# Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis

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## ABSTRACT

**Context** Clinical trials have demonstrated that preventive neuromuscular training (PNMT) can be effective to reduce ACL injuries in young females. However, the magnitude of the overall effect of PNMT for ACL injury reduction has not reached consensus. In addition, the effects of individual exercises in PNMT that optimise ACL injury reduction are unknown.

**Objective** The purpose of this project was to systematically review previously published clinical trials and evaluate types of exercises that best support ACL injury reduction in young females.

**Data sources** The key words 'knee', 'anterior cruciate ligament', 'ACL', 'prospective', 'neuromuscular', 'training', 'female', and 'prevention' were used for studies published from 1995 to May 2012 in PubMed and EBSCO host.

**Study selection** Inclusion criteria for the current analysis were: (1) documented number of ACL injuries, (2) employed a PNMT intervention that aimed to reduce ACL injuries, (3) had a comparison group, (4) used a prospective controlled study design, (5) recruited female athletes and (6) recorded exercises implemented in the PNMT.

**Data extraction** The number of ACL injuries and female athletes in each group (control and intervention) were extracted. In addition, exercises were categorised into four types and analysed for each investigation.

**Data synthesis** A total of 14 clinical trials met the inclusion criteria. The subgroup analyses identified fewer ACL injuries in PNMT that focused on strengthening (OR 0.32, 95% CI 0.23 to 0.46, p=0.001), proximal control exercises (OR 0.33, 95% CI 0.23 to 0.47, p=0.001) and multiple exercise interventions (OR 0.32, CI 0.22 to 0.46, p=0.001).

**Conclusions** The current subgroup analyses indicate strengthening, proximal control exercises and multi exercise genres increased efficacy in PNMT intervention designed to reduce ACL injury in young female athletes.

## INTRODUCTION

The ACL plays an integral role in knee joint mechanics. When the ACL is ruptured, an individual often experiences multiple functional difficulties including the inability to decelerate, cut and pivot in addition to the presence of pain and effusion in the knee joint.[1] At the collegiate level, ACL injuries result in the greatest loss of time from athletic participation when compared to ankle and traumatic head injuries.[2] Approximately 350 000 individuals seek ACL reconstruction (ACLR) surgery to repair or reconstruct the ruptured ACL and restore knee function in the USA annually.[3]

Although ACLR is currently the gold standard treatment, met with limitations. A study showed that 23% of high school age athletes who had ACLR surgeries tore their contralateral or reconstructed ACL within 1 year of return to their sport.[4] In addition, 42% of female soccer players who had ACLR demonstrated radiographic knee osteoarthritis (OA) signs within 10 years, and 75% of them commented that the OA symptoms negatively affected their quality of life.[5] Another study reported 71% of individuals who had an ACLR surgery developed a moderate level of knee OA within 10–15 years.[6]

Owing to the negative health consequences following an ACL injury, prevention should be a focus of ACL-related research. The key to the development of effective prevention strategies is to identify modifiable risk factors. While some studies report an association between ACL injury and anatomical,[7 8] hormonal[9] and genetic[10–12] components, they are not modifiable in current medical practices. Conversely, biomechanical and neuromuscular components are modifiable. Recent biomechanical and neuromuscular analysis studies determined specific risk factors such as increased knee abduction angles, limited knee flexion, asymmetrical landing and abnormal ground reaction force (GRF) for ACL injury in young females.[13–15] Controlling the magnitude of external loading at the knee joint by improving muscular support[16] and altering athletic techniques[17] through preventive neuromuscular training (PNMT) appeared to be an effective intervention. Recent meta-analyses that evaluated the effectiveness of PNMT as a whole demonstrated that PNMT intervention effectively reduced ACL injury in young females.[18]

The studies in the meta-analyses contained diverse PNMT programmes, and it is difficult to identify what type of exercise optimally addressed the abnormal knee joint angles,[13] insufficient trunk control,[14 15] and risky cutting techniques,[19] which resulted in decreased knee loading and ACL protection. Clinical trials performed by Gilchrist *et al*[20] and Steffen *et al*[21] in female soccer players demonstrated a 73.4% and 29.4% ACL relative risk reduction (RRR) in ACL injury, respectively, in participants who received PNMT intervention compared to those who undertook their routine

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warm-up.[22] The difference in ACL RRR in the two clinical trials may be because of the different PNMT interventions. Gilchrist *et al*[20] implemented a combination of warm-up, stretching, strengthening, plyometrics and agility. In contrast, Steffen *et al*[21] instituted trunk stability, balance and plyometrics. The only common exercise in each trial was plyometrics.

It appears that performing these exercises promotes muscle development that improves movement patterns and protects the ACL, but it is unclear what the most effective exercises are. Recent studies that analysed PNMT interventions for ACL injury reduction reported that feasibility and intervention implementation were a major limitation.[23–25] Determining the exercise genres that are most effective when incorporated in the PNMT for ACL injury reduction in young females is essential. Four exercise genres, balance, plyometrics, strengthening and proximal control, are included in PNMT programmes. The purpose of the current analysis was to systematically review previously published clinical trials using PNMT intervention aimed at reducing ACL injury in young females and examining exercises that demonstrate the greatest prophylactic effects on ACL injury reduction.

## METHODS

### Literature search and criteria

A literature search was performed on 31 May 2013 using PubMed and EBSCO host (CINAHL, MEDLINE and SPORTDiscus) with a publication date range from 1995 to 2011. The key words search was performed by applying a combination of the following words: 'knee', 'anterior cruciate ligament', 'ACL', 'prospective', 'neuromuscular', 'training', 'female', and 'prevention' (table 1). Language was limited to English and participants were all human. The following inclusion criteria were applied: (1) the number of ACL injury incidents was reported, (2) a PNMT intervention aimed at reducing ACL incidence was applied, (3) a comparative group was used, (4) a prospective controlled trial study design was employed, (5) female athletes were included as participants and (6) exercises implemented in the PNMT were detailed. Abstracts, posters and unpublished data were excluded (figure 1). During this process, discrepancies in inclusion and exclusion of studies were discussed among authors (primary author (DS) and second author (GDM)).

**Table 1** Stepped PubMed/EBSCO host search strategy with the number of studies

| Step | Strategy | PubMed | EBSCO |
|---|---|---|---|
| #17 | Search (#11) AND (#16) | 402 | 76 |
| #16 | Search (#12) OR (#13) OR (#14) OR (#15) | 24 897 | 41 136 |
| #15 | Search "preventing" [TIAB] | 5101 | 1122 |
| #14 | Search "preventive" [TIAB] | 2496 | 2348 |
| #13 | Search "prevent" [TIAB] | 8551 | 2003 |
| #12 | Search "prevention" [TIAB] | 13 521 | 14 814 |
| #11 | Search(#5) AND (#10) | 4377 | 3616 |
| #10 | Search (#6) OR (#7) OR (#8) OR (#9) | 76 185 | 75 651 |
| #9 | Search "female" [TIAB] | 15 605 | 25 488 |
| #8 | Search "training" [TIAB] | 10 336 | 26 450 |
| #7 | Search "neuromuscular" [TIAB] | 1455 | 2646 |
| #6 | Search "prospective" [TIAB] | 52 817 | 21 939 |
| #5 | Search (#1) OR (#2) OR (#3) OR (#4) | 13 050 | 60 968 |
| #4 | Search "ACL" [TIAB] | 438 | 1104 |
| #3 | Search "anterior cruciate ligament" [TIAB] | 565 | 4330 |
| #2 | Search "knee" [TIAB] | 5074 | 18 321 |
| #1 | Search "injury" [TIAB] | 8156 | 39 322 |

Date was limited from 1 January 1995 to 31 May 2012. Language was limited in English. Species were limited in humans. Sex was limited in women. MEDLINE was used for a journal category selection for PubMEd. CINAHL, MEDLINE and SPORTDiscus were included in the EBSCO search.
TIAB, title and abstract.

### Quality assessment of studies

The Physiotherapy Evidence Database (PEDro) scale was used to analyse the methodological quality of the included studies. The PEDro score of each study reviewed was previously reported.[18]

### Level of evidence and strength of recommendation assessment method

To evaluate the quality of the current analysis, the Strength of Recommendation Taxonomy (SORT) was implemented.[26] The SORT is used to evaluate the quality of the included studies and strength of recommendation, which helps generate a grade of strength of recommendation for the current analyses.

### Data extraction

The overall number of ACL injuries in each group (control and intervention) and the number of participants in each group (control and intervention) were extracted for data analysis by the primary author. To investigate the effect of exercise genres, the types of exercise employed in PNMT programmes were also extracted from each study. Specifically, exercises were carefully examined, and those that were primarily balance, plyometric, strengthening and proximal control exercises were extracted. The exercises were categorised as

Balance—Postural exercises with an unstable base of support and/or a single-leg support with or without external perturbations.[17]

Plyometric—Exercises with ballistic movements containing both concentric and eccentric phases.[17] (eg, exercises focused on optimisation of the stretch shortening cycle such as jump and landing).

Strengthening—Exercises that aim to promote greater muscular force generation.

Proximal control—Exercises that involved segments proximal to the knee joint.

Proximal control training was analysed because recent evidence shows a link between proximal segments and ACL injury[14,15] and knee loading.[19,27] When the exercise descriptions were not clear, the primary author (DS) and second author (GDM) had discussions until a classification agreement was reached. An email was sent to the corresponding author listed in the original paper when the necessary information for the analysis was not in the published manuscript.

### Data analysis

To investigate the type of exercise that attains prophylactic effects of PNMT, a subgroup analysis with 95% CI was used. Exercises performed in each PNMT programme were dichotomised based on the status of the exercises implemented in the PNMT, and the number of overall ACL injuries was categorised by the selected exercise classification.

It was assumed that the effect size of each study was different, and a random-effects model was chosen to minimise variability among the included studies. To compare a ratio of ACL injuries in participants between the intervention and control groups, an OR was used. Egger's regression and a trim and fill plot were used to examine potential risks of publication bias assessment.

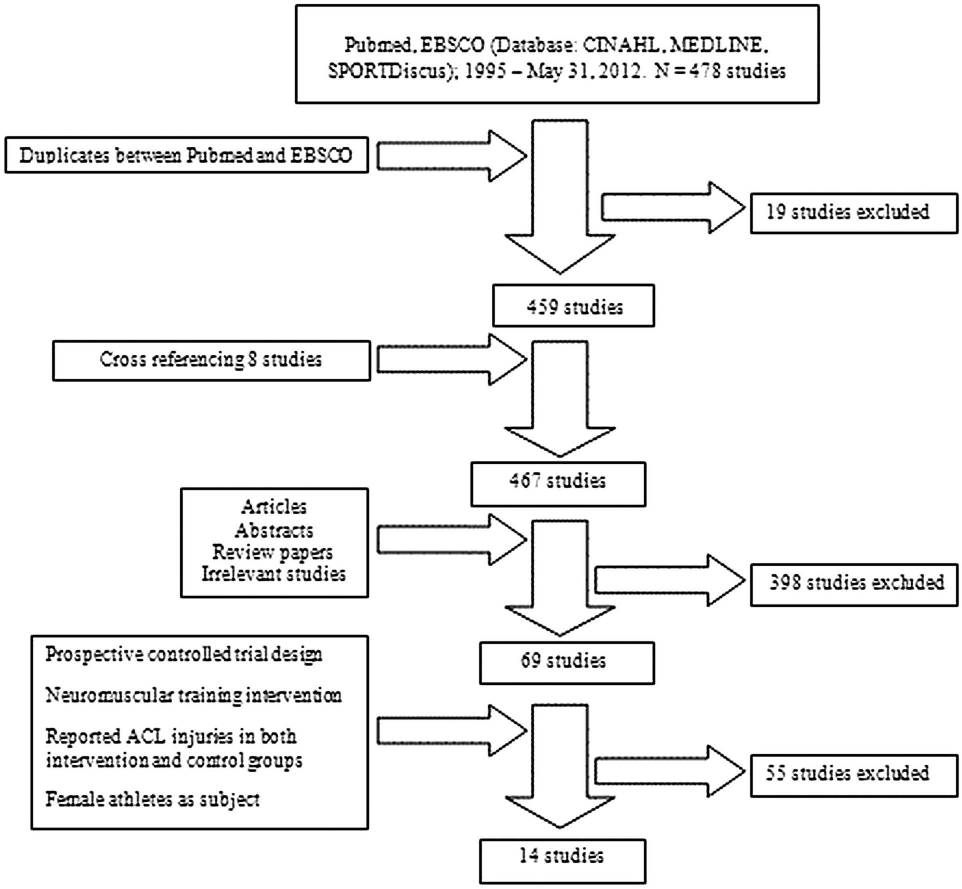



**Figure 1** Flow chart of the literature review.

All analyses were performed by meta-analysis software. (Biostat, Englewood, New Jersey, USA).

## RESULTS

A total of 459 original studies were collected, including cross-referenced studies. Of these, 13 clinical trials met the inclusion criteria. One study[28] that did not completely meet the inclusion criteria (no control group) was included as it met the purpose of the current project. Therefore, a total of 14 studies[20 21 28–39] were included in the current analyses (figure 1). The quality of each study, level of evidence, sports, number of teams and ages of each PNMT programme and other related information are summarised in online supplementary table S1, and the relevant methodological quality, as evaluated by the PEDro scores, was expressed in table 2.

### Balance exercises

The subgroup analysis that evaluated the number of ACL injuries relative to PNMT with no balance versus balance exercises in the 14 reviewed clinical trials[20 21 28–39] showed no statistical differences in PNMT with balance exercises[21 28 30 33–35 37–39] (OR 0.59, 95% CI 0.42 to 0.83, p=0.003) compared to no balance exercises[20 29 31 32 36] (OR 0.34, 95% CI 0.20 to 0.56, p=0.001; figure 2).

### Plyometrics exercises

The subgroup analysis that compared the number of ACL injuries based on PNMT with no plyometrics versus plyometrics in the 14 reviewed clinical trials[20 21 28–39] showed that there was no statistical difference between PNMT with plyometrics[20 21 29 31 32 34–36 38] (OR 0.39, 95% CI 0.26 to 0.57, p=0.001) and PNMT without plyometrics[28 30 33 37 39] (OR 0.59, 95% CI 0.39 to 0.89, p=0.012; figure 3).

### Strength exercises

The subgroup analysis that assessed the number of ACL injuries in PNMT with no strengthening versus strengthening in the 14 reviewed clinical trials[20 21 28–39] showed a significant ACL injury reduction in PNMT with strengthening exercises[20 21 29 31–34 37–39] (OR 0.32, 95% CI: 0.23 to 0.46, p=0.001), but not in programmes without a strengthening component[28 30 35 36] (OR 1.02, 95% CI: 0.63 to 1.64, p=0.953; figure 4).

### Proximal control exercises

The subgroup analysis that assessed the number of ACL injuries in PNMT between no proximal control exercises versus proximal control exercises[20 21 28–39] showed a significantly greater ACL injury reduction in PNMT with proximal control exercises[20 21 29 32–34 37–39] (OR 0.33, 95% CI 0.23 to 0.47, p=0.001) compared to PNMT without proximal control training[28 30 31 35 36] (OR 0.95, 95% CI 0.60 to 1.50, p=0.824; figure 5).

### Evidence synthesis

The PEDro scale can further generate a grade of strength of recommendation based on the level of consistent evidence from A to C based on SORT. In the current analysis, seven of the included clinical trials[20 21 31 33 34 38 39] were rated as level I (high quality individual randomised control trial), while seven clinical trials[28–30 32 35–37] were rated as level II (lower quality clinical trial and cohort study; table 3). Although the number of

**Table 2** PEDro scores of the reviewed studies

| | | PEDro scale | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reviewed studies** | **Total scores** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
| Hewett *et al** | 3 | – | | | | | | | X | X | X | |
| Soderman *et al* | 4 | – | X | | X | | | | | | X | X |
| Heidt *et al* | 5 | – | X | | | | | X | X | X | X | |
| Myklebust *et al** | 5 | – | | | | | | X | X | X | X | X |
| Mandelbaum *et al** | 3 | – | | | | | | | X | | X | X |
| Olsen *et al* | 7 | – | X | | X | | | X | X | X | X | X |
| Petersen *et al** | 2 | – | | | | | | | | | X | X |
| Pfeiffer *et al** | 2 | – | | | | | | | | | X | X |
| Steffen *et al* | 7 | – | X | X | | | | X | X | X | X | X |
| Gilchrist *et al* | 4 | – | X | | X | | | | | | X | X |
| Pasanen *et al* | 8 | | X | X | X | | | X | X | X | X | X |
| Kiani *et al** | 4 | – | | | X | | | X | | | X | X |
| LaBella *et al* | 6 | – | X | X | | | | | X | X | X | X |
| Walden *et al* | 7 | – | X | X | X | | | X | | X | X | X |

X 'yes' score. Blank 'no' score. PEDro scale is optimised for evaluation of randomised control trials; thus, the PEDro assessment score for the non-randomised control should be interrupted with caution. Studies with * are not randomised trials. (1) Eligibility criteria specified, (2) Random allocation of participants, (3) Allocation concealed, (4) Similar groups at baseline, (5) Blinding of participants, (6) Blinding of intervention providers, (7) Blinding of outcome assessors, (8) Outcomes obtained from 85% of participants, (9) Use of intent-to-treat analysis if protocol violated, (10) Between-group statistical comparison, (11) Point measures and measures of variability.
PEDro, Physiotherapy Evidence Database.

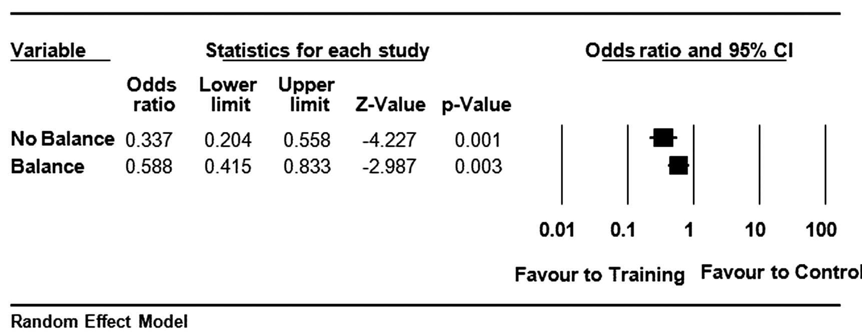



**Figure 2** Subgroup analysis of 14 clinical trials—balance exercises.

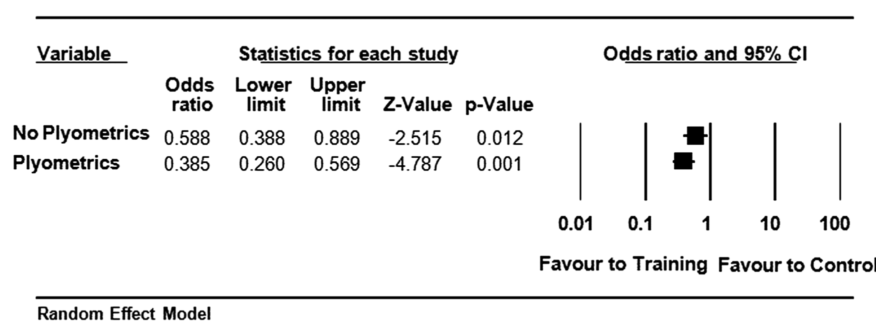



**Figure 3** Subgroup analysis of 14 clinical trials—plyometric exercises.

level I and II clinical trials are equivalent, the current meta-analysis supports consistency of evidence since 11 of the 14 reviewed clinical trials demonstrated fewer ACL injuries in PNMT intervention groups compared to control groups. In addition, a summary effect of the meta-analysis (figure 6) supports the evidence consistency. Based on the consistency of the results from the included clinical trials, the strength of recommendation grade for the current evidence is A (recommendation based on consistent and good quality patient-oriented evidence).

## Heterogeneity

The $I^2$ statistics of the subgroup PNMT analyses was significant in strength (p=0.001) and proximal training (p=0.001), but not in balance (p=0.075) and plyometrics (p=0.145).

## Bias assessment

Egger's regression for the publication bias for the 14 reviewed clinical trials showed an intercept at −0.17 (95% CI −1.93 to 1.59, p=0.41, one tailed), which indicated no publication bias in the current analysis, and the trim and fill plot also displayed no publication bias (figure 7).

## DISCUSSION

The purpose of the current analysis was to determine which PNMT exercises had a greater prophylactic effect in clinical trials that aimed to reduce ACL injury in young females. Four exercise categories, balance, plyometrics, strength and proximal control training, were examined. The results indicated that clinical trials that instituted PNMT with strength and proximal

**Figure 4** Subgroup analysis of 14 clinical trials—strength exercises.

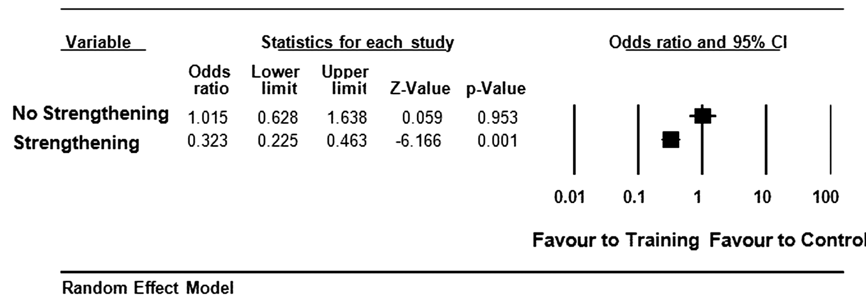



**Figure 5** Subgroup analysis of 14 clinical trials—proximal control exercises.

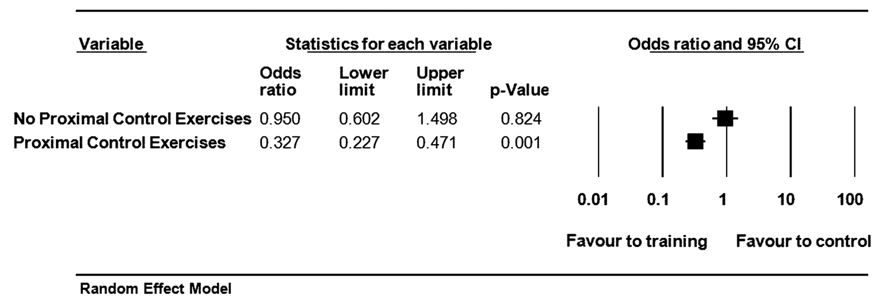


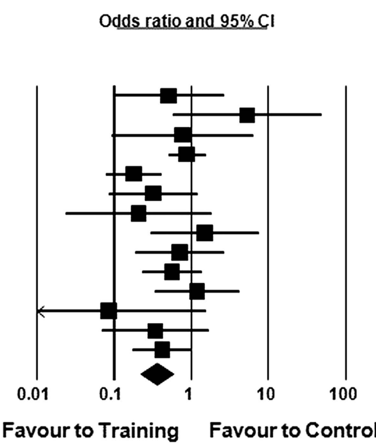

**Table 3** Summary of Reviewed Studies including study design, level of evidence, sports, number of teams and ages

| Reference (year) | Study design | Level of evidence | Sports | Number of teams | Ages (years) |
|---|---|---|---|---|---|
| Hewett *et al* (1999)[29] | Prospective non-randomised cohort | 2b | Soccer<br>Volleyball<br>Basketball | 15 teams (control)<br>15 teams (intervention) | 14–18 (range) |
| Soderman *et al** (2000)[30] | Prospective randomised control | 2b | Soccer | 6 teams (control)<br>7 teams (intervention) | C:20.4±5.4<br>I:20.4±4.6<br>(mean) |
| Heidt *et al* (2000)[31] | Prospective randomised control | 1b | Soccer | 258 individuals (control)<br>42 individuals (intervention) | 14–18<br>(range) |
| Myklebust *et al*† (2003)[28] | Prospective non-randomised crossover | 2b | Handball | 60 teams (1st year)<br>58 teams (2nd year) | 21–22<br>(mean) |
| Mandelbaum *et al* (2005)[32] | Prospective non-randomised cohort | 2b | Soccer | 207 teams (control)<br>97 teams (intervention) | 14–18<br>(range) |
| Olsen *et al* (2005)[33] | Prospective cluster randomised controlled | 1b | Handball | 59 teams (control)<br>61 teams (intervention) | 16–17<br>(mean) |
| Petersen *et al* (2005)[35] | Prospective matched cohort | 2b | Handball | 10 teams (control)<br>10 teams (intervention) | C:19.8<br>I:19.4<br>(mean) |
| Pfeiffer *et al* (2006)[36] | Prospective non-randomised cohort | 2b | Soccer<br>Volleyball<br>Basketball | 69 teams (control)<br>43 teams (intervention) | 14–18<br>(range) |
| Steffen *et al* (2008)[21 49] | Prospective block randomised controlled | 1b | Soccer | 51 teams (control)<br>58 teams (intervention) | 15.4<br>(mean) |
| Gilchrist *et al* (2008)[20] | Prospective cluster randomised controlled | 1b | Soccer | 35 teams (control)<br>26 teams (intervention) | C:19.9<br>I:19.9<br>(mean) |
| Pasanen *et al* (2009) | Prospective cluster randomised controlled | 1b | Floorball | 14 teams (control)<br>14 teams (control) | 24<br>(mean) |
| Kiani *et al* (2010)[37] | Prospective cluster non-randomised cohort | 2b | Soccer | 49 teams (control)<br>48 teams(intervention) | C:15.0<br>I:14.7<br>(mean) |
| LaBella *et al* (2011)[38] | Prospective cluster randomised controlled | 1b | Soccer<br>Basketball | 53 teams (control)<br>53 teams(intervention) | C:16.2<br>I:16.2<br>(mean) |
| Walden *et al* (2012)[39] | Prospective cluster randomised controlled | 1b | Soccer | 109 teams(control)<br>121 teams(intervention) | C:14.1<br>I:14.0<br>(mean) |

*Although the study was a randomised controlled design, the follow-up rate was low (51.2%). Therefore, the level of evidence was rated as 2b.
†For analysis purposes, only data from the first intervention year were used.

**Figure 6** Meta-analysis of 14 clinical trials (adapted from Myer *et al*[18] with permission).

| Study name | Odds ratio | Lower limit | Upper limit | p-value |
|---|---|---|---|---|
| Hewett et al 1999 | 0.503 | 0.097 | 2.609 | 0.414 |
| Soderman et al 2000 | 5.310 | 0.578 | 48.779 | 0.140 |
| Heidt et al 2000 | 0.762 | 0.093 | 6.255 | 0.800 |
| Myklebust et al 2003 | 0.870 | 0.499 | 1.516 | 0.624 |
| Mandelbaum et al 2005 | 0.179 | 0.077 | 0.413 | 0.001 |
| Olsen et al 2005 | 0.318 | 0.086 | 1.181 | 0.087 |
| Petersen et al 2005 | 0.206 | 0.024 | 1.787 | 0.152 |
| Pfeiffer et al 2006 | 1.497 | 0.301 | 7.440 | 0.622 |
| Steffen et al 2008 | 0.705 | 0.189 | 2.633 | 0.603 |
| Gilchrist et al 2008 | 0.563 | 0.234 | 1.357 | 0.201 |
| Pasanen et al 2008 | 1.182 | 0.329 | 4.246 | 0.798 |
| Kiani et al 2010 | 0.085 | 0.005 | 1.535 | 0.095 |
| LaBella et al 2011 | 0.340 | 0.068 | 1.688 | 0.187 |
| Walden et al 2012 | 0.419 | 0.169 | 1.040 | 0.061 |
| Total | 0.541 | 0.354 | 0.828 | 0.005 |




Meta Analysis, Random Model.

control training demonstrated the greatest prophylactic effects. Prophylactic effects were not statistically different between PNMT with and without plyometrics, but greater ACL injury reduction was recorded in PNMT with plyometrics. More specifically, incorporating plyometrics, strengthening and proximal control training into PNMT programmes can lead to ACL injury risk reduction by 61% in plyometrics, 68% in strengthening, and 67% in proximal control in young females. Balance exercises demonstrated a 41% reduction in ACL injury rate compared to a 66% reduction by PNMT without balance exercises (figure 2).

Plyometric exercises in PNMT often incorporated jumping forwards and backwards, jumping side to side, and tuck and scissor jumps.[20 21 29 31 32 34–36 38] Several studies that incorporated those exercises demonstrated 17–26% reduction in GRF on landing after 6–9 weeks of training.[40–42] It is crucial to note that both studies progressed the plyometric exercises periodically and supervised each training session,[40 41] particularly reinforcing sound knee alignment upon landing.[20 21 29 34–36 38] High GRF was identified as one of the risk factors for future non-contact ACL injury in female athletes.[13] Therefore, implementing a set of plyometric exercises into PNMT to reduce the GRF in landing manoeuvres may contribute to providing a protective mechanism against ACL injury.

One of the most commonly incorporated strength exercises in PNMT programmes was the Russian/Nordic hamstring curl. The hamstrings, an antagonist of the quadriceps, provide a posterior shear force on the tibia. This is important because the ACL anterior-medial bundle is under maximum tension in the

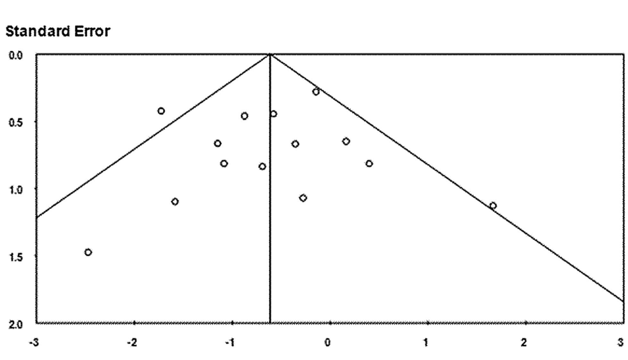



**Figure 7** Trim and fill plot for testing the publication bias.

final 30° of knee extension.[43] The anterior shear force generated during knee extension, as well as the contact phase of landing, is mainly determined by the quadriceps muscle action via the patella tendon-tibia shaft angle.[44 45] Therefore, strengthening the hamstrings can counterbalance the anterior shear force produced by the quadriceps and may protect the ACL. Consistent evidence was documented for enhancing the hamstring peak torque.[40 46 47] The hamstring strength and knee flexion angles on landing before and after PNMT programmes showed that 8 weeks of training increased hamstring isokinetic strength by 9.8%.[46] In addition, when hamstring forces are decreased, gastrocnemius muscles take a compensatory role.[48]

Subgroup analyses of protocols that included proximal control exercise were performed because recent studies identified a link between proximal segment control and knee joint injury.[14 15] Athletes who sustained severe ligamentous knee injuries, including ACL injuries, demonstrated greater deficits in trunk neuromuscular control compared to athletes who did not sustain severe injuries.[14] Cutting and landing patterns recorded on video revealed that lateral trunk flexion and knee abduction angles were greater in women who tore their ACL compared to male and female control players.[15] Clinical trials have incorporated exercises for the trunk such as bench[39 49] and side bench,[39 49] as well as sit-ups/abdominal curl,[29 37] push-up,[38] and upper body weight training including bench press, pullover, pulldown and hyperextension.[29] Proximal stability training reduced the knee abduction excursion angle in a single leg squat, suggesting that proximal stability training induced positive alterations in lower limb kinematics.[47]

The finding that PNMT interventions without balance exercises demonstrated greater prophylactic effectiveness compared to preventive PNMT with balance exercises was unexpected. This result is contradictory to numerous laboratory studies that showed that balance exercise altered kinematics and kinetics of the knee joint.[50–52] It is possible that the number of exercises incorporated in the PNMT was insufficient. Among the 14 studies, three implemented only one type of exercises. Two of the clinical trials solely examined effectiveness of balance exercises[28 30] and one of them without additional training modes actually demonstrated greater ACL injury incidence relative to a control group.[30] A significant difference was observed between PNMT programmes that had only one type of exercise and multiple types of exercises (figure 8). Other PNMT programmes[21 33 34 38 39] that instituted balance exercises in combination with other training modes showed substantial

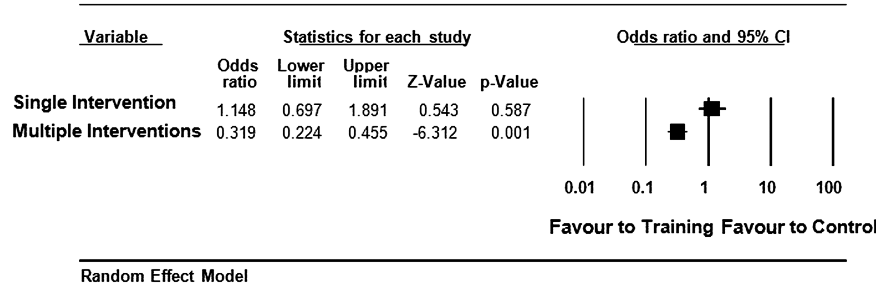



**Figure 8** Subgroup analysis of 14 clinical trials—a number of incorporated exercises.

prophylactic effects on ACL injury reduction. Thus, a more appropriate interpretation is that balance exercise alone appeared not to prevent ACL injuries[28 30]; however, balance exercise in conjunction with other types of exercises appeared to be effective.[21 33–35 38 39]

To support this notion, a study that analysed 15 intervention studies concluded that a combination of several types of exercise is superior to using strength exercise only.[53] Hence, a combination of the exercises may be synergistic and protect the knee joint during dynamic movements. Plyometric exercise is a useful exercise intervention to reduce ACL injury risk; however, using only plyometric exercise does not seem to produce the desired prophylactic effects. A clinical trial[36] that measured the effects of plyometric exercises on ACL injury reduction in collegiate female basketball, soccer and volleyball athletes demonstrated an equal number of ACL injuries between the intervention and control groups. Other PNMT programmes that instituted a combination of plyometrics and other types of exercises demonstrated prophylactic effects[20 21 29 31 32 35 36 38] with the exception of one study.[34]

An elevated knee abduction moment predicts future ACL injury with 78% sensitivity and 73% specificity.[13] Since then, most trials have incorporated plyometric exercises with verbal feedback designed to alter the knee abduction landing pattern. Seven of the nine clinical trials instituted verbal feedback techniques between athletes or from trained instructors during plyometric exercises.[20 21 29 34–36 38] Feedback appears effective in altering landing patterns in frontal planes.[54–57]

Plyometric exercises also reduced GRF and asymmetrical landing patterns,[40 41] reducing the side to side asymmetry landing force following plyometric exercises.[51] Verbal cues during plyometric exercises such as 'land like feather' can emphasise soft landing.[29] Another technique to reduce GRF is to increase the knee flexion range, as a small knee flexion range is a major risk factor of future ACL injury in female athletes.[13]

There is a biomechanical association between hamstrings and the trunk with dynamic movement.[58 59] Hamstring force generation is greater in trunk flexion compared to trunk extension.[58] Additionally, greater trunk flexion decreases the knee joint moment in a single leg landing task[60 61] as well as the actual ACL strain in a single leg task.[59] Two previously published studies reported an association between decreased trunk control and increased ACL injury risk.[14 15] Therefore, it can be theorised that training proximal segments, hamstrings, hips and trunk, modules the trunk kinematics and hamstrings force output, which synergistically functions in reducing ACL strain[59] during various task demands which occur in sporting events.

In order to further enhance trunk control, balance training may be required to build proximal segment stability. An asymmetrical landing pattern and landing with one foot is a risk factor for ACL injury.[13] Balance training with plyometrics may alter asymmetrical landing patterns.[62] Balance training with high school female athletes demonstrated improvement in the centre of pressure in the medial-lateral direction[51] and reduced GRF 7% during the single leg landing.[51] A balance index score,[63] which was identified as a predictive variable for future ACL injury in female athletes, also improved.[64]

## Limitations

Among the 14 reviewed clinical trials, 7 [20 21 31 33 34 38 39] had a randomised design and were rated as level I (high quality individual randomised control trial), and the remaining 7 [28–30 32 35–37] used a prospective cohort design and were classified as level II (lower quality clinical trial and cohort study). Randomisation is known as an effective method to reduce potential bias. Therefore, although the SORT level of evidence for this meta-analysis was A, the level of evidence would be more affirmative if more clinical trials employed the randomised design. In addition, the two heterogeneity analyses demonstrated significant difference among studies. This can be explained by a limited number of reviewed studies. Fewer numbers of studies make an accurate estimation of heterogeneity difficult.[65] Thus, fewer numbers of available studies and variation in the quality of the studies included in the subgroup analyses mean that these results should be interpreted with caution.

This study is generalisable only to the young female population. Only one study[66] in the male population was found but it was not included because of the inclusionary criteria. Additionally, there was diversity in the type of sports in the reviewed clinical trials. The sports used were soccer,[20 21 29–32 36–39] handball,[28 33 35] basketball[29 36 38] and floorball.[34] More studies are necessary in order to investigate the effects of specific exercises on ACL reduction in handball, basketball and floorball. Also, recent studies[67 68] have reported the effects of adherence on ACL injury reduction, which needs to be investigated in future studies.

Lastly, it was challenging to allocate the exercises of each study into the four defined categories. Many studies involved a jump-landing manoeuvre in their PNMT programmes. In this manoeuvre, a few studies emphasised sound knee alignments at the landing phase, and those exercises were categorised as balance exercises in this analysis. However, some of them also required eccentric and concentric muscle contractions in the manoeuvre, which is defined as a plyometric exercise.

## CONCLUSION

This review with a subgroup analysis examined exercises that reduced ACL injury in young female athletes. The analysis found that PNMT with strengthening and proximal control exercises significantly reduced ACL injury incidences compared to PNMT programmes without those exercise components. PNMT with plyometric exercises reduced ACL injury incidences, but was not statistically significant. PNMT with balance exercises alone did not demonstrate ACL injury reduction; however, this may be related to the number of exercises incorporated in

PNMT rather than the balance exercises themselves. Two studies that incorporated only a single exercise mode did not reduce ACL injuries. Studies that combined multiple exercise modes including plyometrics, strengthening, trunk and balance exercises demonstrated greater ACL injury reduction. Thus, our recommendation is to incorporate those exercises in PNMT programmes that aim to reduce the number of ACL injuries in female athletes. Young females can then maintain athletic participation, further promoting physically active lifestyles for the long term.

### What is known about the issue

Preventive neuromuscular training is an effective intervention to reduce ACL injuries in young females.

### What this study adds to existing knowledge

The current subgroup analysis identified specific types of exercises (strengthening and proximal control training) that attained the greatest prophylactic effectiveness in reducing ACL injuries in young females.

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Supplementary table 1. Summary of studies included in the review.

| Reference (Year) | Study design | Level of evidence | Sports | Number of teams | Age (mean±SD)[f] | Type | Length | Frequency | Weekly time spent during in-season |
|---|---|---|---|---|---|---|---|---|---|
| Hewett et al. (1999) | Prospective non-randomized cohort | II | Soccer Volleyball Basketball | 15 teams (control) 15 teams (intervention) | 14 – 18 yr (range) | Stretching, plyometrics, Weight training | 60 – 90 minutes | 3 days per week in pre-season | N/A[e] |
| Soderman et al. (2000)[a] | Prospective randomized control | II | Soccer | 6 teams (control) 7 teams (intervention) | C:20.4 ±5.4 yr I: 20.4 ±4.6 yr | Balance with balance boards | 10 – 15 minutes | Each day for 30 days. 3 days per week rest of the season | 10-15 min |
| Heidt et al. (2000)[b] | Prospective randomized control | I | Soccer | 258 individuals (control) 42 individuals (intervention) | 14 – 18 yr (range) | Cardiovascular, Plyometrics, Strength, flexibility, agility, and sports specific drills | 75 minutes | 3 days per week in pre-season | N/A[e] |
| Myklebust et al. (2003) | Prospective non-randomized cross over | II | Handball | 60 teams (1st yr) 58 teams (2nd yr) 52 teams (3rd yr) | 21-22 yr | Balance with mats and wobble boards | 15 minutes | 3 days per week for 5-7 weeks. Once a week for rest of the season | 15 min |
| Mandelbaum et al. (2005) | Prospective non-randomized cohort | II | Soccer | 207 teams (control) 97 teams (intervention) | 14-18 yr (range) | Basic warm-up, stretching, strengthening, plyometrics, | 20 minutes | 2-3 times per week in in-season | 40-60 min |

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|---|---|---|---|---|---|---|---|---|---|
| | | | | | | and agility | | | |
| Olsen et al. (2005) | Prospective cluster randomized controlled | I | Handball | 59 teams(control) 61 teams (intervention) | 16-17 yr | Warm-up, technique, balance, strength and power | 15-20 minutes | 15 consecutive sessions. Once a week for rest of the season | 15-20 min |
| Petersen et al. (2005)[c] | Prospective matched cohort | II | Handball | 10 teams(control) 10 teams (intervention) | C:19.8 I: 19.4 yr | Education, balance-board exercise, jump training | 10 minutes | 3 times per week in pre-season. Once per week for rest of the season | 10 min |
| Pfeiffer et al. (2006) | Prospective non-randomized cohort | II | Soccer Volleyball Basketball | 69 teams(control) 43 teams (intervention) | 14-18 yr (range) | Plyometrics | 20 minutes | 2 times per week in in-season | 40 min |
| Steffen et al. (2008) | Prospective block randomized controlled | I | Soccer | 51 teams (control) 58 teams (intervention) | 15.4 yr | Core stability, balance, plyometrics | 15 minutes | 15 consecutive sessions. Once a week for rest of the season | 15 min |
| Gilchrist et al. (2008) | Prospective cluster randomized controlled | I | Soccer | 35 teams (control) 26 teams (intervention) | C:19.9 yr I: 19.9 yr | Basic warm-up, stretching, strengthening, plyometrics, and agility | 20 minutes | 3 times per week in in-season | 60 min |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Pasanen et al. (2008) | Prospective cluster randomized controlled | I | Floorball | 14 teams (control) 14 teams (intervention) | 24 yr | Running techniques, balance and body control, plyometrics, strengthening | 20-30 minutes | 2-3 times per week for pre-season (intensive training period) and once a week in in-season (maintenance period) | 40-90 min |
| Kiani et al. (2010)[d] | Prospective cluster non-randomized cohort | II | Soccer | 49 teams (control) 48 teams (intervention) | C: 15.0 I: 14.7 yr | Core strengthening, balance | 20-25 minutes | 2 days per week for 2 months. Once a week for rest of the season | 20-25 min |
| LaBella et al. (2011) | Prospective cluster randomized controlled | I | Soccer Basketball | 53 teams (control) 53 teams (intervention) | C: 16.2 I: 16.2 yr | Strengthening, plyometrics, balance, agility | 20 minutes | 3 times per week in pre- and in-season | 60 min |
| Walden et al. (2012) | Prospective cluster randomized controlled | I | Soccer | 109 teams (control) 121 teams (intervention) | C: 14.1 I: 14.0 yr | Core stability, balance, jump-landing with knee alignment feedback | 15 minutes | 2 times per week. | 30 min |

a. Although the study was a randomized controlled design, the follow-up rate was low (51.2%). Therefore, the level of evidence was rated as II.
b. For the analysis purpose, data from 1st year intervention year was only used.
c. Although there was no specific statement, the neuromuscular training indicated plyometric components.
d. Although there were jump-landing maneuvers, repeated stretch-shortening cycle were not employed in the training.
e. The NMT was performed only during a pre-season. N/A stands for Not Applicable.
f. Unless otherwise indicated.
"C" stands for control group. "I" stands for Intervention group.