Journal of Physiotherapy 68 (2022) 255–261

AUSTRALIAN PHYSIOTHERAPY ASSOCIATION

Journal of PHYSIOTHERAPY

journal homepage: www.elsevier.com/locate/jphys

Research

Injury prevention programs that include plyometric exercises reduce the incidence of anterior cruciate ligament injury: a systematic review of cluster randomised trials

Wesam Saleh A Al Attar [a,b,c], Jumana M Bakhsh [a], Ehdaa H Khaledi [a,d], Hussain Ghulam [e], Ross H Sanders [b]

[a]Department of Physical Therapy, Faculty of Applied Medical Sciences, Umm Al Qura University, Makkah, Saudi Arabia; [b]Discipline of Exercise and Sport Science, Faculty of Medicine and Health Sciences, The University of Sydney, Sydney, Australia; [c]Department of Sport, Exercise and Health, Faculty of Medicine, University of Basel, Basel, Switzerland; [d]Department of Physical Therapy, King Abdullah Medical City, Makkah, Saudi Arabia; [e]Department of Physical Therapy, Faculty of Applied Medical Sciences, Najran University, Najran, Saudi Arabia

KEYWORDS

Injury risk reduction
Sporting injuries
Knee injury
ACL injury
Physical therapy

ABSTRACT

Question: Do injury prevention programs that include plyometric exercises reduce the incidence of anterior cruciate ligament (ACL) injuries in sport? **Design**: Systematic review of (cluster) randomised trials with meta-analysis. **Participants**: Sporting participants of any age, sex or competition level. **Interventions**: The experimental intervention was an injury prevention program that included plyometric exercises. The control intervention was the usual warm-up program, which did not include plyometric exercises. **Outcome measures**: Exposure-based ACL injury rates. **Results**: The initial search yielded 7,302 articles, of which nine met the inclusion criteria. All nine articles reported cluster randomised trials, providing data on 14,394 participants. The pooled results showed that injury prevention programs that include plyometric exercises reduce the risk of ACL injury by 60% per 1,000 hours of exposure compared with the control group, with an injury risk ratio (IRR) of 0.40 (95% CI 0.26 to 0.63). Data from subgroups of these trials estimated that this preventative effect may be stronger in males (IRR 0.21, 95% CI 0.07 to 0.62) and weaker in females (IRR 0.51, 95% CI 0.30 to 0.87), albeit with less precise estimates. Subgroup analysis also suggested a stronger effect on non-contact ACL injuries (IRR 0.34, 95% CI 0.18 to 0.65), whereas the effect on contact ACL injuries remained uncertain (IRR 0.59, 95% CI 0.15 to 2.30). **Conclusions**: Injury prevention programs that incorporate plyometric exercises substantially decrease the risk of ACL injuries more than warm-up programs that do not include plyometric exercises. The preventive effect appears to be stronger among males and in the prevention of ACL injuries that do not involve contact with another player. PROSPERO CRD42020196982. **[Al Attar WSA, Bakhsh JM, Khaledi EH, Ghulam H, Sanders RH (2022) Injury prevention programs that include plyometric exercises reduce the incidence of anterior cruciate ligament injury: a systematic review of cluster randomised trials. *Journal of Physiotherapy* 68:255–261]**

Introduction

Anterior cruciate ligament (ACL) tears are estimated to number 250,000 each year in the USA, with an average annual cost exceeding two billion dollars.[1] In young sporting participants, up to 96% of ACL injuries are reported to be non-contact in nature,[2] occurring without any direct physical contact by other players with the athlete's body. These types of injuries can occur under any conditions that cause the stress on the ACL to increase beyond its capacity. These conditions include performing actions such as cutting when running or landing after jumping.[3] About 79% of ACL injuries occur during sports activities when participants land on one leg (with their whole body weight) in a position where the knee is at a minimal degree of flexion.[2] ACL injuries may result in long-term clinical sequelae such as posttraumatic knee osteoarthritis.[4–8]

ACL injuries are common in a very wide range of sports. In soccer, for example, the high incidence of ACL injuries is believed to relate to tasks such as landing from attempts to head the ball and forceful cutting manoeuvres to get around other players.[9,10] In the USA, billions of dollars each year are spent on imaging, surgery, bracing and rehabilitation of these injuries.[1] In response, the Fédération Internationale de Football Association (FIFA) programs for injury prevention have been promoted and deployed worldwide.[11]

Strategies for the prevention of ACL injuries include a wide variety of interventions, such as neuromuscular training, proprioceptive training, stretching, plyometrics, movement training, core strengthening, balance training, resistance training and speed training.[12] Plyometric exercises comprise a very popular form of physical intervention that involve performing loaded jumping-type exercises using the stretch-shortening cycle muscle action.[13,14] Although plyometrics

https://doi.org/10.1016/j.jphys.2022.09.001

training is widely used to increase the power of subsequent movements,[14] it has also been examined as a preventative intervention for ACL injuries.

Within the last 5 years, five reviews have been conducted that in some way evaluated the effectiveness of plyometric exercises on reducing the rate of ACL injuries.[15–19] Stevenson et al[16] concluded that neuromuscular training programs including plyometric exercises are the most effective for ACL injury prevention; non-randomised studies were included in that review so the conclusions may be open to some bias. Nessler et al[17] evaluated programs to prevent ACL injuries and sought to identify risk factors that are linked with such injuries. Although they concluded that plyometrics can help to reduce ACL injuries, only two of the included studies used plyometric exercises; furthermore, the review did not have a formal search strategy. Neither of these reviews conducted any meta-analysis. The remaining three reviews used robust searches and meta-analysis.[15,18,19] Two of the reviews examined the effect of multicomponent neuromuscular training in female athletes only, so they cannot guide management of males.[15,18] Moreover, there was considerable variability in the experimental interventions that they pooled together and the components of the control intervention were not stated.[15,18] The final systematic review meta-analysed eight (cluster) randomised trials involving 13,562 male and female athletes.[19] The included programs incorporated components such as strengthening, plyometrics and agility exercises along with training in the proper landing technique using feedback. However, key factors related to the delivery of the injury prevention program and the specific exercises included in each program were highly variable. For example, trials that delivered exercise components for strength, plyometrics, agility and flexibility but not balance were meta-analysed together with a trial that delivered balance training and none of the other components, making it very difficult to know what components should be incorporated in an injury prevention program to achieve the pooled effects calculated in the meta-analyses.

Since those five reviews were conducted, additional relevant trials have been published, so an updated systematic review is required to assess the effectiveness of injury prevention programs that include plyometric exercises in reducing the incidence of ACL injuries in sport.

Therefore, the study question for this systematic review was:

Do injury prevention programs that include plyometric exercises reduce the incidence of anterior cruciate ligament injuries in sport?

Methods

This systematic review was prospectively registered and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines.[20]

Identification and selection of studies

Search strategy

The literature search strategy involved structured searches of PubMed, Medline, Web of Science, Cochrane Library and the Physiotherapy Evidence Database (PEDro) for relevant articles published in 1985 or later. The searches were based around the following keywords: *anterior cruciate ligament injury*, *ACL*, *injury prevention program*, *plyometrics training*, *injury rates*, *FIFA*, *knee injuries* and *athlete*. See Appendix 1 on the eAddenda for a detailed search strategy.

Eligibility criteria

Cluster-randomised trials or randomised trials were eligible for inclusion in the review if they met the inclusion criteria listed in Box 1. Studies were excluded if they did not report player exposure hours or used protective equipment as part of the intervention.

Box 1. Inclusion criteria.

Design
- (Cluster) randomised controlled trials
- Published in English

Participants
- Sports players
- No restriction by age, sex or skill level

Intervention
- Injury prevention programs that included plyometric training exercises, such as the FIFA 11+ injury prevention program

Outcome measures
- Reported at least two of: number of ACL injuries, ACL injury rate and exposure hours

Comparisons
- An injury prevention program that included plyometric training exercises versus usual/standard warm-up program that did not include plyometric training exercises

Inclusion procedure

Two researchers (WSA and JB) working independently completed the search process, including the removal of duplicates and assessment of each remaining article's title and abstract against the eligibility criteria. Articles that did not meet the eligibility criterion were excluded. A third researcher (EK) assisted the group to reach a consensus in any cases of disagreement. Articles that appeared potentially eligible from their title and abstract were retrieved in full text and assessed to determine eligibility. All articles included in the review and any relevant literature reviews identified during the searches underwent reference tracking to identify further potentially eligible studies.

Assessment of characteristics of studies

Methodological quality

The quality of the randomised trials included was assessed using the PEDro scale,[21] which is a useful tool and a valid measure of the methodological quality of clinical trials.[22] Although the scale consists of 11 items, the first item (eligibility criteria and source) is not used in calculating the score.[23] PEDro scores therefore range from 0 to 10 and reflect risk of bias and completeness of reporting.

Participants

The age and sex of the participants and their compliance with the study interventions were extracted for each included trial to characterise the experimental and control groups. The sport undertaken and the skill level of the participants were also extracted.

Intervention

The components of the injury prevention program were extracted from each included trial, along with the prescribed frequency of use and the total duration of the intervention period. The corresponding information was extracted from the control group of each study. Where necessary, the original authors were contacted to obtain these details.

Outcome measures

Data were extracted to calculate injury rate, which could be the number of ACL injuries and exposure hours, or ACL injury rates. Follow-up duration and compliance rate were also extracted from the included trials.

Data analysis

Commercial reference management software[a] was used for storage, collation and screening of studies. Primary outcome results from individual studies were extracted and collated in commercial spreadsheet software[b] prior to preparation and transfer into commercial meta-analysis software[c].

Meta-analysis

The number of incident injuries was divided by the total time at risk and multiplied by 1,000 to refer to the injury incidence rate (IRR). The IRR was calculated as injury incidence rate in the experimental group divided by the injury rate in the control group. An IRR < 1 indicates that the experimental intervention has a protective effect. Based on the assumption that the studies had diverse populations and different doses of exercise, we used the invariance random-effects model to assume that the data being analysed were drawn from a hierarchy of different populations whose differences related to that hierarchy. Commercial meta-analysis software[c] was used to calculate the overall sample size, the confidence interval for each study and the pooled results.

Publication bias

If 10 studies were available, it was intended to create a funnel plot to assess publication bias. The Egger's test[24] and Begg's test[25] would then be applied to establish the degree of asymmetry and the 'trim and fill' method[26] would be used to estimate missing studies due to publication bias in the funnel plot.

Definitions of injury and workload

ACL injury

An ACL injury was defined as a partial or complete rupture of the ligament that occurs for the first time or as a recurrence. The ligament injury could occur in isolation or in combination with other knee joint injuries.[27]

Workload

The workload of the participants was described as the number of active hours spent during the study in either training or competitive play.[28]

Results

Flow of studies through the review

The initial database searches yielded 7,302 articles. After eliminating duplicates, 4,724 articles remained and were screened based on their titles and abstracts. Of these, 68 were considered potentially eligible and retrieved as full-text articles and further assessed for eligibility. Of these, 59 were excluded because they did not meet the eligibility criteria. Thus, nine articles were included in the quantitative analysis of this review. Figure 1 shows the flow of articles through the search, screening and inclusion processes.

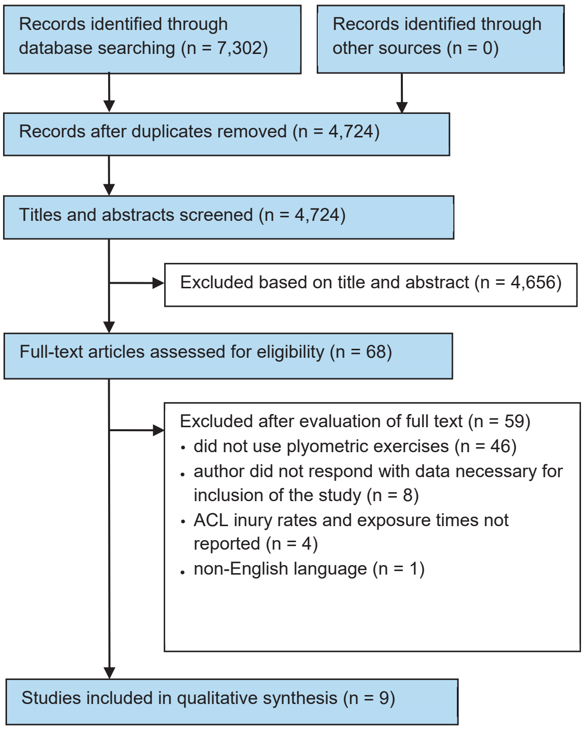

Figure 1. Flow of trials through the review.

Characteristics of studies

Table 1 illustrates the characteristics of the nine included studies and Table 2 shows the injury rates and hours of exposure of the intervention and control groups. All nine studies were cluster-randomised trials.[27,29–36] Three studies were conducted in the USA,[30,32,33] two studies were conducted in Norway,[29,31] and single studies were conducted in Iran,[36] Sweden,[27] Germany[34] and Australia.[35] Four studies included only female participants,[27,30–32] three studies included only male participants,[33,35,36] and two studies included female and male participants.[29,34] The duration of programs ranged from 3 months to one season.

Experimental and control intervention components

One of the Norwegian studies used the FIFA 11 for 15 consecutive sessions and thereafter once a week during the rest of the season.[31] One study used FIFA 11+ three times a week,[33] and another study used FIFA 11+ kids twice a week.[36] Olsen et al[29] used a structured warm-up program to improve running, cutting and landing techniques, neuromuscular control, balance and strength at every training session for 15 consecutive sessions and then once a week. Gilchrist et al[30] used a warm-up program including basic components in stretching, strengthening, plyometrics, agility activities and avoidance of high-risk positions three times a week. LaBella et al[32] used a 20-minute neuromuscular warm-up (strength, balance, plyometric and agility) twice a week. Waldén et al[27] used a 15-minute neuromuscular warm-up program (one-legged knee squat, a pelvic lift, a two-legged knee squat, the bench, the lunge and jump/landing technique) twice a week. Achenbach et al[34] used neuromusclar training (strength exercises, plyometric exercises, jump and landing exercises, and proprioceptive exercises) two to three times a week. Al Attar et al[35] used the pre-training and post-training FIFA 11+ program two to three times a week.

For the control group, participants' usual warm-up program was used in seven studies.[27,29–34] Al Attar et al[35] used the pre-training FIFA 11+ program and Zarei et al[36] used a standard warm-up program in the control groups, and the 11+ Kids program used by the intervention group.

Methodological quality

The internal validity of the included studies was assessed using the PEDro scale (Table 3).[21] The method of randomisation generation was defined in all included studies.[27,29–36] The intervention allocation was concealed in five included studies,[27,31,33,35,36] but not clarified in four studies.[29,30,32,34] Seven studies had sufficient information about the groups' characteristics and similarity at baseline,[27,29,30,32,33,35,36] while two studies did not.[31,34] None of the studies were administered with blinding of the subjects and therapists,[27,29–36] while assessors were blinded in two studies.[27,31] Participant follow-up was sufficient in four of nine studies.[29,31–33] Intention-to-treat analysis was applied in six studies,[27,29,31,32,35,36] while it was not in three studies.[30,33,34] Proper point and variability measures of the study outcome and appropriate statistical comparisons were reported in all studies.[27,29–36]

Effect of the intervention

Pooled injury estimates

The pooled data of 14,394 participants, 985,938 exposure hours, and 103 ACL injuries were collected from the included studies (Table 2).

Overall reduction in ACL injuries based on total exposure hours

Overall, the pooled results showed 60% greater reduction in ACL injuries per 1,000 hours of exposure among those who received the

Table 1
Characteristics of the included studies (n = 9).

Study Design Country	Participants	Intervention		Outcome measures
		Exp	Con	
Achenbach 2017 [34] Cluster RCT Germany	N = 279 Age *(y)* = 13 to18 Gender = F, M Compliance *(%)* = NA Adolescent handball	Neuromuscular training (included plyometric exercises) 2 to 3/week × one season	Standard warm-up 2 to 3/week × one season	ACL injury
Al Attar 2017 [35] Cluster RCT Australia	N = 280 Age *(y)* = 14 to 35 Gender = M Compliance *(%)* = 83 Amateur soccer	FIFA 11+ IPP performed before and after training (included plyometric exercises) 2 to 3/week × 6 months	FIFA 11+ IPP performed before training only 2 to 3/week × 6 months	ACL injury
Gilchrist 2008 [30] Cluster RCT USA	N = 1,435 Age *(y)* = 19 to 20 Gender = F Compliance *(%)* = 72 Collegiate (Division 1) soccer	PEP program (included plyometric exercises) 3/week × 3 months	Standard warm-up 3/week × 3 months	ACL injury
LaBella 2011 [32] Cluster RCT USA	N = 1,492 Age *(y)* = 14 to 18 Gender = F Compliance *(%)* = 80 Youth soccer and basketball	Neuromuscular training (included plyometric exercises) 2/week × 6 months (one season)	Standard warm-up 2/week × one season	ACL injury
Olsen 2005 [29] Cluster RCT Norway	N = 1,837 Age *(y)* = 15 to 17 Gender = F, M Compliance *(%)* = 87 Youth handball	Structured warm-up program (included plyometric exercises) 1 to 5 /week × 8 months	Standard warm-up 1 to 5 /week × 8 months	ACL injury
Silvers-Granelli 2015 [33] Cluster RCT USA	N = 1,525 Age *(y)* = 18 to 25 Gender = M Compliance *(%)* = 73 Collegiate soccer	FIFA 11+ IPP (included plyometric exercises) 3/week × 6 months	Aerobic warm up 3/week × 6 months	ACL injury
Steffen 2008 [31] Cluster RCT Norway	N = 2,020 Age *(y)* = 13 to17 Gender = F Compliance *(%)* = 52 Youth soccer	FIFA 11 IPP (included plyometric exercises) 1 to 5/week × 8 months	Standard warm-up 1 to 5/week × 8 months	ACL injury
Waldén 2012 [27] Cluster RCT Sweden	N = 4,564 Age *(y)* = 12 to 17 Gender = F Compliance *(%)* = NA Youth soccer	Neuromuscular training (included plyometric exercises) 2/week × 7 months	Standard warm-up 2/week × 7 months	ACL injury
Zarei 2019 [36] Cluster RCT Iran	N = 962 Age *(y)* = 7 to 14 Gender = M Compliance *(%)* = 50 to 100 Children soccer	FIFA 11+ Kids IPP (included plyometric exercises) 2/week × 9 months	Standard warm-up 2/week × 9 months	ACL injury

Con = control group, Exp = experimental group, F = female, FIFA 11+ IPP = Fédération Internationale de Football Association Medical and Research Centre (F-MARC) injury prevention program, M = male, NA = not assessed, RCT = randomised controlled trial, PEP = Prevent injury and Enhance Performance program.

injury prevention programs that included plyometric exercise compared with the control group (IRR 0.40, 95% CI 0.26 to 0.63). The inconsistency statistic indicated no heterogeneity between studies (I^2 = 0%) (Figure 2); see Figure 3 on the eAddenda for a detailed forest plot.

Reduction of ACL injuries in subgroups

In the studies where data for contact and non-contact injuries were pooled, injury prevention progams that included plyometric exercises showed a 59% injury reduction per 1,000 hours of exposure (IRR 0.41, 95% CI 0.24 to 0.70). In studies where only contact ACL

Table 2
Injury rates per 1,000 hours of exposure in the experimental and control groups of the included studies.

Study	Exp				Con			
	N	ACL injuries	Exposure hours	Injuries/1,000 hours	N	ACL injuries	Exposure hours	Injuries/1,000 hours
Achenbach 2017[34]	168	1	26,278	0.038	111	2	17,929	0.112
Al Attar 2017[35]	144	0	35,802	0.000	136	3	31,616	0.095
Gilchrist 2008[30]	583	7	35,220	0.199	852	18	52,919	0.340
LaBella 2011[32]	737	2	28,023	0.071	755	6	22,925	0.262
Olsen 2005[29]	958	3	93,812	0.032	879	10	87,483	0.114
Silvers-Granelli 2015[33]	675	3	35,226	0.085	850	16	44,212	0.362
Steffen 2008[31]	1,073	4	66,423	0.060	947	5	65,725	0.076
Waldén 2012[27]	2,479	7	149,214	0.047	2,085	14	129,084	0.108
Zarei 2020[36]	443	0	31,934	0.000	519	2	32,113	0.062
Pooled data	7,260	27	501,932		7,134	76	484,006	

Table 3
PEDro scores for the included trials (n = 9).

Study	Random allocation	Concealed allocation	Groups similar at baseline	Participant blinding	Therapist blinding	Assessor blinding	< 15% loss to follow-up	Intention-to-treat analysis	Between-group difference reported	Point estimate and variability reported	Total (0 to 10)
Achenbach 2017[34]	Y	N	N	N	N	N	N	N	Y	Y	3
Al Attar 2017[35]	Y	Y	Y	N	N	N	N	Y	Y	Y	6
Gilchrist 2008[30]	Y	N	Y	N	N	N	N	N	Y	Y	4
LaBella 2011[32]	Y	N	Y	N	N	N	Y	Y	Y	Y	6
Olsen 2005[29]	Y	N	Y	N	N	N	Y	Y	Y	Y	6
Silvers-Granelli 2015[33]	Y	Y	Y	N	N	N	Y	N	Y	Y	6
Steffen 2008[31]	Y	Y	N	N	N	Y	Y	Y	Y	Y	7
Waldén 2012[27]	Y	Y	Y	N	N	Y	N	Y	Y	Y	7
Zarei 2020[36]	Y	Y	Y	N	N	N	N	Y	Y	Y	6

N = no, Y = yes.

injuries were examined, there was a 41% injury reduction due to the injury prevention programs that included plyometric exercises (IRR 0.59, 95% CI 0.15 to 2.30). Among the studies where only non-contact ACL injuries were examined, there was a 66% injury reduction (IRR 0.34, 95% CI 0.18 to 0.65). The inconsistency statistic showed moderate heterogeneity among the studies of contact ACL injuries (I^2 = 33%), while contact and non-contact injury studies along with non-contact injury studies were homogeneous (I^2 = 0%) (Figure 4); see Figure 5 on the eAddenda for a detailed forest plot.

The studies that reported data for males only showed that injury prevention programs that included plyometric exercises caused a 79% ACL injury reduction per 1,000 hours of exposure in males (IRR 0.21, 95% CI 0.07 to 0.62), whereas the value was a 50% reduction in the studies of females (IRR 0.51, 95% CI 0.30 to 0.87). There was a 71% reduction (IRR 0.29, 95% CI 0.09 to 0.91) in the studies that pooled data for both males and females. The inconsistency statistic indicated homogeneity between the results from the studies of males only and females only (I^2 = 0%) (Figure 6); see Figure 7 on the eAddenda for a detailed forest plot.

Publication bias

Because there were fewer than 10 studies included in any of the meta-analyses, the planned analyses of Egger's test[24] and Begg's test[25] were not undertaken.

Discussion

This systematic review and meta-analysis of nine cluster randomised controlled trials[27,29–36] provided very clear evidence that injury prevention programs that include plyometric exercises have a significant effect in reducing ACL injuries among sporting participants. The meta-analysis revealed that injury prevention programs that included plyometric exercises reduced ACL injury rate by 60% per 1,000 hours of exposure.

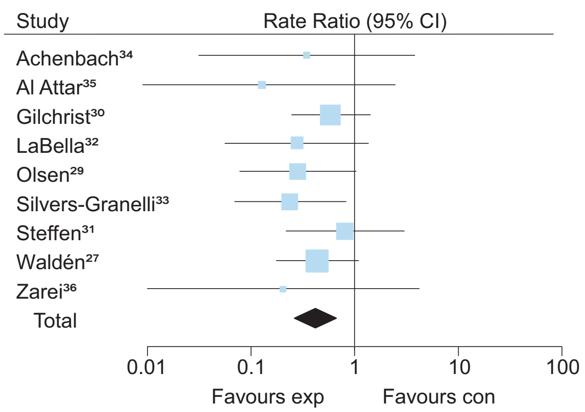

Figure 2. Forest plot of the effect of injury prevention programs that included plyometric exercises versus control on anterior cruciate ligament injury risk ratio. Con = control group, Exp = experimental group.

The mean reductions in risk observed in this review were large: 60% overall and ranging from 41 to 79% in the various subgroups. These effects are certainly large enough to make it worthwhile to change the components of sporting participants' usual injury prevention program to include plyometric exercises. Implementing this change in clinical practice involves so little effort that even much weaker effects would make adopting plyometric exercises for injury prevention worthwhile. Therefore, even the weakest estimated reductions in risk (shown by the upper limit of the confidence intervals) of 37% overall and ranging from 9 to 38% in most of the various subgroups are also arguably worthwhile. The exception was the effect on injuries that involved contact with another player, where the confidence interval showed that the effect of incorporating plyometric exercises into an injury prevention program remains very uncertain.

The subgroup analysis by mechanism of injury (contact versus non-contact) was an important analysis because most ACL injuries are caused by non-contact mechanisms.[2,37,38] The pooled results

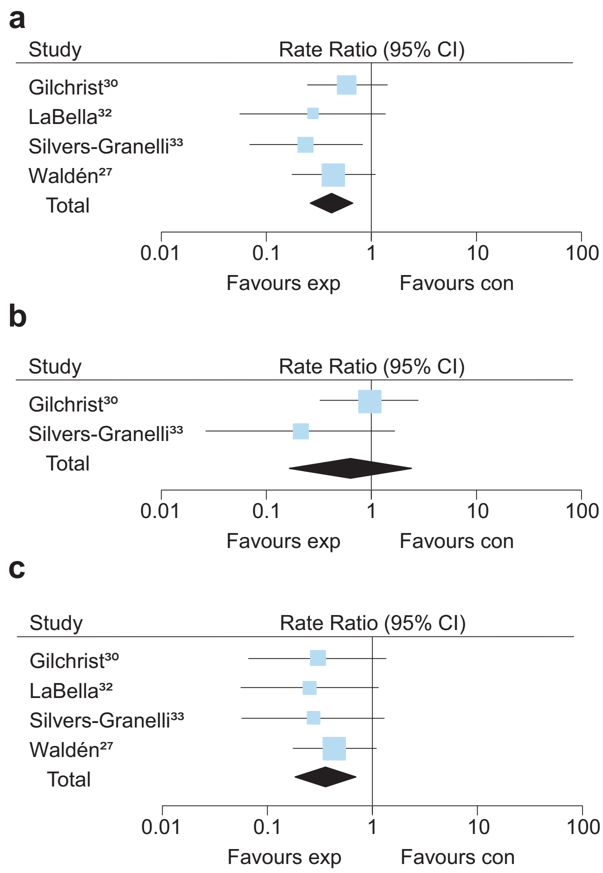

Figure 4. Forest plot of the effect of injury prevention programs that included plyometric exercises versus control on anterior cruciate ligament injury risk ratio, subgrouped by studies of (a) pooled contact and non-contact injuries, (b) contact injuries, and (c) non-contact injuries. Con = control group, Exp = experimental group.

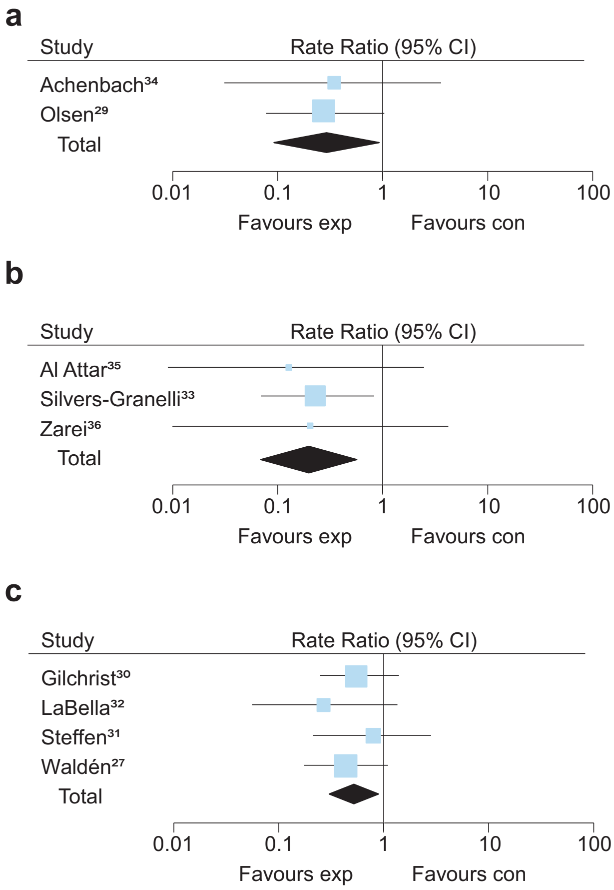

Figure 6. Forest plot of the effect of injury prevention programs that included plyometric exercises versus control on anterior cruciate ligament injury risk ratio, subgrouped by studies of (a) pooled males and females, (b) males, and (c) females. Con = control group, Exp = experimental group.

provided evidence that injury prevention programs that include plyometric training reduce non-contact ACL injuries by around 66% (IRR 0.34, 95% CI 0.18 to 0.65) but the estimate that they reduce contact injuries by 41% was very uncertain (IRR 0.59, 95% CI 0.15 to 2.30). If plyometric injury prevention programs are truly less effective (or even ineffective) on contact ACL injuries, this may be because the mechanism of injury involves external forces that are beyond what can be countered by the additional balance and agility arising from the incorporation of plyometrics. The wide confidence interval for this subgroup is partly due to there being only two studies of contact injuries compared with four studies of non-contact injuries. Thus, the 41% reduction in contact injuries is not a precise enough estimate to guide decision-making about prevention of contact injuries. Given that the overall decrease in injury risk when data for contact and non-contact injuries were pooled confirms a worthwhile effect, the clinical implication remains firmly that plyometrics should be incorporated in injury prevention, despite the uncertainty about the effect on contact injuries specifically.

These findings provide valuable evidence to support the position statement of the American National Athletic Trainers' Association, which advises that non-contact and indirect contact ACL injuries are reduced by multicomponent injury prevention programs that include at least three of: plyometrics, balance, flexibility, agility and strengthening.[39] However, the recommendation in that position statement is based on Level B evidence because it partly relies on non-randomised studies; with the current review, that recommendation can now change to level A evidence. Also, it could be modified to indicate that plyometrics should be one of the components present. The literature emphasises that the inclusion of plyometric exercises in injury prevention programs reduces non-contact ACL injuries by mitigating causative factors in ACL injuries, such as by decreasing landing force, knee flexion and knee valgus moments during landing, as well as increasing muscle activation and proprioception.[10,40–42] However, not all studies support this proposed mechanistic pathway;[43,44] for example, female athletes who completed a neuromuscular training program that included plyometric training did not experience all the changes in the biomechanical performance that had been anticipated from the theory of how plyometric exercises are protective.[44] While it would be good to more accurately understand the mechanism behind the preventive effect, the estimates of the magnitude of the effects are large enough and precise enough for clinicians to implement injury prevention programs that include plyometric exercises as evidence-based injury prevention management.

Although the ACL injury rate reduction was clearly worthwhile in both males (IRR 0.21, 95% CI 0.07 to 0.62) and females (IRR 0.51, 95% CI 0.30 to 0.87), the reduction seems greater among males than females. Nevertheless, the estimated effect in females is still clearly worthwhile. This is consistent with another published analysis that concluded that female athletes who performed plyometric exercises within their preventive program had a lower ACL injury risk than those who did not,[45] albeit with some non-randomised studies included in that analysis.

Three of nine included studies reported the data of players with a previous ACL injury.[27,30,32] However, the number of players who received ACL injuries and the injury rate for players with and without a history of a previous ACL injury was provided in one of those studies,[30] whereas only the total number of players with previous ACL injury for both intervention and control groups was reported in the other two studies.[27,32] Therefore, subgroup analysis based on the history of ACL injury could not be conducted due to the heterogeneity of the available data. We recommend further cluster-randomised controlled trials on this topic could report a subgroup analysis of participants with and without previous history of an ACL injury.

Further research is needed to evaluate the effect of injury prevention programs that include plyometric exercises on ACL injury risk. Such research could also investigate the best training parameters of plyometric-based training, and evaluate its effectiveness in reducing ACL injuries among specific sport populations.

This systematic review and meta-analysis employed subgroup analyses based on the mechanism of injury and sex, as well as reporting the exposure hours. These procedures minimised the heterogeneity between included studies and provided knowledge of potential contributors to ACL injury risk. Although the review was able to include data on a variety of sports and training elements in the prevention programs, further clinical trials could examine the effect of plyometric exercise on the incidence of ACL injuries in other sport populations.

In conclusion, this systematic review and meta-analysis indicates that injury prevention programs that include plyometric exercises have a significant preventive effect against ACL injuries among both male and female sporting participants. The results suggest that ACL injury rates reduce by 60% in teams that perform injury prevention programs that include plyometric exercises compared with teams that do not. Accordingly, these findings may encourage the physiotherapists, coaches and players to include plyometrics exercises within players' prevention programs.

What was already known on this topic: Anterior cruciate ligament injuries are common in competitive sport and may have long-term sequelae such as posttraumatic knee osteoarthritis. Multicomponent injury prevention programs seem to reduce the risk of anterior cruciate ligament injury but it is unclear which components need to be present.
What this study adds: Injury prevention programs that incorporate plyometric exercises substantially decrease the risk of anterior cruciate ligament injuries more than warm-up programs that do not include plyometric exercises. The preventive effect appears to be stronger among males and in the prevention of those injuries that do not involve contact with another player.

Footnotes: [a] Endnote version X8, Thomson Reuters, Philadelphia, USA.

[b] Microsoft Excel for Mac 2011, Microsoft Corporation, Redmond, USA.

[c] Comprehensive Meta-Analysis software V.3, Biostat Inc, Englewood, USA.

eAddenda: Appendix 1 and Figures 3, 5 and 7 can be found online at https://doi.org/10.1016/j.jphys.2022.09.001

Ethics approval: Nil.

Competing interests: The author(s) declare that they have no competing interests.

Source(s) of support: The authors would like to thank the Deanship of Scientific Research at Umm Al-Qura University for supporting this work by Grant Code: 22UQU4350385DSR02.

Acknowledgements: The authors would like to acknowledge Evangelos Pappas, Ahmad Alanazi and Amirah Akkam for their expert opinion and assistance in writing the manuscript.

Author contributions: Study conceptualisation, protocol design and registration (WSA), data collection and extraction (JMB, EHK), data analysis (WSA), data interpretation (WSA, JMB, EHK), writing the manuscript (WSA, JMB, EHK, HSG, RHS), critical revision (WSA, RHS); all listed authors read and approved the final version for publication.

Data sharing: All data generated or analysed during this study are included in this published article.

Provenance: Not invited. Peer reviewed.

Correspondence: Wesam Saleh A. Al Attar, Department of Physical Therapy, Umm Al Qura University, Saudi Arabia. Email: wsattar@uqu.edu.sa

References

1. Silvers HJ, Mandelbaum BR. ACL injury prevention in the athlete. *Sports Orthop Traumatol*. 2011;27:18–26.
2. Olsen O-E, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004;32:1002–1012.
3. Hashemi J, Breighner R, Chandrashekar N, et al. Hip extension, knee flexion paradox: a new mechanism for non-contact ACL injury. *J Biomech*. 2011;44:577–585. https://doi.org/10.1016/j.jbiomech.2010.11.013
4. Levine JW, Kiapour AM, Quatman CE, et al. Clinically relevant injury patterns after an anterior cruciate ligament injury provide insight into injury mechanisms. *Am J Sports Med*. 2013;41:385–395. https://doi.org/10.1177/0363546512465167
5. Chu CR, Beynnon BD, Buckwalter JA, et al. Closing the gap between bench and bedside research for early arthritis therapies (EARTH): report from the AOSSM/NIH U-13 Post-Joint Injury Osteoarthritis Conference II. *Am J Sports Med*. 2011;39:1569–1578. https://doi.org/10.1177/0363546511411654
6. Nebelung W, Wuschech H. Thirty-five years of follow-up of anterior cruciate ligament-deficient knees in high-level athletes. *Arthroscopy*. 2005;21:696–702. https://doi.org/10.1016/j.arthro.2005.03.010
7. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis*. 2004;63:269–273. https://doi.org/10.1136/ard.2003.008136
8. Quatman CE, Kiapour A, Myer GD, et al. Cartilage pressure distributions provide a footprint to define female anterior cruciate ligament injury mechanisms. *Am J Sports Med*. 2011;39:1706–1713. https://doi.org/10.1177/0363546511400980
9. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:705–729.
10. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc*. 2009;17:859–879.
11. Al Attar WSA, Soomro N, Pappas E, Sinclair PJ, Sanders RH. How effective are F-MARC injury prevention programs for soccer players? A systematic review and meta-analysis. *Sports Med*. 2016;46:205–217.
12. Renstrom P, Ljungqvist A, Arendt E, et al. Non-contact ACL injuries in female athletes: an International Olympic Committee current concepts statement. *Br J Sports Med*. 2008;42:394–412. https://doi.org/10.1136/bjsm.2008.048934
13. Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med*. 2010;40:859–895. https://doi.org/10.2165/11318370-000000000-00000
14. Meylan C, Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. *J Strength Cond Res*. 2009;23:2605–2613. https://doi.org/10.1519/JSC.0b013e3181b1f330
15. Petushek EJ, Sugimoto D, Stoolmiller M, Smith G, Myer GD. Evidence-based best-practice guidelines for preventing anterior cruciate ligament injuries in young female athletes: a systematic review and meta-analysis. *Am J Sports Med*. 2019;47:1744–1753.
16. Stevenson JH, Beattie CS, Schwartz JB, Busconi BD. Assessing the effectiveness of neuromuscular training programs in reducing the incidence of anterior cruciate ligament injuries in female athletes: a systematic review. *Am J Sports Med*. 2015;43:482–490. https://doi.org/10.1177/0363546514523388
17. Nessler T, Denney L, Sampley J. ACL Injury Prevention: What Does Research Tell Us? *Curr Rev Musculoskelet Med*. 2017;10:281–288. https://doi.org/10.1007/s12178-017-9416-5
18. Crossley KM, Patterson BE, Culvenor AG, Bruder AM, Mosler AB, Mentiplay BF. Making football safer for women: a systematic review and meta-analysis of injury prevention programmes in 11 773 female football (soccer) players. *Br J Sports Med*. 2020. https://doi.org/10.1136/bjsports-2019-101587
19. Huang YL, Jung J, Mulligan CMS, Oh J, Norcross MF. A majority of anterior cruciate ligament injuries can be prevented by injury prevention programs: a systematic review of randomized controlled trials and cluster-randomized controlled trials with meta-analysis. *Am J Sports Med*. 2020;48:1505–1515. https://doi.org/10.1177/0363546519870175
20. Moher D, Liberati A, Tetzlaff J, Altman DG, Group P. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med*. 2009;6:e1000097.
21. Moseley AM, Elkins MR, Van der Wees PJ, Pinheiro MB. Using research to guide practice: The physiotherapy evidence database (PEDro). *Braz J Phys Ther*. 2020;24:384–391.
22. de Morton NA. The PEDro scale is a valid measure of the methodological quality of clinical trials: a demographic study. *Aust J Physiother*. 2009;55:129–133.
23. Cashin AG, McAuley JH. Clinimetrics: Physiotherapy Evidence Database (PEDro) Scale. *J Physiother*. 2019;66, 59–59.
24. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ*. 1997;315(7109):629–634.
25. Begg CB, Mazumdar M. Operating characteristics of a rank correlation test for publication bias. *Biometrics*. 1994;50:1088–1101.
26. Duval S, Tweedie R. Trim and fill: a simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. *Biometrics*. 2000;56:455–463.
27. Waldén M, Atroshi I, Magnusson H, Wagner P, Hägglund M. Prevention of acute knee injuries in adolescent female football players: cluster randomised controlled trial. *BMJ*. 2012;344.
28. Al Attar WSA, Soomro N, Sinclair PJ, Pappas E, Sanders RH. Effect of injury prevention programs that include the Nordic hamstring exercise on hamstring injury rates in soccer players: a systematic review and meta-analysis. *Sports Med*. 2017;47:907–916. https://doi.org/10.1007/s40279-016-0638-2
29. Olsen O-E, Myklebust G, Engebretsen L, Holme I, Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *BMJ*. 2005;330:449.
30. Gilchrist J, Mandelbaum BR, Melancon H, et al. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med*. 2008;36:1476–1483.
31. Steffen K, Myklebust G, Olsen OE, Holme I, Bahr R. Preventing injuries in female youth football–a cluster-randomized controlled trial. *Scand J Med Sci Sports*. 2008;18:605–614.
32. LaBella CR, Huxford MR, Grissom J, Kim K-Y, Peng J, Christoffel KK. Effect of neuromuscular warm-up on injuries in female soccer and basketball athletes in urban public high schools: cluster randomized controlled trial. *Arch Pediatr Adolesc Med*. 2011;165:1033–1040.
33. Silvers-Granelli H, Mandelbaum B, Adeniji O, et al. Efficacy of the FIFA 11+ injury prevention program in the collegiate male soccer player. *Am J Sports Med*. 2015;43:2628–2637.
34. Achenbach L, Krutsch V, Weber J, et al. Neuromuscular exercises prevent severe knee injury in adolescent team handball players. *Knee Surg Sports Traumatol Arthrosc*. 2018;26:1901–1908.
35. Al Attar WSA, Soomro N, Pappas E, Sinclair PJ, Sanders RH. Adding a post-training FIFA 11+ exercise program to the pre-training FIFA 11+ injury prevention program reduces injury rates among male amateur soccer players: a cluster-randomised trial. *J Physiother*. 2017;63:235–242. https://doi.org/10.1016/j.jphys.2017.08.004
36. Zarei M, Abbasi H, Namazi P, Asgari M, Rommers N, Rössler R. The 11+ Kids warm-up programme to prevent injuries in young Iranian male high-level football (soccer) players: A cluster-randomised controlled trial. *J Sci Med Sport*. 2020;23:469–474.
37. Al Attar WSA, Alshehri MA. A meta-analysis of meta-analyses of the effectiveness of FIFA injury prevention programs in soccer. *Scand J Med Sci Sports*. 2019;29:1846–1855.
38. Montalvo AM, Schneider DK, Webster KE, Yut L, Galloway MT, Heidt RS, et al. Anterior cruciate ligament injury risk in sport: A systematic review and meta-analysis of injury incidence by sex and sport classification. *J Athl Train*. 2019;54:472–482.
39. Padua DA, DiStefano LJ, Hewett TE, et al. National Athletic Trainers' Association position statement: prevention of anterior cruciate ligament injury. *J Athl Train*. 2018;53:5–19.
40. Alikhani R, Shahrjerdi S, Golpaigany M, Kazemi M. The effect of a six-week plyometric training on dynamic balance and knee proprioception in female badminton players. *J Can Chiropr Assoc*. 2019;63:144.
41. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Adams KJ, Shea KG. Effects of a knee ligament injury prevention exercise program on impact forces in women. *J Strength Cond Res*. 2004;18:703–707.
42. Willadsen EM, Zahn AB, Durall CJ. What Is the Most Effective Training Approach for Preventing Noncontact ACL Injuries in High School–Aged Female Athletes? *J Sport Rehabil*. 2019;28:94–98.
43. Pfeiffer RP, Shea KG, Roberts D, Grandstrand S, Bond L. Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *J Bone Joint Surg Am*. 2006;88:1769–1774.
44. Chappell JD, Limpisvasti O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med*. 2008;36:1081–1086.
45. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med*. 2006;34:490–498.