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Training interventions to reduce the risk of injury to the lower extremity joints during landing movements in adult athletes: a systematic review and meta-analysis

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ABSTRACT

Objective Aim of this systematic review was to summarise training interventions designed to reduce biomechanical risk factors associated with increased risk of lower extremity landing injuries and to evaluate their practical implications in amateur sports.

Design Systematic review and meta-analysis.

Data sources MEDLINE, Scopus and SPORTDiscus.

Eligibility criteria Training intervention(s) aimed at reducing biomechanical risk factors and/or injury rates included the following: (1) prospective or (non-)randomised controlled study design; (2) risk factors that were measured with valid two-dimensional or three-dimensional motion analysis systems or Landing Error Scoring System during jump landings. In addition, meta-analyses were performed, and the risk of bias was assessed.

Results Thirty-one studies met all inclusion criteria, capturing 11 different training interventions (eg, feedback and plyometrics) and 974 participants. A significantly medium effect of technique training (both instruction and feedback) and dynamic strengthening (ie, plyometrics with/without strengthening) on knee flexion angle (g=0.77; 95% CI 0.33 to 1.21) was shown. Only one-third of the studies had training interventions that required minimal training setup and additional coaching educations.

Conclusion This systematic review highlights that amateur coaches can decrease relevant biomechanical risk factors by means of minimal training setup, for example, instructing to focus on a soft landing, even within only one training session of simple technique training. The meta-analysis emphasises implementing technique training as stand-alone or combined with dynamic strengthening into amateur sport training routine.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Lower limb injuries in sports occur due to high-risk movements like jump landing tasks with rapid deceleration and stops.
⇒ A reduced knee flexion angle, improved ground reaction force and a knee valgus during landing movements are risk factors for lower extremity injuries.
⇒ Performing injury prevention programmes at least twice a week improved neuromuscular and motor performance and reduces the injury risk.

WHAT THIS STUDY ADDS

⇒ Technique training, that is, external instruction and feedback on jump landing performance, and dynamic strengthening, that is, plyometrics with increasing intensity, can reduce biomechanical risk factor during landing movements.
⇒ Static balance training on a wobble board alone had no significant effect in reducing risk factors for jump landing injuries and is, therefore, not recommended.
⇒ Prevention of jump landing injuries requires moderate time consumption (around 30 min), basic training material like cones and hurdles and mostly no specific trainer education.
⇒ Future studies should consider analysing jump landing movements using an easy to apply, validated method such as the Landing Error Scoring System to allow for direct comparison with previous research

INTRODUCTION

Sport injuries are internationally recognised as a public health problem not only in elite sport, but also at the amateur level.[1] In North Rhine-Westphalia, 40% of all sport injuries occur during sporting activities such as team ball sports or gymnastic and most frequently in the lower extremities, like the knee and ankle joint[2]. Fractures (38%) and ligament ruptures (34%) of the ankle and knee form the largest part of these lower extremity injuries.[2 3] Regardless of gender, the consequences of these lower extremity injuries, such as anterior cruciate ligament (ACL) rupture, ankle sprain or patella tendinopathy, are severe. For instance, an ACL rupture is accompanied by a long and expensive rehabilitation period and increased reinjury rates especially in athletes aged under 20 years.[4 5] Most lower extremity injuries occur during complex movements such as a jump-landing and change in direction tasks (eg, side-cutting).[6 7] Single or double limb landing manoeuvres with rapid decelerations, stops or repetitive jump landings were identified as frequent injury mechanisms.[8–11] A well-balanced landing strategy is essential for effective absorption of impact forces from landing. Therefore, among others, synergistic lower extremity joint coordination and alignment of the hip, knee and ankle joint in the sagittal plane, with dynamic muscle control of the lower extremity and upper body (eg, core muscle), is required.[9 12 13]

Biomechanical risk factors for jump landing injuries have been identified in movement analyses studies. A reduced range of motion of the lower extremity joints (eg, less knee or hip flexion) can lead to a stiffer landing technique with a decrease in force absorption, which can subsequently increase the risk of lower extremity injury.[9 14] In particular, a knee flexion angle smaller than 30° (ie, a more extended knee) at initial contact during a single or double limb landing may affect ACL load.[15 16] Consequently, at a reduced knee flexion angle, the synergistic hamstring muscle force is directed parallel to the ACL, which is placed vertically to the tibia plateau, thus limiting the hamstring potential to counteract stress on the ACL due to anterior tibial shift.[9 11 17–21] An increased knee valgus based on simultaneous hip adduction and internal rotation during closed-chain knee flexion with additional ankle eversion is another underlying biomechanical risk factor for jump landing injuries.[22 23] Lastly, a decrease in ankle plantar flexion during initial contact results in less ankle dorsiflexion during subsequent landing manoeuvre.[9] This reduced ankle dorsiflexion has been associated with knee overuse injuries such as patellofemoral pain[8 9 24] and ankle inversions trauma.[25 26]

Due to the high prevalence and possibly severe consequences of jump landing injuries, adequate injury prevention, that is, reducing injury risk by improving the biomechanical risk factors, is crucial. Injury prevention has already been implemented in amateur and professional sport settings[27] and multiple training interventions have been reported. These training interventions are intended, among others, to improve the athlete sports performance, reduce injury risk and costs of injury treatments for the club and athletes.[27] For example, training interventions, such as FIFAs 11+ twenty min warm up programme developed for football players of all ages, reduce the general injury risk up to 35%, and have been incorporated into the training routine of some football clubs.[28 29] Performing the FIFA training intervention at least twice per week leads to improvement in neuromuscular and motor performance.[28 29] Training interventions have also been developed to specifically reduce the likelihood of injury after jump landing movements. For example, Aerts *et al* advise to perform their training intervention twice a week, including gradually increasing lower extremity strengthening, plyometrics, and technique instructions, that is, teach the athlete how to align the lower extremity joints during landing.[30]

Despite the need and availability of effective injury prevention programmes, detailed training interventions are often not a part of a normal training routine, especially in an amateur sports setting. As an example, significant injury reduction depends, among others, on the qualification of the coach (eg, knowledge about injury prevention) and medical monitoring, which is mostly limited in an amateur sports setting.[31] An analysis of the integration of injury prevention in general amateur sports showed that only 21% of 70 amateur coaches used specific training interventions such as FIFA 11+ in football.[2] Furthermore, new evidence-based training interventions are published almost annually, which is not easy to summarise and integrate into a training routine for amateur and professional coaches and athletes.[32] To successfully implement training interventions in amateur sport settings, training materials must be affordable and self-explanatory, as specialised staff such as an educated programme controller (ie, athletic trainer) or physiotherapist are often not available. Considering the limited training time in amateur sports, training interventions should not be time-consuming. Thus, there is a need to summarise evidence-based training interventions that improve jump landing manoeuvre and evaluate whether the programme is implementable in amateur sports.

The aim of this study is to systematically review training interventions for adult athletes that aim to reduce biomechanical risk factors for lower extremity joint injuries during jump landing performances, and to critically evaluate them, regarding their practicability, in terms of required materials, coach education and time consumption, in amateur sports settings.

METHODS

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines from 2020.[33 34]

Search strategy

The electronic databases (search engines) MEDLINE (PubMed), SPORTDiscus (EBSCO) and Scopus were searched from the database's inception to 20 December 2021. The combination of the following keywords was used as search terms: 'athletes OR sports'; 'unilateral landing OR bilateral landing OR jump-landing OR jump task OR landing'; 'intervention protocol OR intervention OR training protocol OR exercise OR training OR prevention'; 'kinematics OR kinetics OR biomechanics OR knee flexion angle OR knee valgus OR injury risk OR injury rate OR landing error scoring system' (online supplemental table 2).

Study selection

The eligibility criteria were created using the PICO(S) model for clinical questions and are summarised in table 1. Included interventions aimed to improve risk factors during jump landing performance and compared an intervention group to a control group with sham or

Table 1 Study criteria for inclusion in the review

Participants	Adult male and female athletes (>18 to <45 years), with a minimum of two training sessions per week or at least active college or comparable athlete, without acute (<6 weeks) or chronic (>6 weeks) injury to the lower extremity. Participants did not receive surgery of the lower extremity joints because of a rupture or fracture.
Intervention	Training programmes or interventions which aimed to improve the jump landing strategy or injury risk and thus the biomechanical risk factors for a single or double leg jump landing injury. Interventions must be integrable into amateur sports setting, that is, no need for specialised staff such as an educated programme controller (ie, athletic trainer) or physiotherapist to implement the programme.
Control group	If there is a control group, it should receive a sham treatment or no intervention.
Outcome	Measurement of lower extremity injury rate, either laboratory based, for example, 3D-motion analysis and force plate data, or by means of in-field measures, for example, valid scoring system and expert ratings like the Landing Error Scoring System, while examining single and double leg landings. The biomechanical risk factors consist of increased knee valgus, smaller hip flexion angle, reduced knee flexion angle/moment, or increased GRF especially of the knee.
Study type	Prospective/retrospective or observational (non-)randomised controlled intervention trials.

3D, three dimensional; GRF, ground reaction force.

without additional intervention ((non)-randomised controlled trials, RCTs) or to the intervention group's baseline levels (eg, pre–post or cross-over trials).[35] The outcome measurements should be assessed using reliable tools (eg, VICON Motion Systems, Landing Error Scoring System (LESS)) and analyse jump performance (eg, drop jumps, countermovement jumps).

English and German publications were considered, and geographical restrictions were not applied. Studies were excluded when participants were soldiers, because of their special military training programme. Also, simulation studies were excluded.

Two independent reviewers applied predetermined eligibility criteria to screen titles and abstracts in the Rayyan-Intelligent systematic review software (Rayyan System, Cambridge, Massachusetts, USA).[36] An abstract was included when the two reviewers independently assessed it as satisfying the inclusion criteria. Afterwards, full texts were screened and were excluded if they did not fulfil inclusion criteria. Conflicting classifications, of both abstracts and full texts, were discussed and resolved.

Data extraction

Data extraction included: Study identifiers (authors name, year of publication), study design, study sample size and participants' characteristics (age, gender, activity level). The data were organised according to the training intervention methods, and results were added for the main outcome variables (eg, biomechanical risk factors). Training interventions were classified as (A) technique training, that is, improving the landing technique by instructions, feedback or skill training, (B) dynamic strengthening, that is, plyometrics or a combination of strengthening and plyometrics, (C) static strengthening, that is, strengthening without plyometrics or (D) balance training (static or dynamic). An included training intervention was defined as a 'prevention programme' if an apparent sequence of different forms of exercises was used and the author of the study titled this form of training as a 'prevention programme'. In addition, the different gender responses (ie, men and women) to the training interventions were identified. Furthermore, in terms of practicability of training interventions, the required training materials were sorted according to the training techniques (A–D) and the education of the coach and training time consumption were listed.

Methodological assessment

Two independent reviewers assessed the risk of bias. The Cochrane Risk of Bias tool for randomised trials (RoB2)[37] was applied. The aimed target trial for the analysed studies, was a randomised clinical trial with a control and an intervention group consisting of female and male amateur athletes performing an intervention.[33,34] In addition, the intention-to-treat effect was chosen to interpret study outcomes.[38] The 'Risk of bias in Non-randomised Studies-of Interventions' (ROBINS-I) tool was used to analyse other study designs.[38] Online supplemental table 3 summarises the adapted controlled questions for the corresponding seven bias domains.[38]

Data analysis

For RCTs with a biomechanical risk factor as a primary outcome in results, the standardised mean differences (SMDs), known as Cohen's d effect sizes, with associated 95% CIs were calculated, and a meta-analysis was performed.[39]

Moreover, to avoid within-group effect size correlation, the SMDs were only calculated if two experimental groups or an additional control group were analysed (ie, RCT or CT study design).[40] If a study contributed more than one effect size to the meta-analysis, a combining group approach (eg, putting means and SD of Group A and B together) was used as basis for effect size calculation[37] to circumvent double-counting (eg, comparing group A with group C and group B with group C again). In addition, to capture the effectiveness of the intervention, only the effect size of the measurement directly after the intervention (ie, post-test) was considered if multiple measures were collected.

As the considerable between-study heterogeneity was anticipated, a random-effects model was used to pool effect sizes. The 'DerSimonian-Larid' estimator was used to calculate the heterogeneity variance τ^2.[41] Knapp-Hartung adjustment[42] was applied to calculate the CIs around the pooled effect. Moreover, the heterogeneity index I^2 with its 95% CI and additional prediction intervals were calculated. I^2 was interpreted according to Higgins and Thompson 25%=low; 50%=moderate; 75%=substantial. In addition, if I^2 >50% an outliers (ie, CI of studies did not overlap with CI of pooled effect) and influence analyses (ie, leave-one-out method) were performed to study the robustness of the true effect.[43–45] Finally, asymmetries of the effect size distribution due to bias distribution were assessed using Egger's test[46] and were visually examined using a funnel plot of effect sizes relative to SE. All analyses were performed by the 'meta' V.5.2–0 of R language (R core team, Vienna, Austria). The thresholds for the interpretation of the effect sizes were as follows: 0.20=small; 0.50=moderate; 0.80=large.[47] Statistical significance was set at p<0.05.

RESULTS

Search results

The initial database search yielded 2387 results. After removal of duplicates, 1717 records remained. Title and abstract screening resulted in 133 full-text articles that were assessed based on the inclusion criteria. The final full text screening resulted in 31 included studies, of which the flow of the PRISMA selection process is summarised in figure 1. The intervention studies included 15 RCT's, 15 pre–post intervention studies without a control group, and one cross-over intervention study. The study characteristics are presented in table 2 and additional details are presented in online supplemental table 1.

Study characteristics

Sample sizes of the RCTs ranged from 16 to 116 participants with an overall sample size of 682. The sample size of the pre–post intervention studies ranged from 8 to 37 participants with an overall sample size of 280. Eight participants participated in the single cross-over study. Eighteen of the 31 studies included only female participants, 5 studies had only male participants and 8 studies analysed both men and women. Accordingly, more than half of the results were derived from the analysis of female athletes (64%). Three-quarter of all participants were amateur athletes (730), followed by division 1 and 2 collegiate athletes (184) and high-performance athletes (60).

Intervention characteristics

Fifteen interventions were classified as technique training (A), 12 as dynamic strengthening (B), 2 as static strengthening (C) and 2 as balance training (D). The training intervention duration varied between studies with either

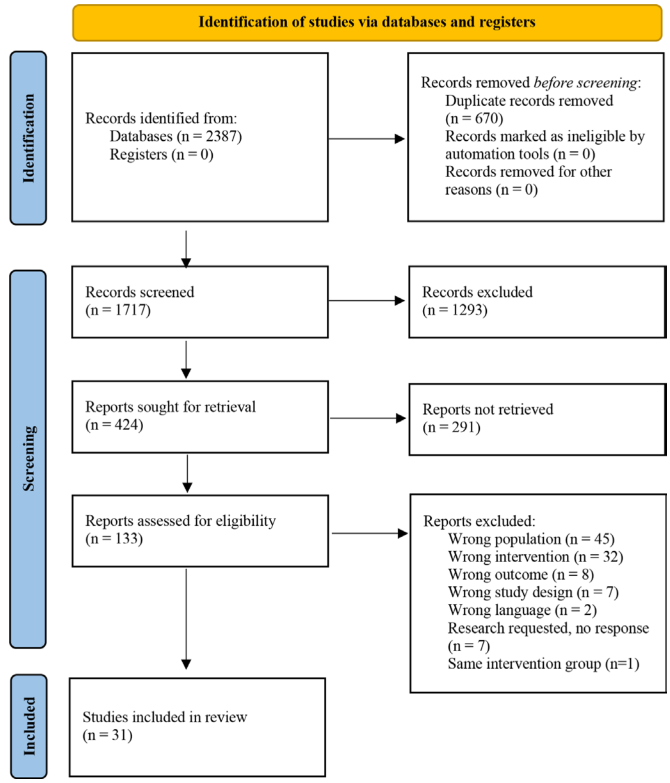

Figure 1 PRISMA flow chart of study selection process. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

1 single training session in total (18 studies) or multiple training sessions performed 2–3 times per week for a total duration of three to 12 weeks (13 studies) (online supplemental table 1). The session duration of each training intervention lasted between 5 and 15 min (10 studies), 12–20 min (3 studies), 15–30 min (4 studies), 40–60 min (5 studies). In 10 studies, no exact training session duration was given, but they lasted 1 (8 studies), 2 (1 study) or a maximum of 3 (1 study) training sessions.

Different types of double limb (22 studies) and single limb (9 studies) jump landing tasks were observed to assess the outcome measurements and included variants of drop jumps (19 studies) and/or countermovement jumps (6 studies), volleyball, basketball or netball -specific jumps (3 studies), tuck jump (1 study), stop jump task (2 studies), lateral single leg jump (1 study) and maximal vertical jump (1 study).

Intervention outcomes

Fifteen studies reported ground reaction force (GRF) outcomes, 23 studies reported joint angle, 5 studies reported joint moment outcome and 3 studies reported LESS as outcome. All but two studies[48 49] reported significant differences in outcomes before and after the intervention.

A significant reduction of biomechanical risk factors was reported for all four training types (A-D). In the following, the findings of the 15 RCTs organised by training type (A–D) and gender are reported to focus

Table 2 Characteristics and (non-)significant main results of included studies, assigned to technique training, dynamic strengthening, static strengthening or balance training

Author	Study design	Total N	Athletes	Training sessions (1/more)	GRF	Joints	LESS
A. Technique training							
Jump landing performance—instruction							
Almonroeder[65]	Pre–post	16	A	1		>knee and hip flexion angle	
Benjaminse[54]	RCT	40	S.p.	1			Improved LESS
Chijimatsu [79]	Pre–post	15	A	1		<internal rotation angle	
McNair[56]	RCT	80	A	1	<peak GRF		
Milner[80]	Cross-over	12	A	1	<peak vGRF	>peak knee flexion angle	
Mizner[70]	Pre–post	37	A	1	<peak vGRF	>peak knee flexion angle	
Tate[52]	RCT	26	A	1	<peak vGRF	>knee flexion angle knee abduction angle (n.s).	
Turner[64]	Pre–post	24	P	1		>knee abduction angle	
Welling[51]	RCT	40	A	1	<vGRF	>knee flexion angle	
Jump landing performance—feedback							
Cronin[81]	Pre–post	15	P	1	<vGRF		
Etnoyer[57]	RCT	43	A	1		>peak knee flexion angle	
Leonard[82]	Pre–post	23	A	1	<vGRF		
Oñate[55]	RCT	51	A	1	<peak vGRF	>knee angular displacement	
Shams[53]	RCT	45	A	1			Improved LESS
Jump landing performance—skill training							
Shimokochi[69]	Pre–post	20	A	1	<GRF	>knee flexion angle	
B. Dynamic strengthening							
Plyometrics							
Dello Iacano[83]	Pre–post	18	P	More	>peak GRF		
Herrington[84]	Pre–post	15	A	More		<knee valgus angle	
Nagano[85]	Pre–post	8	A	More		>knee flexion angle	
Makaruk[62]	RCT	36	A	More	<vGRF	>knee flexion angle	
Vescovi[48]	RCT	20	A	More	<vGRF		
Combi strengthening							
Dai[86]	Pre–post	28	A	1		>hip and knee flexion angle	
Peng[87]	Pre–post	12	A	1	<peak GRF	>hip and knee flexion angle >ankle plantarflex. and dorsiflex. angle	
Stearns and Powers[88]	Pre–post	21	S.p.	1		>knee and hip flexion angle <peak knee abduction angles	
Yang[60]	RCT	36	A	1	♂< GRF ♀< GRF (n.s.)	♂>knee and hip flexion ♀>knee and hip flexion (n.s.)	
Prevention programmes							
Aerts[58]	RCT	116	A	More		>hip flexion and maximal left knee flexion angle (♂)	
Fox[59]	RCT	16	A	More		>hip external rotation angle >knee angular displacement	
O'Malley[61]	RCT	78	A	1			Improved LESS

Continued

Table 2 Continued

Author	Study design	Total N	Athletes	Training sessions (1/more)	GRF	Joints	LESS
C. Static strengthening							
Core workout							
Araujo[89]	Pre–post	16	A	More	<peak vGRF		
Warm-up programme							
Avedesian[90]	Pre–post	12	A	1		<peak hip adduction angle >knee abduction and internal rotation angle	
D. Balance training							
Static balance training							
Silva[49]	RCT	24	A	1	vGRF (n.s.)	Plantar flexion angle (n.s.)	
Dynamic balance training							
Letafatkar[63]	RCT	31	A	1		<knee flexion angle	

A, amateur; dorsiflex, dorsiflexion; GRF, ground reaction force; LESS, Landing Error Scoring System; n, sample size; n.s., non-significant; P, professional; plantarflex, plantarflexion; RCT, randomised controlled trial; S.p., semi professional; vGRF, vertical GRF.

on cause-and-effect relationships instead of reporting correlations.[50] In addition, the findings of the meta-analyses are reported.

Technique training focused on improving the athlete's landing technique through three forms of instruction (three RCTs) and feedback (four RCTs). Forms of instruction consisted of external focus (directing the athlete's attention away from the movement), internal focus (direct focus on the movement) and video instruction.

Postintervention, all three forms of instructions led to a significant improvement in knee flexion angle[51 52] and a significant reduction in knee valgus moment in drop jump landing.[51] A significant decrease in GRF was reported after all forms of technique training, except video instruction. The LESS scoring was significantly improved (fewer errors) when using external focus and video instruction or feedback.[51–56]

The long-term effect of technique training on biomechanical risk factors is not clear: 1-week postintervention, the vertical GRF during landing can increase again[51 52] or further improve, that is, become less during landing.[55] The positive effect of the intervention on the knee joint angle seems to reduce after 1–4 weeks[52 57] or there is no clear trend.[51] Benjaminse *et al* demonstrated an improved LESS and knee joint angle for external focus and video instruction groups 1 week after the intervention compared with baseline, however, postintervention data were not reported.[54]

Dynamic strengthening training interventions included plyometric exercises (two RCTs), a combination of plyometrics and lower extremity strengthening (one RCT) and plyometric prevalent prevention programmes consisting of exercises including plyometrics but where trainers are also instructed to improve technique (three RCTs).

One prevention programme with plyometric exercises of increasing intensity significantly improved the knee flexion angle landing pattern in males.[58] A reduction in knee valgus and improvement of hip flexion and external rotation angle were reported after dynamic strengthening.[58 59] Another programme used a combination of strengthening and plyometric exercises and was able to improve knee flexion angle at peak impact.[60] In addition, one prevention programme consisted of a warm-up programme combining strengthening, stretching and balance exercises. The application of this programme significantly decreased LESS scores directly after an 8-week intervention.[61] No clear effects of plyometrics were observed for the GRF, where both significant[62] and non-significant findings were reported.[48]

Only Yang *et al* studied the long-term effect of a 4-week dynamic strengthening intervention. The positive effect on the knee flexion angle remained over time (up to 12 weeks), while the initial positive effect of the training on the vertical GRF was not consistent over time.[60]

Balance training included static balance training on a wobble board (ie, no external perturbation) (one RCT) and dynamic balance training consisting of increasing perturbation-enhanced neuromuscular training, such as sport-specific technique performance on a rocker board (one RCT).

The intervention programme focusing on static balance[49] did not result in significant changes in biomechanical risk factors, whereas the dynamic balance training significantly increased the initial knee flexion angle during landing.[63]

Regarding gender differences, both genders significantly improved risk factors in terms of knee flexion angle significantly by technique training such as teaching plantarflexed landing, feedback, external instruction,[51 54–56] and dynamic balance training with increasing perturbation-enhanced neuromuscular tasks[63] (five RCTs).

For meta-analyses, 15 RCTs were available. Due to inconsistent evaluation and reporting of outcome variables, only two variables, the knee flexion angle and vertical GRF, could be examined. The meta-analyses used 11 RCTs in total.

Four studies showed a large (>0.80),[52 57 58 63] one study showed a moderate (>0.50)[57] and one study a small (>0.20)[51] effect size for knee flexion angle. The between-study heterogeneity variance was estimated at τ^2 =0.53 (95% CI 0.25 to 5.72) with a high heterogeneity (I^2 =83%; 95% CI 64% to 92%). Based on substantial heterogeneity in the main analysis (I^2 >50%), an outliers and influence analysis was performed and effect sizes of Letefatkar *et al* and Makaruk *et al* were removed from the random-effect model.[62 63] Finally, a significantly medium pooled effect size (*g*=0.77; 95% CI 0.33 to 1.21) was found for the three technique training interventions and one prevention programme (dynamic strengthening) on knee flexion angle (p=0.01).

A large effect size (>0.80) for GRF was shown in one study.[56] Four studies showed a small effect size (>0.20)[51 52 55 62] and three studies had no effect.[48 49 60] The between-study heterogeneity was estimated at τ^2 =0.11 (95% CI 0.00 to 0.80) with a moderate heterogeneity (I^2 =48%; 95% CI 0 to 77%) and a non-significant pooled small effect (g=−0.24; 95% CI −0.63 to 0.16).

Publication bias analysis of both meta-analyses showed no asymmetry in a visual inspection of funnel plots, and application of Egger's test was not possible due to the limited number of studies analysed (<10 studies each) (figure 2).

Required material and coach education characteristics

Table 3 summarises the practicability of the interventions in terms of training material and coach education required to perform the intervention. Most interventions required materials such as boxes (height ranged from 20 to 50 cm), a BOSU, ball or balance board. In addition, cones, hurdles, walls and mattresses were the second most common training materials. For feedback interventions, a video camera and monitor were needed in two out of four interventions, and in one intervention, a video of an expert performing a jump landing model must be provided. For instruction interventions, 3 out of 10 studies required an expert performing or instructing the landing manoeuvre on video.

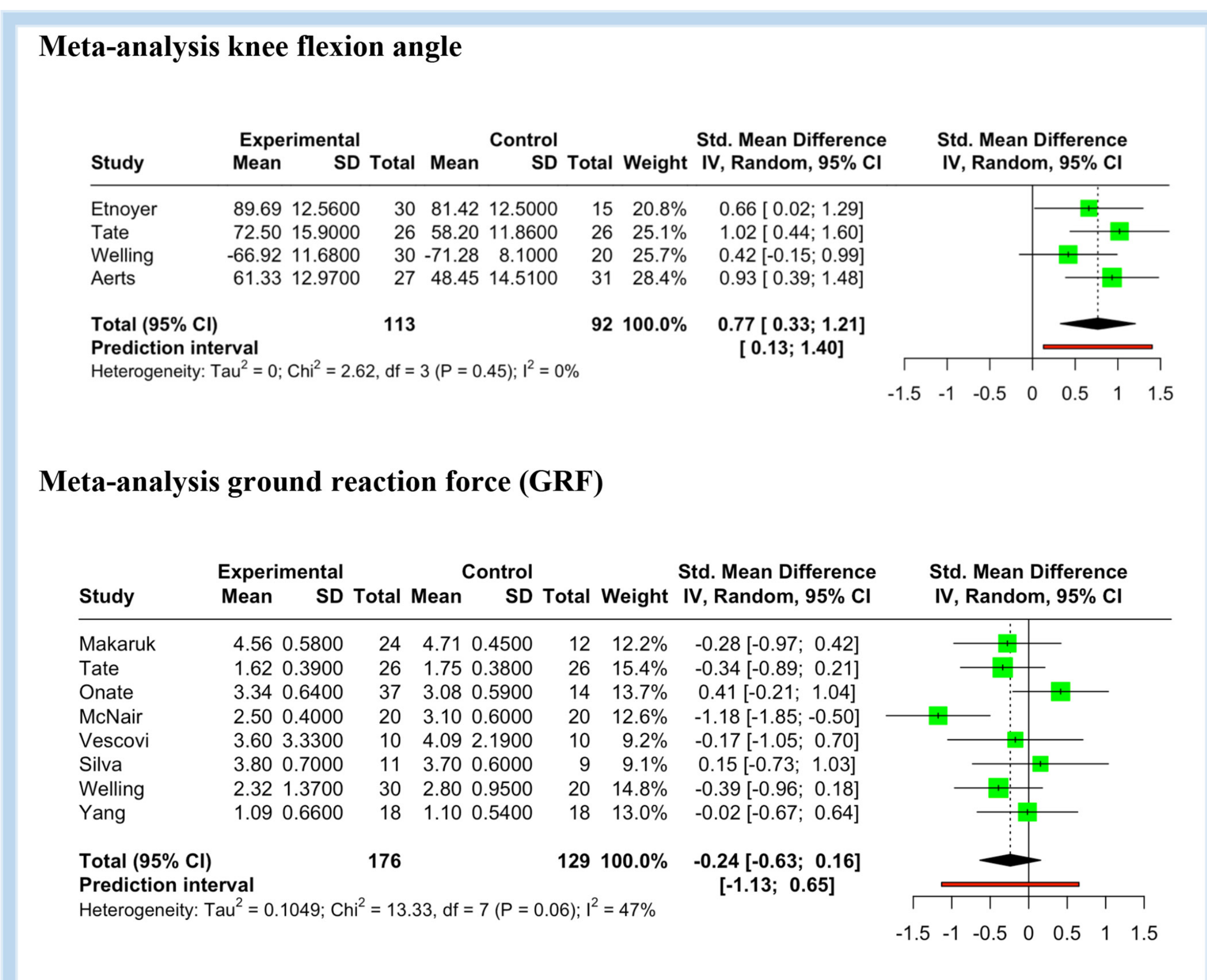

Figure 2 Meta-analysis of knee flexion angle and ground reaction force (GRF) outcome variable.

Table 3 Required training material and intervention description of included studies ordered by training intervention

Author	Intervention description	Trainer education	Training material
A. Technique training			
Jump landing performance—instruction			
Almonroeder[65]	Verbal internal versus external focus instruction followed by drop landings		31 cm box
Benjaminse[54]	Verbal internal, external focus and expert video instruction followed by double-legged landings		Video, monitor, box, LESS
Chijiatsu[79]	Video landing instruction of own drop vertical jumps landings		Bicycle, box, monitor, camera
McNair[56]	Technical instruction, auditory cue, imagery on double leg landing		30 cm box
Milner[80]	Three adapted verbal instructions on countermovement jump landing techniques		–
Mizner[70]	Uninstructed drop jump followed by verbal instruction on landing technique		31 cm box
Tate[52]	Supervised countermovement jump training with instruction/information and home-based training		Mirror, camera, instruction
Turner[64]	Bilateral barefoot drop-landings with expert video instruction		30.5 cm box, video, monitor
Welling[51]	Instruction on drop vertical jump followed by feedback (LESS score)		30 cm box, LESS, camera, monitor
Jump landing performance—feedback			
Cronin[81]	Bilateral jump-landings while spiking a volleyball of a toss by coach followed by verbal feedback		Volleyball, volleyball net, cone
Etnoyer[57]	Self or combination feedback (LESS Score and expert video) of box drop jump		30 cm box, camera, monitor, video, LESS
Leonard[82]	Dyad or expert feedback during squat jump		Feedback checklist
Oñate[55]	Basketball rebounding task on jump-ball device with self/expert/combo feedback		Camera, monitor, checklist, jump-ball (patent pending) testing device
Shams[53]	Plyometric exercises combined with feedback or tape		Mirror, cone, wall, scripted cueing
Jump landing performance—skill training			
Shimokochi[69]	Three different single-legged drop landing styles		Boxes (30, 45 cm)
B. Dynamic Strengthening			
Plyometrics			
Dello Iacano[83]	Vertical/horizontal alternate 1-leg drop jumps, landing from top of a platform		25 cm box
Herrington[84]	Progressive jump-training programme		Wall
Makaruk[62]	Single or repeated jumps with weekly increasing sets or jump height of four different jump forms		Slat, boxes (20, 30, 40 cm), hurdles
Nagano[85]	Balance and jump training divided in technique and performance phases		Square balance board
Vescovi[48]	Sportsmetrics: Jump exercises with increasing intensity over 6 weeks		Cones, mattress
Combi strengthening			
Dai[86]	Jump-landing-jump task with resistance band above ankles joint		30 cm box, LifeLine Medison band
Peng[87]	Drop jumps with elastic band loads (0% and 20% body weight)		Boxes (40, 50 cm), elastic band
Stearns and Power[88]	Hip-focused training programme with increasing difficulty		BOSU and ball
Yang[60]	Hip extension training and plyometrics (eg, jumps in different directions)		Box, hurdles, medicine ball, foam roller, BOSU balance board and ball
Prevention programme			
Aerts[58]	Coach-supervised jump-landing prevention programme on jump-landing technique		Poster, DVD, mattress, wall, balls
Fox[59]	Down 2 Earth		Illustrated programme, ball
C. Static strengthening			

Continued

Table 3 Continued

Author	Intervention description	Trainer education	Training material
Core workout			
Araujo[89]	Increasing core exercises (eg, plank variants, crunches, Russian twists		–
Warm-up programme			
Avedasian[90]	Two different warm up protocols		–
O'Malley[61]	GAA-15 standardised warm-up programme		Training partner, programme
D. Balance Training			
Static balance training			
Silva[49]	Wobble board training		Wobble board, ball, balloon, wall
Dynamic balance training			
Letefatkar[63]	Weekly increasing perturbation drills with verbal instruction		BOSU, balance boards, TheraBand, weight scale

The trainer education box was tacked if: (1) a training brochure must be studied before training intervention, (2) an instruction video must be watched, (3) LESS must be assessed, (4) expert jump-landing technique must be performed.
BOSU, BOSU Balance traininer; Down 2 Earth, netball-specific prevention programme; DVD, Digital Video Disk; GAA-15, Gaelic Athletic Association warm up programme; LESS, Landing Error Scoring System.

Fourteen studies required coach education, with three training interventions including a training brochure or poster with detailed information on the exercises.[58 59 61] No information was provided on how long it takes to master these programmes. One training intervention introduced instructions via DVD for coaches,[58] three interventions required knowledge about LESS[51 54 57] and one provided a checklist of jump landing performance for coaches.[55] Five exercises required knowledge and performance of correct jump landing.[51 54 55 57 64]

Risk of bias in studies

The risk of bias of the included studies, sorted by study design, are shown in figure 3. Twenty-six studies showed an overall moderate risk of bias. Across the RCTs, higher risk of bias was due to lack of blinding of participants and researchers (11 studies), lack of a randomisation tool (3 studies), or due to missing information regarding a prespecified analysis plan that was finalised before unblinded outcome data were available

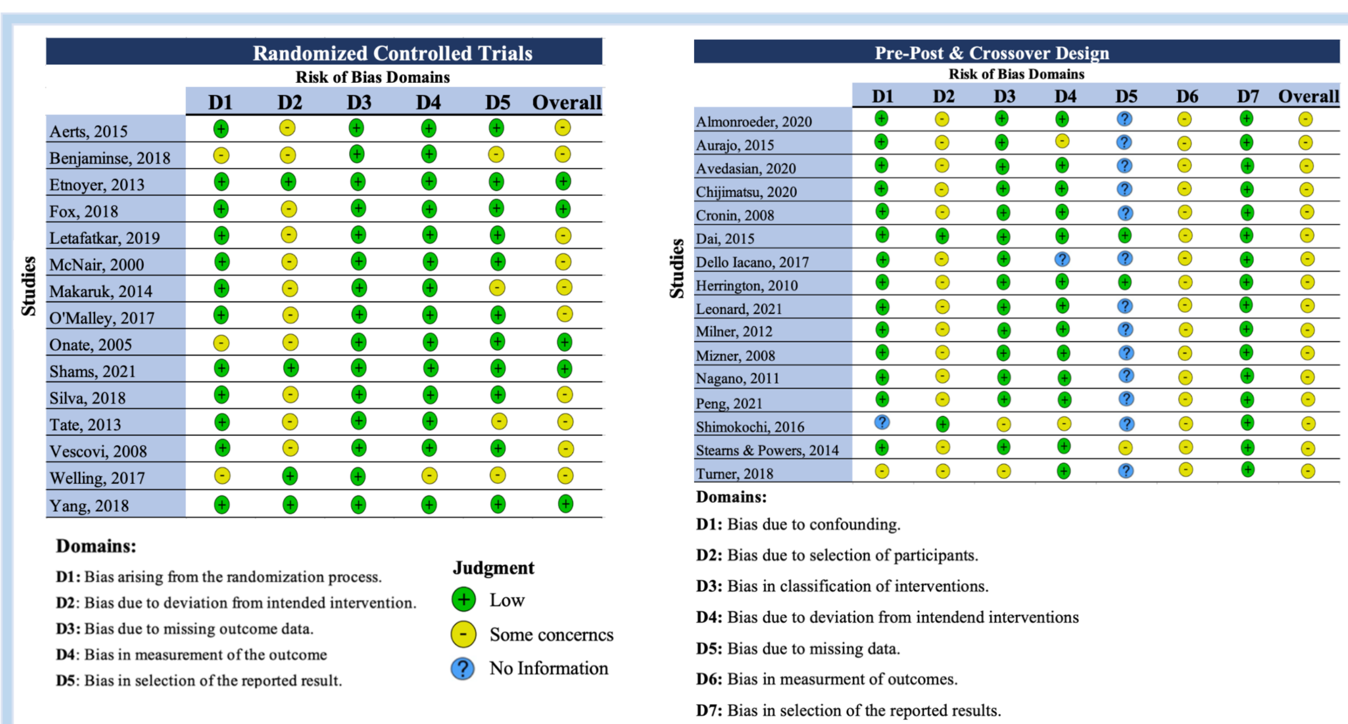

Figure 3 Risk of bias of the included studies sorted by study design.

for the analysis (4 studies). All pre–post and cross-over studies had a moderate risk of bias mostly due to missing follow-up outcome measurement on a second date (16 studies).

DISCUSSION

This systematic review and meta-analysis evaluated 31 training interventions, aimed at reducing biomechanical risk factors for lower extremity injuries during landing movements, and their practical implications for amateur sports. Four training types were portrayed: technique, dynamic or static strengthening, and balance training. All but two studies were able to significantly improve biomechanical risk factors in terms of GRF, joint angle, joint moment and LESS outcomes. Due to the large variation in outcome measures in the RCTs, only two meta-analyses could be performed. The meta-analysis did not find a significant effect of interventions on the GRF. Only a significant medium pooled effect of 0.77 (p=0.01) was found on improvement of the knee flexion angle during landing.[51 52 57 58] Moreover, all interventions were practicable in terms of required material, coach education and time consumption (tables 2 and 3, online supplemental table 1).

Relevant intervention types

Technique training and dynamic strengthening improved the knee joint flexion angle in the meta-analysis and thus can be recommended interventions in amateur setting. These intervention types were accompanied by other improvements in biomechanical risk factors and were also successfully integrated into other study programmes in this review. First, technique training as external focus instruction resulted in a significant improvement in knee flexion angle[65] and LESS score[54] compared with internal focus instruction. The positive effect of external focus is based on the enhanced motor system to self-organise the movement, which will result in an improved movement pattern (ie, optimal kinetic solution), compared with internal focus.[65] These results are in line with the general positive effects of external focus instruction on motor learning and movement technique when compared with internal focus instruction.[66 67] Furthermore, the review showed that one to three technique training session based on feedback or instruction improved knee flexion angle,[57] LESS score[53 54] and reduced GRF.[52 55] This rapid performance improvement after a maximum of three sessions seems to be useful for integrating this intervention into training routine.[68]

Second, changing the unilateral landing technique to landing on the toes with the body leaning forward also resulted in a reduction of risk factors in three pre–post studies.[64 69 70] Particularly, a toe landing pattern increased the knee flexion angle and reduced GRFs.[69] Whereas heel contact (dorsiflexion) at initial ground contact can be the cause of non-contact ACL injuries.[71] Thus, analysing the athletes landing technique should be considered and landing on the toe should be preferred when performing single or double leg landings.[69]

Lastly, a warm-up programme including a combination of dynamic strengthening, technique and balance training was useful as injury prevention strategy.[61] These findings are in line with the study of Herman *et al*, who showed the reduction of lower extremity injuries in amateur athletes using neuromuscular warm-up strategies combining, among others, dynamic strengthening and perturbation training.[72]

Large variation of outcome measures

General consideration of biomechanical risk factors within the included studies showed large variation in outcome measures, which affected direct comparison of risk factors (eg, maximum knee flexion angle and knee flexion angle over time). Future studies should consider analysing jump landing movements using, for example, the LESS, which identifies movement deficiencies and poor landing technique, as it serves as a validated method and simplifies assessment in the field and direct comparison between studies.[73] Using the LESS score enables extraction of individual biomechanical risk factors from the score (eg, knee valgus) and comparison of these partial results between studies.[74] In addition, caution should be taken when using two-dimensional motion capture analysis while focusing on the dynamic knee valgus during landing movements, as it consists of proximal (hip adduction/internal rotation) and distal (tibial abduction) movement to the knee, which take place in two different planes of motion. Therefore, three-dimensional analysis represents the gold standard for kinematic analyses.[75]

Gender differences

Regarding gender differences, 65% of the results were obtained for female samples. As women have been reported to be at higher risk for knee injuries, injury prevention is crucial for them. Female athletes reduced biomechanical risk through dynamic and static strengthening, technique training and dynamic balance training, like male athletes. A study by Crossley *et al* has shown that it is beneficial to use a multifaceted intervention programme (eg, strength, plyometric exercises, dynamic balance training) to reduce the rate of lower extremity injury in women.[76] The included studies support these findings and show significant reduction of biomechanical risk factors by applying a combination of plyometrics and strengthening exercise (ie, dynamic strengthening).[59]

Practicability of intervention implementation

When referring to the practicability of the training intervention the results suggested a moderate time commitment (around 30 min), minimal training material and coach education, which make the interventions integrable into training routine (table 3 and online supplemental table 1). The examined interventions mainly used materials which are often part of the existing training equipment, for example, hurdles and boxes or no additional material, and thus facilitate the application of the training programme.[52 67 77] A barrier to implement the intervention in amateur sports could be the incurred costs for monitors or cameras that were used in some studies to provide feedback regarding jump landing performance. However, significant improvement in LESS score were also obtained when visual feedback was provided with mirrors, which drastically reduced costs if available.[53]

Although good coach education reduces injury risk,[77] the present review demonstrated that targeted simple training interventions can significantly reduce biomechanical risk factors, thus circumventing the time and cost hurdle of continuing education in amateur sports. However, successful training intervention depend on programme adherence. Steffen *et al* reported a larger positive effect of FIFA 11+ when participants showed high adherence compared with low adherence athletes.[78]

Limitations and strength of the review

As all research, this review was subject to limitations of the included studies. First, the unaccounted-for influence on outcomes, such as sample frequency, footwear, age and activity level of participants was acknowledged as limitations. Second, more than half of the results of this review came from the analysis of female athletes (65%). Therefore, caution is advised in the general transfer of results for male amateur sport athletes. Third, direct comparison of biomechanical risk factors between studies was difficult because the collection of these parameters in the studies was not uniform. Fourth, the meta-analysis, which showed a significant result of increasing knee flexion angle, only included four RCTs (figure 2). Furthermore, baseline values differed between groups and influenced the intervention effects.[49 55] Nevertheless, risk of bias analyses of the 31 included studies showed a mostly moderate risk. Main reason for this was the missing follow-up outcome measurement of the pre–post and cross-over studies on a second date. Therefore, future studies should aim to perform a RCT to increase the quality of the results and add a follow-up measurement to reduce the risk of bias. So far, the results suggest that the interventions have a positive effect on the biomechanical risk factors directly post intervention, but it is not clear if these effects hold long-term if training is not performed or neglected.[51 52 57 60]

The key strength of this review is the comprehensive literature search conducted in three databases, rigorous checking of the extracted data performed by two independent reviewers, and the additional risk of bias analyses carried out with the most reliable Cochrane Risk of Bias Tools (RoB2, ROBINS-I) performed independently by the main author and a third reviewer. In addition, 70% of the included studies analysed amateur athletes, so the transfer of the results to amateur sports is given.

CONCLUSION

This systematic review emphasises that implementing technique training in form of instruction or feedback, and dynamic strengthening in form of plyometrics, can improve biomechanical risk factors for lower extremity injuries during landing movements in adult amateur athletes. The meta-analysis showed that technique training (as stand-alone or in combination with plyometric training) has a significant positive effect on the knee flexion angle and should therefore be recommended. Further, the practicability in terms of limited additional required material, coach education and training duration has been demonstrated for amateur settings. Future studies should report more consistent parameters such as the LESS and should test the long-term effects of often temporary interventions.

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Table 1 Characteristics of included studies, assigned to technique training, dynamic strengthening, static strengthening, or balance training

Author (Study Design)	**Participants**	**Intervention**	**Main Results**
a. Technique Training			
Jump Landing Performance – Instruction			
Almonroeder, 2020 (*Pre-Post*)	♀ Regular active athletes (basketball, soccer, volleyball) (*n*= 16; 21.81±2.59) experienced in jump and landing tasks (4/10 Tegner Activity Scale)	**Training:** 2 different sets of instruction ○ Internal focus (e.g., 'focus on bending your knees when you land') ○ External focus (e.g., 'focus on landing softly') **Duration:** 7 drop landings for baseline, internal and external focus condition (21 jumps in total)	• Both: < landing force, > hip and knee flexion angle versus baseline ($p<0.05$*) • External focus: > knee flexion at time of the peak force & < leg stiffness compared to internal focus ($p<0.05$*)
Benjaminse, 2018 (*RCT*)	♀, ♂ Ball sport athletes (*n*=40, 20 ♂ & ♀; 22.5±1.6 years), active ≥4 h p.week, assigned to: - *Verbal Internal Focus (VIF)* (*n*=10) - *Verbal External Focus (VEF)*(*n*=10) - *Video (V)* (*n*=10) - *Control (C)*(*n*=10)	**Training:** group specific instruction & Feedback (LESS Score (VEF & IF) ○ *VIF*: 'extend your knees as rapidly as possible after the landing.' ○ *VEF:* 'push yourself as hard as possible off the ground after landing.' ○ *V*: expert performing task, must imitate him. Feedback (VEF & VIF possible → LESS score) **Duration:** pretest (5 baseline trials), 2 training blocks (each 10 trials), post-test (after training, each 10 trials)	• VEF: improved LESS score ♀ ($p<0.05$*) • V: improved LESS score ♂ & ♀($p<0.05$*)
Chijimatsu, 2020 (*Pre-Post*)	♀ Athletes (*n*=15; 20.7±0.7 years) regular sport activities (4 basketball, 2 volleyball, 2 badminton, 4 tennis, 2 track & field, 1 dancing), active 30 min. a day ≥3 p.week	**Training:** 15 single leg drop vertical jumps including video landing instruction of their own jumps: ○ Pelvic and trunk remain horizontal in the frontal plane. **Duration:** 5 min. warm-up (stationary bike)	• Post-instruction: < peak knee abduction moment ($p=0.004$*) and internal rotation angles at initial contact ($p=0.037$*)
McNair, 2000 (*RCT*)	♀,♂ recreational athletes (*n*=80; 24±7). ♀(*n*=53), ♂ (*n*=27), 1-2h active for 3-5 p.week, randomly assigned to -*Technical instruction* -*Auditory* -*Imagery* -*Control*	**Training:** ○ *Technical instruction:* limb position instructions ○ *Auditory cue*: listen to impact sounds ○ *Imagery*: metaphorical ○ *Control:* own feedback system for soft landing **Duration:** 8 double leg jump landings from a 30cm box, 1 session	• Technical instruction: <peak GRF compared to control ($p<0.05$*) • Auditory cue: <peak GRF compared to control ($p<0.05$*) • No sig. differences between technical and auditory cue No sig. differences between imagery & control group

Milner, 2012 (Crossover)	♀ Athletes (*n*=12; 25±2 years) active ≥3h p.week, random order of instructions	**Training**: 3 instructions (CMJ landing) after control instruction ○ control: 'step on the force plate with one leg on each plate, squat as low as you require, jump as high as possible, and land on the force plate *with one leg on each plate*" ○ knees: '(…) *with knees over toes* ○ equal: *'(…) with equal weight distribution on both your feet* ○ softly: *'(…) as softly as possible.*' **Duration:** 5 trials, 1 session	• Knees: > peak knee flexion compared to others (soft: *p*=0.024*; equal weight: *p*=0.021*) • Equal: < asymmetry peak vGRF compared to others (control: *p*=0.024*; knees: *p*=0.010*; soft: *p*=0.042*) • Softly: < peak vGRF compared to others (control: *p*=0.018*; knees: *p*=0.027*; equal weight: *p*=0.036*)
Mizner, 2008 (*Pre-Post*)	♀ Collegiate athletes (*n*=37; 19.5±1.2 years) in high-demand sports (soccer: 10, basketball: 11, tennis: 9, volleyball: 7)	**Training:** verbal instruction DVJ landing technique (31cm box) after uninstructed DVJ ○ Instruction: 'land as softly & quiets as possible, increase the amount of knee bending when landing, land on your toes, keep the chest over your knees and knees over the toes, avoid knee valgus during landing. Including Cues for athletes to focus on shock absorption.' **Duration:** 5 minute instruction, ≥ 4 practice trials with feedback & 3 successful test trials; 1 testing session ≤2h	• Short-term improvement in peak knee flexion angle, < peak vGRF and peak knee abduction angle (*p*<0.001*) • Muscle strength: poor predictor of improvements
Tate, 2013 (*RCT*)	♀ Athletes (*n*= 26; 18-30 years), sport involving jumping, with medial knee displacement (jump-landing task), active > 2 p.week for 30 min., randomly assigned to: - *Instruction & Home-Based Training* (*n*=13; 21.7±1.9 years) - *Control* (*n*=13; 20.6±2.4 years; sham instruction)	**Training:** supervised CMJ training (both groups) ○ Experimental: training in front of a mirror, info & photos of correct knee position ○ Control: provided incorrect (knee valgus) and correct model (no knee valgus) & 2 home-based trainings. Instruction: 'jump as high as you can.' **Duration:** 2 supervised, 2 home based intervention	• Experimental group: > knee flexion angle after home-based training 1 & 2 compared to control (*p*<0.05*) & < peak vGRF after home-based training 1 & 2 compared to baseline and control (*p*<0.05*). No significant change in knee abduction angle or moment.
Turner, 2018 (*Pre-Post*)	- ♀ *Dancers* (*n*=12; minimum of 7 years dance experience, >12h training p.week) - ♀ *Non-dancers* (*n*=15; active > 2-3 x p.week > 30 min., intensity: 3-6 MET up to >6METs) (*n*= 27; 18-25 years).	**Training:** bilateral barefoot DL (30.5 cm box). 2 videos with no verbal instruction following video with verbal instructions. Feedback as needed after first 2 videos ○ Verbal instruction: 'hip feed wide as possible, toes pointing forward, balls of feet at the front of the edge of the box, landing with toes touch down first with upright trunk, no knees fall in towards each other' **Duration:** 3 practice trials, 3 successful trials, 1 session	• Instruction: > knee abduction angle (i.e., valgus) in non-dancers & not in dancers (*p*=0.014*)

Welling, 2017 (*RCT*)	♀, ♂ Ball team sports clubs (Groningen) (*n*=40, ball sports minimal 4h p.week.), assigned half ♂ & ♀: - *Verbal Internal Focus (VIF)* (*n*=10; 22.10±2.64 years; Football (5), Volleyball (3), Handball (2)) - *Verbal External Focus* (VEF) (*n*=10; 22.60±1.35; Football (3), Handball (3), Basketball, Hockey, Korfball, Volleyball (á 1)) - *Video (V)* (*n*=10; 22.90±0.57 years; Football (3), Handball (3), Basketball (2), Korfball & Volleyball (á 1)) - *Control* (*n*=10; 22.40±1.35 years; Volleyball (4), Football (3), Basketball, Handball, Hockey (á 1))	**Training:** instruction on DVJ performance ('Jump as high as possible after you have landed off the box') followed by group specific instructions & feedback (LESS score) for all except of control: ○ VIF: 'Extend your knees as rapidly as possible after the landing on the force plate' ○ VEF: 'Push yourself as hard as possible off the ground after landing on the force plate' ○ V: 'try to imitate the jump best you can' **Duration:** 5 DVJ each group (pre- & posttest) after general & group instruction following training block 1 and 2 (each 10 jumps)	• **VIF**: ♂: > knee flexion (non-dominant leg) pretest compared to 2 training block (*p*=0.043*, *d*=0.57); ♀: > knee valgus moment (non-dominant leg, post-test) compared to retention (*p*=0.039*, *d*=0.60) • **VEF**: ♂ < knee valgus moment (post-test, non-dominant leg; *p*=0.003*, *d*=2.63) & ♀ (retention; *p*=0.034*, *d*=1.00) • **V**: ♂: > knee flexion angels (non-dominant, post-test; *p*=0.021*, *d*=2.60) & retention (*p*=0.019*, *d*=2.15) compared to VIF & training block 1 & 2 (*p*=0.008*, *d*= 1.22; *p*=0.030*, *d*=0.030). ♀: > knee flexion angle (non-dominant leg, retention) compared to post-test (*p*=0.008*, *d*=1.27) & < vGRF (*p*=0.031*, *d*=0.36)
Jump Landing Performance – Feedback			
Cronin, 2008 (*Pre-Post*)	♀ NCAA Division 1 intercollegiate volleyball players (*n* = 15; 21.3±2.4 years) trained volleyball ≥ 3x p. week with additional strength training ≥ 2x p. week.	**Training:** bilateral JL while spiking a volleyball off a toss by coach (practice-jump) following reading & listening to same instruction (first jumps). Following, 2 min. instruction with demonstration, practice, same verbal & visual feedback for all participants followed by 5 jumps with no feedback (second jumps). ○ Instructions: 'landing on forefoot to rearfoot, symmetrical across both legs, knee flexion approaching 90°' **Duration**: 1 session, av. best 2 jumps	• Augmented feedback: < vGRF (*p*=0.01*)
Etnoyer, 2013 (*RCT*)	♀ Recreational & varsity athletes (*n*=43; 21.47±1.55 years) randomly assigned to -*Self-feedback* (*n*=15) -*Combination* (*n*=15) feedback -*Control* (*n*=13, no feedback)	**Training:** box-DJ as pretest & landing technique feedback based on their group ○ Self-feedback: viewed 4 trials of own box-DJ (LESS criteria) ○ Combination feedback: viewed 2 trials of own box-DJ & 2 jumps of expert (LESS criteria) box-DJ & running-stop-jump transfer (post-test) **Duration:** one session plus retest after one month	• Combined feedback: > peak knee flexion compared to self-feedback at posttest (*p*=0.03*)

Leonard, 2021 (*Pre-Post*)	♀ basketball & volleyball local collage teams (n=23, 19.3±0.93) team randomized to - *Dyad feedback* (n=10) volleyball team - *Expert external feedback* (n=13) basketball team	**Training:** double-baseline VDJ testing & feedback based on condition ○ Dyad feedback: teammate corrected partner on a squat jump landing task by using a technique checklist and 5 min. instruction ○ Expert external feedback: certified athletic trainer, after >20h movement screening training, while athletes using external focus of attention **Duration:** 1 session, 5 trials	• Dyad feedback: <abduction displacement ($p<0.02$*) • Expert feedback: <vGRF from pre to post-test compared to dyad group ($p<0.02$*)
Onate, 2005 (*RCT*)	♀, ♂ Recreational athletes (n=51; 18-25 years), exercising ≥ 3x p.week minimal 20 min. randomly assigned to: - *Videotaped expert model augmented feedback* (expert), - *Videotaped self-model augmented feedback* (self), - *Videotaped combo model augmented feedback*, - *Non-feedback* (control)	**Training:** basketball rebounding task on jump-ball device. Instruction to 'land in their normal manner' for all groups with additional feedback (self, expert) followed by instruction: 'land as soft as possible' for all groups. ○ expert: watches expert jump landing performance ○ self: watches own jump-landing trials ○ combo: watches 2 trials expert, 3 trials own **Duration:** 3 sessions: baseline, performance, retention; 3 sets of training feedback in performance session	• Feedback groups > knee angular displacement (p=0.21*) & < peak vGRF (p=0.21*) during performance & retention • Non-feedback group < peak vertical forces across performance & retention
Shams, 2021 (*RCT*)	♀ Athletes (n=45), regular physical activities last 3 years (13-15 points Baecke Physical Activity Questionnaire – max. 15 points) randomly divided: -*Plyometrics & Feedback* (n=15; 24.0±3.9 years) -*Plyometrics & Tape* (n=15; 24.9±4.5 years) *Control* (n=15; 24.4±4.0 years. No plyometrics)	**Training:** 4 plyometric exercises combined with feedback or tape: ○ Feedback: visual feedback (full length mirror) & scripted verbal cueing at the beginning of the sessions (e.g., 'keep your knees apart from each other'). + verbal feedback during training if they did not maintain desired modification ○ Tape: mulligan tape before training session & scripted information + feedback if needed **Duration:** 2 sessions/week for 6 weeks; 2-3 sets of 10-15 repetition of the four plyometric tasks	• Improvement in LESS score in feedback & tape condition (p=0.001*)

Jump Landing Performance – Skill Training			
Shimokochi, 2016 (*Pre-Post*)	- ♀, ♂ Recreational active athletes (*n*= 20; 23.4±3.6 years). ♂ (*n*= 10; 25.4±3.8) and ♀ (*n*=10; 21.4±1.8) involved in physical activities ≥30 min. p.day, 3x p.week	**Training:** 3 landing styles (dominant leg), from a 30-cm (♀)/ 45-cm (♂) box: ○ Self-selected ○ Body leaning forward, plantarflexed position at foot contact ○ Body upright, flat-footed position **Duration:** 5 single-legged landing trials for each condition	• Flat-footed landing: < knee flexion angles & > magnitude & more landing anteriorly inclined GRF vector relative to the tibia compared to self-selected (*p*<0.05*) • Plantarflexed: > knee flexion° & < magnitude & more posteriorly inclined GRF vector relative to the tibia than self-selected landing (*p*<0.05*)
b. Dynamic Strengthening			
Plyometrics			
Dello Iacano, 2017 (*Pre-Post*)	♂ Elite handball players (*n*= 18, 23.4±4.6 years) >6 years specific jumping & sprinting, ≥ 90% trainings of last 2 seasons, assigned to: - *Vertical Alternate (VDJ)* (*n*=9) - *Horizontal Alternate (HDJ)* (*n*=9)	**Training:** VDJ or HDJ 1-leg drop jumps, landing from 25cm platform **Duration:** 2x p.week, 10 weeks, 5-8 sets, 6-10 rep, 15-30 min.	• > peak GRF (*p*=0.001*) VDJ compared to HDJ (*p*=0.004*)
Herrington, 2010 (*Pre-Post*)	♀ National league division 1 basketball players (*n*= 15, 19.1±1 year, 18-22 years)	**Training:** progressive jump-training program from bilateral to unilateral activities including different jumps (e.g., squat jumps and 180° jumps) with jump performance feedback **Duration:** 15 min. session, 3x p.week, for 4 weeks	• < Average Drop jump and jump shot knee valgus angle on the left leg (*p*= 0.002*; *p*=0.035*) & right leg (*p*=0.0001*; *p*=0.01*).
Nagano, 2011 (Pre-Post)	♀ University basketball athletes (*n*=8, 19.4±0.7 years)	**Training:** Balance and jump training (2 phases): ○ 1: technique phase, 3 basic techniques (e.g., landing on the ball of the foot with the trunk leaning forward) ○ 2: performance phase, increasing intensity & use of proper technique. **Duration:** 20 min. session, 3 days p.week for 5 weeks.	• > Knee flexion angle (post-training trial), then Pre-training 2 trial (*p* < 0.001*) • > absolute change knee flexion (post-training trial), then Pre-training 2 trial (*p* < 0.001*)
Makaruk, 2014 (*RCT*)	♂ College students (*n*=36; physically active: 8h/w) randomly assigned to: - *Single Jump* (SJG, *n*= 12, 22±1.1 years) - *Repeated Jump* (RJG, *n*=12, 22.7±1.4 years) - *Control* (CG, *n*= 12, 22.6 ± 1.8), no additional exercise	**Training:** single (SJG) or repeated jumps (RJG) ○ SJG: 4-5sec break between reps. ○ RJG: no break **Duration:** 3x p.week on non-consecutive days, 6 weeks, 4-8 sets 3 reps, 50-60 min. session after specific warm up.	• RJG: < vGRF & > knee flexion angle (*p*<0.01*); >knee flexion angle compared to control (*p*<0.05*) • SJG: < knee flexion angle (*p*<0.01*); >knee flexion angle compared to control (*p*<0.05*) • RJG vs. SJG: <GRF & >knee flexion angle in RJG

Vescovi, 2008 (*RCT*)	♀ Active college (n= 20, exercises 2-3/w) randomly assigned to: - *Training* (*n*= 10, 20.3 ±1.2 years) - *Control* (*n*= 10, 19.9 ± 1.6 years) no intervention	**Training:** Sportsmetrics^{TM} training ○ variety of plyometric exercises, intensity increased ○ 3 phases: Technique, fundamental, performance **Duration**: 3/week, 6-weeks, 45-60 min. session	• Intervention: < vGRF compared to control (*p* =0.122)
Combi Strengthening			
Dai, 2015 (*Pre-Post*)	♀, ♂ recreational athletes, experienced in sports involving jump-landing (*n*= 28, 13 ♂ & 15 ♀, 21.1±2.4 years). physically active (≥ 2x p.week, 2-3h)	**Training:** jump-landing-jump task with & without resistance band around lower shank, above ankles **Duration:** 3 Trials, 30 sec rest between 2 and 3 trial	• < Initial hip flexion (*p*=0.028*, *d*=1.0), hip abduction (*p*<0.001*, *d*=0.91) and max. knee flexion (*p*=0.046*, *d*=0.17) angle • > Average hip abduction moment during pre-(p<0.001*, *d* =0.91) & early-landing (*p*<0.001*, *d*=1.0)
Peng, 2021 (*Pre-Post)*	♂ Collegiate division II athletes (*n*=12; 20.32±1.86 years) familiar with DJ, involved in sports, training or physical activity 5 days p.week	**Training:** DJ with elastic band loads of 0% & 20% body weight attached to the waist and heels during the airborne and landing phases from 40- & 50-cm box. Elastic bands were released before downward movement (peak knee flexion) **Duration:** one single experimental session, 4 days after familiarization session	• Hip (*p*=0.001*), knee flexion (*p*=0.0025*), & ankle plantarflexion angles (*p*<0.001*), at initial foot contact & ankle dorsiflex. ROM > with 20% body weight loading • Peak GRF of impact (*p*=0.029) & hip flexion ROM (*p*=0.048*) < with 20% body weight loads
Stearns & Powers, 2014 (*Pre-Post*)	♀ Recreational athletes (*n*=21; 18-25 years) physical activity ≥ 30 min. 2x p.week	**Training:** hip-focused training (3 levels, increasing difficulty) ○ Level 1: different jumps (2x20 seconds) & 2 balance exercises on BOSU® (4x30 seconds and 2x20 seconds) ○ Level 2-3: increased complexity & duration of jump/ balance task **Duration:** 20-30 min. session; 12 training sessions over 4-weeks; 1 week level 1 and 2, 2 weeks level 3 (progression only previous level managed)	Drop-jump task • Subjects landed with > peak knee (*p*<0.001*) and hip flexion (*p*=0.008*) and < knee/hip extensor moment ratio (*p*<.001*) • < peak knee abduction angles (*p*=0.04*) and average knee adductor moments (*p*<0.001*)
Yang, 2018 (*RCT*)	♀, ♂ Collegiate basketball (*n*=27, 18-21 years) & volleyball players (*n*=9, 18-21 years), Beijing Sport University, < 30° knee flexion in stop-jump task, ≥5 trainings p.week. Randomly assigned to: - *Intervention* (basketball: 9 ♂ & 5 ♀; Volleyball: 4 ♀)	**Training:** specific program: ○ Warm-up (trunk strengthening) ○ main exercises (hip extension training & plyometrics (e.g., jumps in different directions) ○ warm-down (muscle relaxation & static stretching) **Duration:** 3x p.week, for 4 weeks	Post-intervention tests (weeks 4,8,12 and 20) while maintaining regular training routine: • ♂: > Knee flexion angle at peak impact posterior GRF in stop-jump task (weeks 8,12, and 20 compared to week 0 and control group) (*p*≤0.002*) ♀: No sig. changes in knee flexion angle or GRF

	- *Control* no additional training (basketball: 8 ♂ & 5 ♀, Volleyball: 1 ♂ & 4 ♀).		
Prevention Programs			
Aerts, 2015 (*RCT*)	♀, ♂ Eligible Flemish basketball teams second and third regional divisions (Flanders, Belgium). Teams randomly assigned to: - *Intervention* (*n*= 27 ♂, 24.7±4.9 years, *n=26* ♀, 23.12±5.8 years), additional training - *Control* (*n*= 31 ♂, 26.8±5.4 years, *n*=32 ♀, 23±3.9 years), no additional intervention	**Training:** during warm-up for improvement of jump landing techniques based on: ○ technique (month 1, e.g., squats) ○ fundamental exercises (month 2, squat jumps) ○ performance phase (month 3, difficult increases e.g., max. squat jumps) DVD & poster with correct instruction for coaches **Duration:** 5-10 min. session, 2x p.week, for 3 months	Referring only to results for ♂ (♀ wrong age) • Intervention: improvement max. hip flexion & left knee flexion over time (*p* <0.05*), < right genu valgus at take-off (*p*<0.05*) • Control: no sig. changes in hip and knee flexion over time
Fox, 2018 (*RCT*)	♀ Sub elite netball players randomly assigned to: - *Training* (*n*=8, 22.0±2.5 years) - *Control* (*n*= 8, 23.4±2.7 years)	**Training:** ACL prevention program for netball players (Down to earth (D2E)) ○ Home-based & supervised jump-landing exercises with Instruction (safe landing techniques) **Duration:** 15-20 min., 3x p.week, for 6 weeks	• >Hip external rotation (initial contact) post-training (*p*<0.001*) • >Knee angular displacement in training compared to control after 6 weeks (*p*=0.020*) • 'High-risk' individuals (>peak knee abduction moment) <frontal knee plane moments post-training (p>0.05)
O'Malley, 2017 (*RCT*)	♂ Collegiate teams (*n*= 78, 18.4 – 18.5 years ;2 hurling & 2 football teams) training ≥ 2 p.week randomised in: - *Intervention* (*n*=41, 2 teams) *Control* (*n*=37, 2 teams) no additional intervention	**Training:** 'GAA 15' standardised warm-up program. **Duration:** 15 min., 2x p.week, 8 weeks	• Intervention: < mean LESS after training (*d*= 0.72, *p*= 0.001*) • Both groups: poor movement quality at baseline according to the LESS criteria (LESS > 6).
c. Static Strengthening			
Core Workout			
Araujo, 2015 (*Pre-Post*)	♀ Capoeira athletes (*n*= 16, 27.3±3.7 years) ≥ 2 years capoeira training completed physical activity readiness questionnaire (PAR-Q)	**Training:** plank & bridge variants, crunches, Russian twister, split legs scissors, intensity increased every 2^{nd} week **Duration:** 3x p.week, 6-weeks, 15 min. session	• < DJ peak vGRF during 1 (=drop from the box) and 2 landing phase (=after maximal vertical jump) (*p*<0.001*)

Warm-up Program			
Avedesian, 2020 (*Pre-Post*)	- ♀ Volleyball athletes (*n*= 12; 19.8±1.2 years) trained 3x p.week & competed in nationally sanctioned collegiate club volleyball tournaments.	**Training:** 2 warm-up protocols ○ dynamic: 14 whole-body dynamic exercises (e.g., leg cross overs, high knee-pull, high lunge-pull) ○ Dynamic & static stretching: same dynamic exercises + 7 static stretches major lower extremity muscle **Duration:** 7 min. dynamic warm-up (30sec each exercise); 14 min. dynamic warm-up & stretching, á 30 sec stretch	• Dynamic & static stretching: < in peak hip adduction angle (non-dominant leg) from pre to 15 min. post warm-up (*p*=0.016*, *d*=0.38) • Non-dominant limb: > knee abduction (*p*=0.006*, *d*=0.38) & internal rot. angles (*p*=0.004*, *d*=0.69) during landing compared to dominant limb
d. Balance Training			
Static Balance Training			
Silva, 2018 (*RCT*)	♂ Recreational athletes (*n*= 24; 18-25 years) training ≥ 3-5x p.week, different sports (basketball, soccer, handball, volleyball). - *Intervention* (*n*= 11; 28.8±1.2 years, wobble board training) - *Control* (*n*= 9; 28.2±0.9 years, no wobble board training).	**Training:** wobble board, 15 exercises, progression if task accomplished without falling on one leg for 20 consecutive sec. Level of difficulty: • standing still → rocking in different planes → contra-lateral leg movements → single-leg squats → catching/drippling ball → eyes closed & all with < diameter mounted at ball **Duration:** 30 min., 3x p.week, 4 weeks	• No sig. group-by-time interaction (vGRF) or changes in ankle angles (plantar flexion) after training (single-leg lateral jump-task)
Dynamic Balance Training			
Letafatkar, 2019 (*RCT*)	♀ Collegiate athletes (*n*=31; 20-25 years; handball, basketball & soccer players), neuromuscular quadriceps dominance deficit (Tuck jump assessment), involved in off-season training, 3x p.week up to 120min p.session, randomly assigned: - *Experimental* (*n*=16, additional perturbation training), - *Control* (*n*=15, no additional training)	**Training:** weekly increasing perturbation drills with verbal instructions ('keep your trunk still', 'keep your knees soft', 'relax between perturbation') on different grounds: ○ Rocker board, Roller board, BOSU ball ○ Stationary perturbation drills **Duration:** 1h; 18 sessions for 6 weeks	• Training group: > initial contact flexion angle (*p*=0.001*) & knee flexion displacement angle (=subtracted peak knee flexion angle from initial contact flexion angle; *p*<0.05*) compared to pre-test & control group (Tuck Jack Assessment)

RCT= Randomized Controlled Trial, nRCT= non Randomised Controlled Trial, Pre-Post= Uncontrolled Trial, * = significant changes, p= p-value, h. = hour(s), min.= minutes, sec.= second, max= maximum, p.week= per week, p.session= per session, p.day= per day, w= week, GRF= ground reaction force, vGRF= vertical ground reaction force, x= times, LESS= Landing Error Scoring System, avg= average, box-DJ = box drop jump, CMJ= countermovement jump, DL = drop landing, DVJ= drop vertical jump, VDJ= vertical drop jump, *n*= sample size, *d*= Cohen's d, sig.= significant, ROM= range of motion

Supplementary Table 2 Search strategy including keywords, databases, applied filters, and findings (date of search: December 21st, 2021

	Keywords	Filters	Database	Findings
1	(athletes OR sports OR athletics) AND ("unilateral landing" OR "bilateral landing" OR "jump landing" OR "jump task" OR landing) AND ("intervention protocol" OR intervention OR "training protocol" OR exercise OR training OR prevention) AND (kinematics OR kinetics OR biomechanics OR "knee valgus" OR "knee flexion angle" OR "injury risk" OR "injury rate" OR "injury incidence" OR "landing error scoring system")	Clinical Trial, randomized controlled trial, language: english & german, age: 19-44 years	**MEDLINE**	130
2	(athletes OR sports OR athletics) AND ("unilateral landing" OR "bilateral landing" OR "jump landing" OR "jump task" OR landing) AND ("intervention protocol" OR intervention OR "training protocol" OR exercise OR training OR prevention) AND (kinematics OR kinetics OR biomechanics OR "knee valgus" OR "knee flexion angle" OR "injury risk" OR "injury rate" OR "injury incidence" OR "landing error scoring system")	Keywords close to each other, language: English & german	**SPORT Discus**	1365
3	(TITLE-ABSKEY (athletes OR sports OR athletics) AND TITLE-ABS-KEY ("unilateral landing" OR "bilateral landing" OR "jump landing" OR "jump task" OR landing) AND TITLE-ABSKEY ("intervention protocol" OR intervention OR "training protocol" OR exercise OR training OR prevention) AND TITLE-ABSKEY (kinematics OR kinetics OR biomechanics OR "knee valgus" OR "knee flexion angle" OR "injury risk" OR "injury rate" OR "injury incidence" OR "landing error scoring system"))	Title/ abstract/ keywords	**Scopus**	892

Supplementary Table 3 Questions used in the review to evaluate the risk of bias domains in uncontrolled (before-after) studies with no control group of training methods to reduce the risk for jump landing injuries to the lower extremity based on the work by Sterne et al., 2016

Pre-Intervention domains	
Bias due to confounding	○ Was measurement of outcomes made at sufficient pre-intervention time points? ○ Do the study authors use an appropriate analysis method that accounts for time trends and patterns? ○ Provided material for all participants identical? ○ Unintended differences in intervention performance?
Bias in selection of participants into the study	○ Intended selection of participants (e.g., males and females only)? ○ Activity level of participants similar? ○ Sage age and gender of compared groups? ○ Good health status of participant?
At-intervention domain	
Bias in classification of interventions	○ Training performance/intensity controlled by expert/supervisor/coach?
Post-intervention domains	
Bias due to deviations from intended interventions	○ Measurement of kinematics standardizes? ○ Identical warm-up for all participants? ○ Identical provided information for all participants?
Bias due to missing data	○ No loss of data? ○ Loss of data reported? ○ All results reported?
Bias in measurement of the outcome	○ Appropriate measuring of the outcome? ○ Are outcome measures assessed in valid manner? ○ Data collection directly after intervention and on a second date? ○ Were methods of outcome assessment comparable before and after the intervention?
Bias in selection of the reported result	○ All outcomes reported and evaluated? ○ Mean and SD reported?