, with an SD of 15%, an α level of 5% and a statistical power of 80%. On the basis of our previous work, we estimated that 15% of EMGmax was a relevant between-group difference in VL-ST neuromuscular preactivity.[11]

Statistical analysis

All outcome variables were analysed according to the intention-to-treat principle using a linear mixed model, with *time* (pre and post), *group* (NMT and CON) and *group by time* interaction as fixed factors. The analysis was controlled for sport (football, handball). *Participant* nested in *group* was entered as a random effect. The PROC MIXED function of SAS V.9.2 (SAS Institute, Inc, Cary, North Carolina, USA) was used, which inherently accounts for missing values. As a supplementary analysis, a *per protocol* analysis was performed for the main outcome, where only athletes who attended both baseline and follow-up testing were included. Baseline values were reported as means (±SE), whereas differences from baseline to follow-up were expressed as least square means (95% CIs). For the exploratory analysis, between-group difference in therapist-verified acute time-loss lower extremity injuries was tested with Fisher's exact test. An α level of 5% (two-tailed) was accepted as statistically significant in all analyses.

RESULTS

Study flow and characteristics

Between August and December 2010, 58 female athletes were assessed for eligibility. Prior to the intervention start (January 2011), five players sustained a severe (absence >4 weeks) knee injury, one a severe shoulder injury, two left school, one had long-term illness, two declined to participate and seven did not respond to the invitation. In total, 40 participants (18 football players and 22 handball players) were randomised to either the NMT group (n=20) or the CON group (n=20). Participant flow is presented in figure 1. Baseline characteristics for the participants included in the intention-to-treat analysis are presented in table 1.

Primary outcome and analysis

Within-group analyses

Neuromuscular preactivity data at baseline are presented in table 2. Within-group analysis showed that in the NMT group, VL-ST EMG preactivity difference (VL-ST) significantly decreased from −4±3% at baseline to −16±4% EMGmax at follow-up (p=0.0167; figure 2). In the CON group, VL-ST EMG preactivity difference significantly increased from −4±3% to 27±5% EMGmax at follow-up (p<0.0001; figure 2).

Between-group analysis

There was a statistically significant between-group difference in VL-ST EMG preactivity difference at follow-up. The VL-ST preactivity difference was 43% EMGmax (95% CI 32% to 55%, p<0.0001) lower in the NMT group compared with the CON group (figure 2). In the *per protocol* analysis, the VL-ST preactivity difference was 37% EMGmax (95% CI 19% to 55%, p<0.0002) lower in the NMT group (n=15) compared with the CON group (n=10).

Secondary outcomes and analyses

Within-group analyses

In the NMT group, changes in EMG preactivity level for the individual muscles (quadriceps (VL), medial hamstring (ST; figure 3A, B) and lateral hamstring (BF)) did not reach statistical significance.

In the CON group, VL EMG preactivity during side cutting increased from 25±4% to 43±5% EMGmax at follow-up (p<0.01; figure 3A). ST EMG preactivity decreased following the intervention period (29±2% at baseline vs 17±3% EMGmax; p<0.01; figure 3B). BF EMG preactivity decreased from 21±2% to 12±2% EMGmax (p=0.0027) at follow-up.

Kinematic and kinetic data at baseline are presented in table 3. No changes within groups were observed for maximal valgus moment, valgus angle, and knee and hip flexion angle at IC.

Within-group analyses revealed that hamstring MVC increased in both groups following the 12-week study period. Hamstring MVC increased from 3.6±0.7 to 3.8±0.8 N/kg in the NMT group (p=0.0134). In the CON group, hamstring MVC increased from 3.6±0.7 to 4.0±1.0 N/kg (p=0.0007).

Between-group analyses

On average, lateral quadriceps (VL) preactivity was 23% lower in the NMT group compared with the CON group at follow-up (95% CI 10% to 36%, p<0.0008; figure 3A). In addition, the NMT group increased medial hamstring (ST) preactivity by 18% EMGmax (95% CI −21% to −9%, p<0.0001; figure 3B)

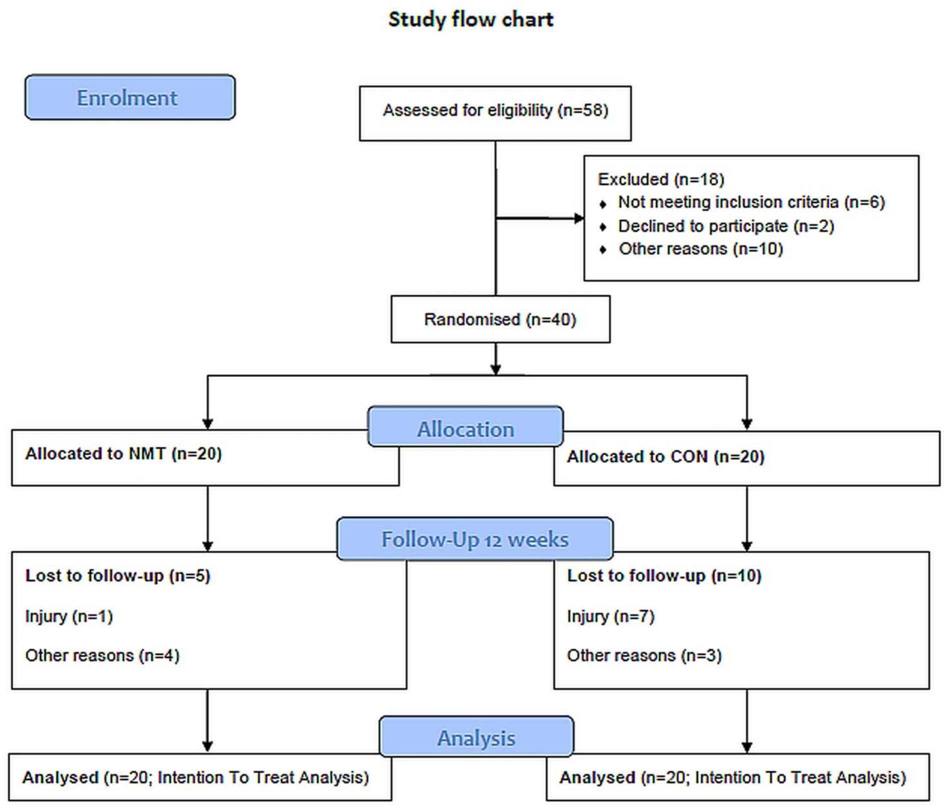

Figure 1 Flow of participants through the intervention (CON, control; NMT, neuromuscular training).

and lateral hamstring (BF) preactivity by 8% EMGmax (95% CI −14% to −2%, p=0.01) compared with the CON group.

No changes between groups were observed for maximal valgus moment or valgus angle at IC. Further, no between-group difference was observed in hamstring MVC at follow-up.

Lower extremity injuries in the intervention period

In the NMT group, one (knee) lower extremity injury was registered during the study period (injury incidence, 5%). In the CON group, 7 (4 ankle and 3 knee) lower extremity injuries were registered during the study period (injury incidence, 35%). The difference in injury incidence was statistically significant (p=0.04).

Adverse events

No adverse events related to the NMT programme were reported during the intervention period.

DISCUSSION

Twelve weeks of NMT in adolescent female football and handball players resulted in an elevated medial hamstring (ST) versus lateral quadriceps (VL) muscle preactivity prior to (0–10 ms) foot strike during cutting. The elevated hamstring muscle recruitment pattern may protect against non-contact ACL injury.[11] In the CON group, the VL-ST EMG preactivity differential increased in favour of the quadriceps muscle (VL) and this pattern is associated with increased risk for ACL injury.[11]

Since elevated VL-ST EMG differences are associated with increased risk of non-contact ACL injury,[11] the decrease in this parameter observed in the NMT group at follow-up may protect against non-contact ACL injury.

Possible mechanisms that underpin our findings

Somewhat unexpectedly, medial hamstring (ST) EMG preactivity was lower in the CON group at the end of the study period. Perhaps a reduced level of muscle activity might produce the same knee flexor force, a hypothesis supported by the finding of an 11% increase in isolated hamstrings strength at follow-up. Since VL (lateral quadriceps) preactivity increased together with the reduction in ST (medial hamstring) activation during side

Table 1 Baseline characteristics (n=40)

	NMT (n=20)	CON (n=20)
Demographics		
Age, year	15.9 (0.4)	15.6 (0.5)
Height, cm	168 (5)	169 (6)
Weight, kg	63.8 (12.4)	63.8 (9.4)

Values are group mean (SD).
CON, control; NMT, neuromuscular training.

Table 2 Neuromuscular preactivity (% of EMGmax) at baseline

	NMT (n=20)	CON (n=20)
VL	28 (4)	25 (4)
ST	31 (2)	29 (2)
Biceps femoris	20 (2)	21 (2)
VL-ST difference	−4 (3)	−4 (3)

Values are group means (SE).
CON, control; EMGmax, maximal peak electromyography amplitude; NMT, neuromuscular training; ST, semitendinosus; VL, vastus lateralis.

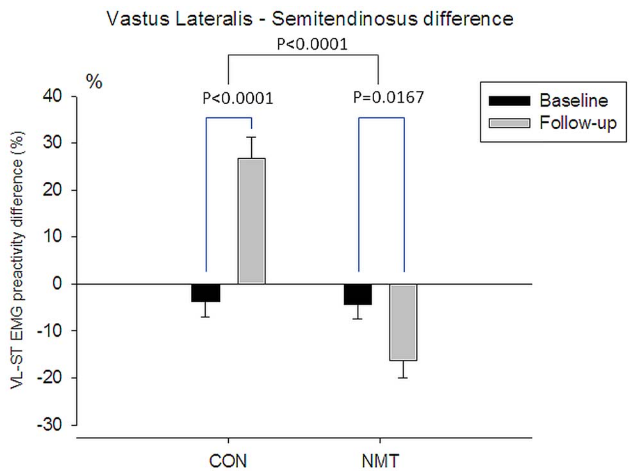

Figure 2 Neuromuscular VL-ST preactivity difference during side cutting at baseline and follow-up in the CON and NMT groups. CON, control; EMG, electromyography; NMT, neuromuscular training; ST, semitendinosus; VL, vastus lateralis.

cutting, the CON group may have adapted their motor activity towards a knee extensor dominated movement pattern,[11] a finding of concern, since it supports the quadriceps dominance theory which postulates that excessive quadriceps forces relative to posterior chain recruitment place the ACL at high risk for injury.[24]

Although VL-ST preactivity levels in the CON group did not reach the level reported in adult female athletes who subsequently sustained non-contact ACL injury (CON: 27±5% vs ACL injured adults: 47±14%[11]), the VL-ST EMG preactivity difference observed in the CON group closely corresponds to the level considered high risk for non-contact ACL injury (high risk zone: differential VL-ST preactivity ≥33%).[11] If this neuromuscular phenomenon occurs transiently during adolescence, it may explain the high risk of ACL injury.[1] Collectively, these observations add weight to the argument for prophylactic NMT of adolescent female athletes.

Table 3 Kinetic and kinematic parameters at baseline

	NMT (n=20)	CON (n=20)
Maximal valgus moment (Nm/kg BW)	0.51 (0.53)	0.50 (0.53)
Knee valgus angle at IC (°)	2.7 (0.4)	3.3 (0.5)

Values are group means (SE).
BW, body weight; CON, control; IC, initial contact; NMT, neuromuscular training.

How long does it take for an intervention to produce changes in muscle activation

Wilderman *et al*[25] reported that 6 weeks of agility training four times weekly increased medial hamstring preactivity during a sidestep movement. Their intervention focused on correct landing techniques for 12 months.[25] Increased medial hamstring (ST) preactivity in adult female elite football and handball players during side cutting has been demonstrated previously following a similar neuromuscular intervention that was continued for a full match season.[16]

In the present study, we report remodelling in the agonist-antagonist (ie, VL-ST) EMG relationship 12 weeks after NMT. Thus, the relative upregulation in medial hamstring (ST) EMG preactivity in the NMT group compared with the CON group, and the decreased VL-ST preactivity difference during the side cutting movement may suggest that our training regime established a more 'ACL protective' strategy.[11]

Prophylactic training has previously been associated with ACL protective adaptations in sports-specific knee joint movement kinematics[26] and kinetics.[27] In adolescent female athletes, Myer *et al*[28] showed that only 6 weeks of NMT improved biomechanical variable factors (eg, knee valgus torque) associated with an elevated ACL injury risk. However, contrary to our hypothesis, we found no differences in biomechanical risk factors. This could be due to a type II error, but the very consistent kinetic and kinematic motor pattern found in this study—for example, valgus angle at IC differed less than 1° from baseline to follow-up in both groups—eliminates any clinical relevant change in this study.[12] The fact that a remodelling of the

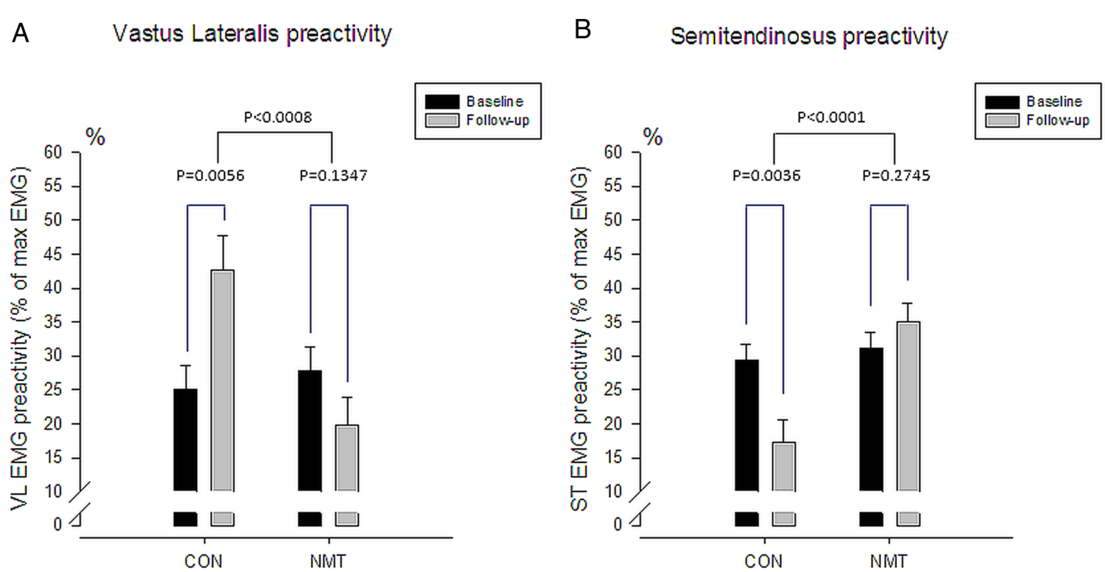

Figure 3 Neuromuscular preactivity in (A) VL muscle and (B) ST muscle during side cutting at baseline and follow-up in study participants randomised to NMT or serving as controlsCON. CON, control; EMG, electromyography; NMT, neuromuscular training; ST, semitendinosus; VL, vastus lateralis.

neuromuscular pattern occurred without any detectable change in the kinetic or kinematic characteristics of the movement indicates that the primary effect of the present prophylactic training programme is most likely purely neuromuscular in nature. That is, muscle activation is modulated to counteract the external loads applied to the knee joint during the side cutting movement.

During the study period, eight players experienced an acute lower extremity injury. A significant difference in the number of injuries was observed between (1 in the NMT group vs 7 in the CON group). Although this may be a type 1 error, our finding aligns with the results of NMT programmes in previous larger studies which prevented acute lower extremity injury.[13]

Limitations

For the players in this study, training exposure increased by an additional four training sessions per week when engaged in Sports College activities. Only Sports College training sessions and not total training exposure (Sports College training combined with team training and team match play) were registered. However, the enrolled participants were comparable with respect to playing level, and the randomisation procedure was controlled for sport (football, handball).

As mentioned, it was not possible to blind the researchers or participants during testing. However, the researcher who performed the statistics, the physical therapist and the study physician who diagnosed the acute injuries were blind to group allocation.

Finally, for the exploratory analysis, only therapist-verified acute time-loss injuries were registered in the intervention period, which may not yield a complete injury profile.

Summary

Our 12-week injury prevention programme, combined with ongoing training and match play in adolescent female athletes, improved neuromuscular activation strategies during side cutting. There was a relative decrease in VL-ST preactivity (ie, towards hamstring dominance) and an increase in ACL-agonist (medial hamstring, ST) preactivity during side cutting movement. We hypothesise that this reflects a more ACL-protective motor strategy in this high-risk population.

What are the new findings?

- The quadriceps and hamstrings neuromuscular activation strategy during a side cutting movement in adolescent athletes can be altered by 12 weeks of evidence-based injury prevention training.
- Evidence-based neuromuscular training induced a more anterior cruciate ligament-protective motor strategy by affecting the agonist-antagonist muscle activity.
- Twelve weeks of evidence-based neuromuscular training did not affect the potential biomechanical risk factors.

How might it impact on clinical practice in the future?

We recommend this training programme as part of an integrated part of weekly training among adolescent female athletes in high-risk sports.

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Contributors MKZ, PA, LLA and JB were responsible for the conception and design of the study. MKZ and MB coordinated the study. GM was responsible for the NMT programme and was the supervisor in the following implementation process at the Sports College. MKZ, MB and HBL managed all testing and data collection. LLA performed the randomisation and statistical analyses. PH was the study physician and the primary medical support for the players. MKZ wrote the first draft of the manuscript, which was critically revised by all co-authors. All authors contributed to the interpretation of findings and approved the final version of the manuscript. MKZ and PA are the guarantors.

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Competing interests None declared.

Patient consent Obtained.

Ethics approval The study was approved by The Committees on Biomedical Research Ethics of the Capital Region of Denmark (H-2-2010-091).

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