STRENGTH TRAINING TO REDUCE BIOMECHANICAL RISK FACTORS FOR ACL INJURIES IN ATHLETES: A SYSTEMATIC REVIEW AND META–ANALYSIS

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Abstract:

Anterior cruciate ligament (ACL) injuries can significantly affect an athlete's ability to participate in sport, emphasizing the importance of prevention strategies to mitigate knee impairments. Strength training has been shown to enhance landing mechanics during sidestepping and jumping, movements often linked to ACL injuries. This systematic review with meta-analysis investigated the effects of strength training on biomechanical risk factors for ACL injuries in athletes. After searching trials up to May 4, 2022, eight articles were included. The articles included in the study seemed to be limited to female athletes who participated in sports that required cutting, jumping, or pivoting. Due to the heterogeneity of the included studies, only three articles (78 participants) could be included in the meta-analysis. The results from the meta-analysis suggest that strength training may favor lower ACL stress as it is correlated with an increased landing knee flexion angle during drop vertical jump. The data are limited, however, and the literature remains sparce in quality and number. This review exposes the need for a deeper understanding of how strengthening influences landing mechanics, reduces knee overload, and decreases the risk of ACL injuries. Future research should focus on standardizing the evaluation of ACL injury-related movements, including the definition of biomechanical outcomes, training interventions, and functional tasks for measurements. Strengthening of pelvic, core and lower body muscles 2-3 times per week seems to lower the ACL injuries risk.

Keywords: *ACL injuries, strength training, biomechanical risk factors*

Introduction

Anterior cruciate ligament (ACL) injuries are prevalent among athletes who participate in landing, cutting and pivoting sports, such as soccer, volleyball or basketball (Dufek & Bates, 2012). It has been shown that 60% of ACL injuries occur in non-contact sidestepping and single sporting tasks (Cochrane, Lloyd, Buttfield, Seward, & McGivern, 2007). Key risk factors include dynamic knee valgus – a medial collapse of the knee during weight bearing caused by hip adduction and femoral internal rotation, combined with tibial abduction and external rotation (Paz, Maia, Farias, Miranda, & Lima, 2016; Pollard, Sigward, Ota, Langford, & Powers, 2006), as well as a reduced knee and hip flexion, which impairs shock attenuation during foot-ground contact (Hewett, Ford, & Hoogenboom, 2010; Sigward, Pollard, & Powers, 2012). These factors increase ACL strain and patellofemoral joint stress (Lee, Morris, & Csintalan, 2003; Markolf, Willems, Jackson, & Finerman, 1998). The most commom mechanism for non-contact ACL injuries is a deceleration event combined with a sudden change in direction while the foot is planted, known as a cutting maneuver (Renstrom, et al., 2008).

The ACL injuries lead to short-term impairments, i.e, joint effusion, muscle weakness, static and functional instability (Daniel, et al., 1994; Filbay & Grindem, 2019) and might induce long-term consequences, including premature development of osteoarthritis (Ireland, 2002; Pinczewski, et al., 2007; Wilk & Arrigo, 2017). While less than half of athletes who undergo ACL reconstruction return to pre-injury competitive levels one year after the surgery, more than half of them abandon their professional careers (Ardern, Taylor, Feller,

& Webster, 2014). ACL injury impairs and reduces participation in sports.

ACL injury prevention is the most effective way to avoid knee impairments. Despite the fact that ACL injury etiology is complex and multifactorial, involving non-modifiable risk factors such as anatomic, genetic and physiological, other risk factors are modifiable, such as the neuromuscular and biomechanical factors (Pfeifer, Beattie, Sacko, & Hand, 2018). These modifiable factors can be changed with training (Ferri-Caruana, Prades-Insa, & Serra-Añó, 2020; Herman, et al., 2008; Hewett, Myer, Ford, & Slauterbeck, 2007; Hopper, Haff, Joyce, Lloyd, & Haff, 2017; McCurdy, Walker, Saxe, & Woods, 2012; Myer, Ford, Brent, & Hewett, 2006, 2007; Zebis, et al., 2008). Protocols combining different types of exercise and fitness components have been shown to reduce incidence of ACL injuries, as well as improve jumping and side cutting techniques (Hewett, et al., 2005; Hewett, Stroupe, Nance, & Noyes, 1996; Meyer & Haut, 2008). Although several studies have reported improvement in landing mechanics after progressive strengthening and neuromuscular training, the injury rates have appeared to double in the past decade (Gianotti, Marshall, Hume, & Bunt, 2009; Janssen, Orchard, Driscoll, & van Mechelen, 2012).

There is a gap between scientific evidence and clinical practice regarding ACL injuries. The purpose of this systematic review was to analyze randomized controlled trials (RCT) that investigated the influence of strength training upon biomechanical risk factors in ACL injuries in athletes. The aim of this study was: 1) to evaluate the effects of strength training on biomechanical risk factors in ACL injuries, compared to no-intervention; 2) to suggest future directions of research to improve the knowledge of how muscle strengthening influences landing mechanics, reduces knee overload, and decreases the risk of these injuries.

Methods

Selection criteria

Types of studies. We included randomized controlled trials (RCT) that investigated the effects of strength training on biomechanical risk factors in ACL injuries of athletes of cutting, landing and pivoting sports compared to a control group (no additional training to a regular sport-specific training). The limitation to RCT aimed to provide reduced risk of bias (RoB) and balance participants between the groups (Hariton & Locascio, 2018). Assessment of RoB using Cochrane's RoB 2 tool (Sterne, et al., 2019) was used to inform meta-analytical comparisons, but not to exclude studies during the selection process.

Types of participants. We included athletes that participated in landing, pivoting and cutting sports in any age group and competitive level, with no history of serious knee injury or other lower extremity injury within the previous six months.

Types of intervention. Included studies should embrace trials including at least one experimental group in which low extremity strengthening exercises were performed, either body-weight exercises and/or resistance training with elastic bands or various types of loads.

Types of outcome measures. The included outcome measures were: 1) knee valgus occurrence on landing and/or cutting tasks; 2) various combinations of tibial movement on landing (e.g., anterior translation + abduction, anterior translation + external rotation); 3) hip internal and external rotation during active range of motion relative to body weight; 4) knee and hip peak flexion and peak ankle dorsiflexion on landing; 5) vertical component of the ground reaction force during landing; 6) EMG amplitude and pre-activity of lower extremity muscles during the landing and cutting task. These outcomes were obtained with kinematic motion analysis (e.g., Vicon system, isoinertial sensors), kinetic analysis on a force plate, and EMG analysis with surface electrodes.

Search methods for studies identification

Bibliographic databases. The following databases were screened up to May 4, 2022: the Cochrane Central Register of Controlled Trials, MEDLINE, EM-BASE, and Pubmed (see Appendix 1). Furthermore, ClinicalTrials.gov was checked to identify any possible trials that have not been published yet.

Other resources. Additionally, reference lists of included trials were checked for further relevant literature.

Data collection and analysis

Protocol registration. This systematic review and meta-analysis adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher, et al., 2015). Assessment of study quality was conducted in accordance with the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) (Guyatt, et al., 2011). Methods were defined and the protocol was pre-registered in PROSPERO with No. CRD42022289200 before commencing the search process. Registration number was attributed on February 12, 2022.

Selection of studies. After obtaining all articles from the aforementioned literature searches, two blinded review authors (JP and KJ) used the Rayyan software to independently screen the abstracts, keywords, and publication type. Any uncertainties or disagreements were solved by discussion between these two reviewers, and if the disagreement remained, the third author (LM) made the final decision. The full-text articles of all inclusioneligible studies were obtained, following inclusion and exclusion criteria.

Data extraction. The two review authors (JP and KJ) independently extracted the necessary information (Table 1) and assessed the risk of bias of the included trials. As well as for the selection of studies, if there was any uncertainty or disagreement not solved by these two reviewers, the third author (LM) made the final decision. The pooled results have been analyzed using standardized mean difference (MD) values.

Risk of bias of independent individual studies. The revised Cochrane RoB tool for randomized trials (RoB 2) was applied (Sterne, et al., 2019) at the outcome level. All five RoB dimensions were assessed: i) randomization process; ii) deviations

Table 1. Characteristics of individual studies

Author (year)	Study design	Participants	Comparison group	Intervention protocol	Outcomes assessed
Ferri-Caruana, et al. (2020)	RCT	Adolescent female soccer players, 15-24 years old (16 intervention; 10 control)	No additional training beyond regular technical and tactical training	Pelvic and core strengthening with resistance bands. 2 sessions/week, 8 weeks. Session duration: 30 min. Participants performed repetitions until reaching a “very hard” intensity (7-8 on the modified Borg scale).	Bilateral drop vertical jump (DVJ): peak hip, knee, and ankle dorsiflexion at landing. Unilateral DVJ: knee frontal plane projection angle.
Hopper, et al. (2017)	RCT	Female netball athletes, 11-13 years old (13 intervention; 10 control)	No additional training beyond regular technical and tactical training	Neuromuscular training program with progressive plyometric and strength exercises, increasing intensity from easy (RPE 3-4) to moderate (RPE 5-6) to hard (RPE 7-8). 3 sessions/week, 6 weeks. Session duration: 60 min.	Unilateral DVJ: bilateral knee valgus at initial contact and maximum knee flexion-extension, vertical ground reaction force immediately after box drop and landing.
Zebis, et al. (2015)	RCT	Female soccer and handball players, 15-16 years old (20 intervention; 20 control)	No additional training beyond regular technical and tactical training	Neuromuscular training with wobble boards, balance mats, and balls to enhance body awareness and motor control at the hip, knees, and ankles during running, cutting, jumping, and landing. Progressively increasing difficulty. 3 sessions/week, 12 weeks. Session duration: 15 min.	Side cutting movement: maximal knee joint valgus moment, knee valgus angle at initial contact, EMG amplitude from vastus lateralis (VL), semitendinosus (ST), and biceps femoris 10 ms before initial contact, normalized to peak EMG during maximal voluntary isometric contraction.
McCurdy, et al. (2012)	RCT	Young adult females with high school athletic experience, 19-23 years old (13 intervention; 16 control)	No training	Resistance training with weight-bearing free weights using a repetition maximum (6-15 RM). 2 sessions/week, 8 weeks.	Bilateral DVJ and unilateral DVJ: maximum and mean knee valgus, knee flexion, and hip flexion angles.
Lim, et al. (2009)	RCT	Adolescent female basketball players, 15-18 years old (11 intervention; 11 control)	No additional training beyond regular technical and tactical training	Sports injury prevention training (warm-up, stretching, strengthening, plyometrics, and agility drills). 8 weeks. Session duration: 20 min.	Rebound jump: maximum knee flexion angle, minimum inter-knee distance, maximum knee internal rotation angle, maximum knee extension moment, and maximum knee valgus moment.
Herman, et al. (2008)	RCT	Female recreational athletes, 18-30 years old (33 intervention; 33 control)	No additional training beyond regular technical and tactical training	Strength training using resistance bands, targeting quadriceps, hamstrings, gluteus medius, and gluteus maximus. 3 sessions/week, 9 weeks.	Stop-jump task.
Grandstrand, et al. (2006)	RCT	Female youth soccer players, 9-11 years old (12 intervention; 9 control)	No additional training beyond regular technical and tactical training	Sportsmetrics Warm-Up for Injury Prevention and Performance (WIPP), including plyometrics, landings, and agility drills. 2 sessions/week, 8 weeks. Session duration: 20 min. Exercise duration was adjusted to ensure technical quality without fatigue.	Bilateral DVJ: knee abduction and adduction at pre-landing, landing, takeoff, and maximum height.
Chimera, et al. (2004)	RCT	Collegiate female soccer and field hockey players, 18-22 years old (9 intervention; 9 control)	No additional training beyond regular technical and tactical training	Sport-oriented plyometric training, with various jump types. 2 sessions/week, 6 weeks. Session duration: 15 min.	Bilateral DVJ: height, EMG amplitude (area, mean, peak) of vastus medialis, vastus lateralis, medial hamstrings, lateral hamstrings, abductor, and adductor muscles. 40-yard shuttle run: maximal sprint speed.

from intended interventions; iii) missing outcome data; iv) measurement of the outcome; and v) selection of the reported result.

Analysis and presentation. An overall analysis was performed for two outcomes: peak landing knee flexion angle during drop vertical jump and peak landing hip flexion angle during drop vertical jump.

Although there are many more biomechanical variables related to ACL injuries, as the ones mentioned in "types of outcome measures", they are either not investigated or they were analyzed on different tasks (see Table 1) in the included studies, which did not allow for their comparison and consequently, their meta-analyses.

Comparisons. The meta-analysis was made with at least two trials of comparable outcome measurements. Only two parameters that appeared in the three articles included were analyzed. Statistical analyses were made using RStudio.

Continuous outcomes. For the parameters that were meta-analyzed, a positive value indicated benefit of the intervention. Heterogeneity was assessed using the I2 statistic, with values of <25%, 25-75%, and >75% considered to represent low, moderate, and high levels of heterogeneity, respectively (Higgins, Thompson, Deeks, & Altman, 2003). Random-effects model was used in all analyses.

Summary of findings table. A 'summary of findings' table (Table 2) was created with the following outcomes: peak landing knee flexion angle during drop vertical jump and peak landing hip flexion angle during drop vertical jump. We used the five GRADE (Grades of Recommendation, Assessment, Development and Evaluation) considerations (study limitations, consistency of effect, imprecision, indirectness and publication bias) to assess the quality of a body of evidence for stated outcomes (Schünemann, et al., 2008).

Outcomes pooled using MDs were re-expressed as absolute mean differences (or changes) by multiplying by a representative control group baseline SD based on Scholten, de Beurs, and Bouter (1999).

Table 2. Summary of findings

Strength training compared to control for biomechanical risk factors for ACL injuries						
Patient or population: biomechanical risk factors for ACL injuries						
Setting:						
Intervention: Strength Training						
Comparison: Control						
Outcomes	**Anticipated absolute effects* [95% CI]**		**Relative effect (95% CI)**	**Number of studies**	**Certainty of the evidence (GRADE)**	**Comments**
	Risk with control	**Risk with strength traning**				
Lower limb kinematics. Peak knee flexion angle during drop vertical jump landing. Follow-up: from 6 to 8 weeks	The mean peak landing knee flexion angle during drop vertical jump was 0º	MD 13.92º, range: [9.31, 18.52]	-	78 (3 RCTs)	⊕⊕⊕⊕ High[a]	Strength training results in a larger peak knee flexion angle during drop vertical jump landing.
Lower limb kinematics. Peak hip flexion angle during drop vertical jump landing. Follow-up: from 6 to 8 weeks	The mean peak landing hip flexion angle during drop vertical jump was 0°	MD 3.81°, range [1.48, 6.14]	-	78 (3 RCTs)	⊕⊕◯◯ Low[a,b]	Strength training results in little to no difference in peak hip flexion angle during drop vertical jump landing.
*The risk in the intervention group (and its 95% confidence interval) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI). CI: confidence interval; MD: mean difference						
GRADE Working Group grades of evidence						
High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.						
Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.						
Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.						
Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.						
Explanations: a. low number of studies and low total number of subjects; b. confidence interval ranging for relevant to clinically important clinically not						

Results

Description of the studies

Results of the search (Figure 1). Sixty-one articles were identified, and a record was found on ongoing trials (clinicaltrials.gov). After checking the references of the three articles included, five other articles met the inclusion criteria. Thirty-one duplicated records were removed, and 28 records were excluded after the title and abstract screening. Thus, finally eight studies were included.

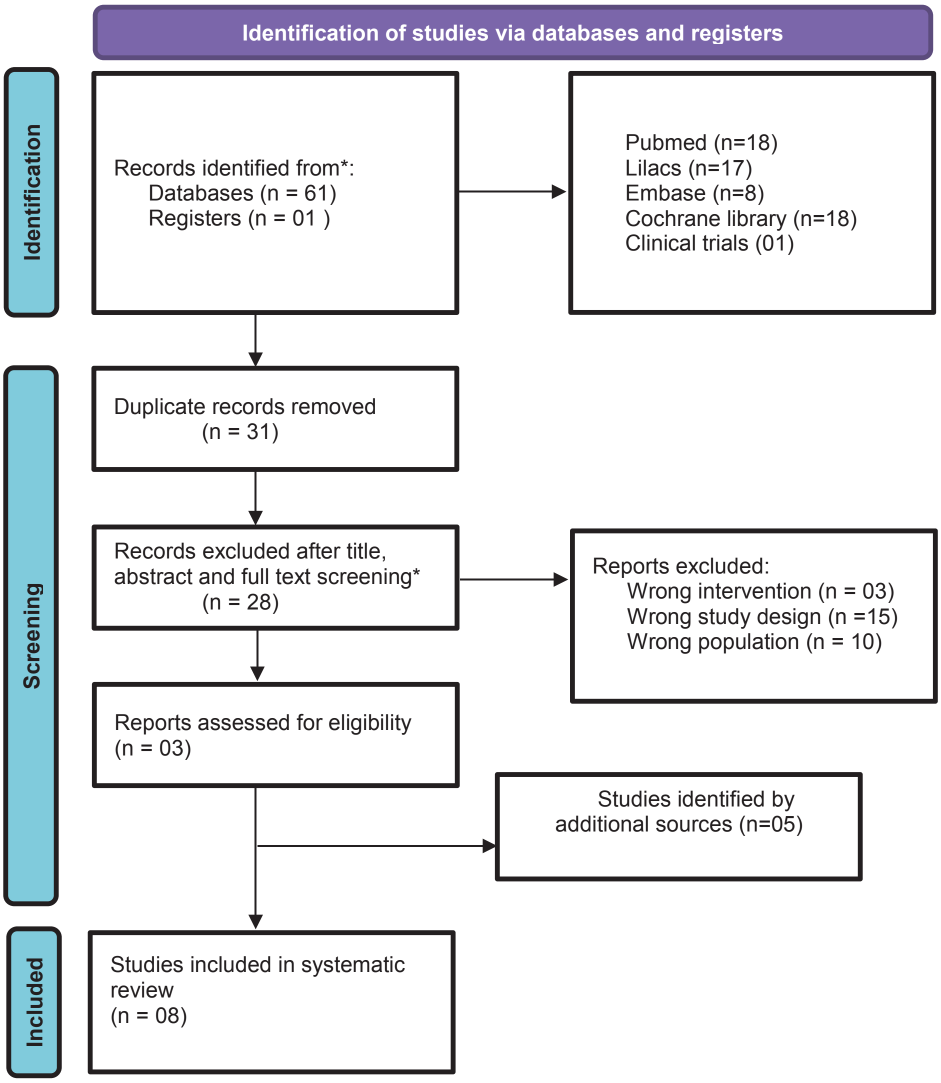
Included studies. The three included RCTs with a total of 78 participants met the inclusion criteria (Ferri-Caruana, et al., 2020 [n=26]; McCurdy, et al., 2012 [n=29]; Hopper, et al., 2017 [n=23]). See Table 1 (Characteristics of individual studies) for further information.

All participants were female (100%), with an average age of 16 years (range from 11 to 23 years). Their average body mass was 59.65 kg, and the range was 43.3 to 71.88 kg. Their average height was 1.65 m, and the range was 1.55 to 1.71 m. The strength training duration was 6-8 weeks. The mean adherence rate was 95% (SD 9.0%).

Risk of bias. In the risk of bias assessment, only one included trial presented some concerns (Grandstrand, Pfeiffer, Sabick, DeBeliso, & Shea, 2006), which did not describe the group allocation process. Other seven included trials were at a low risk of bias. In conclusion, the evidence presented in this review is based upon the low risk of bias of the included studies (Table 3 and Figure 2).

Effects of intervention

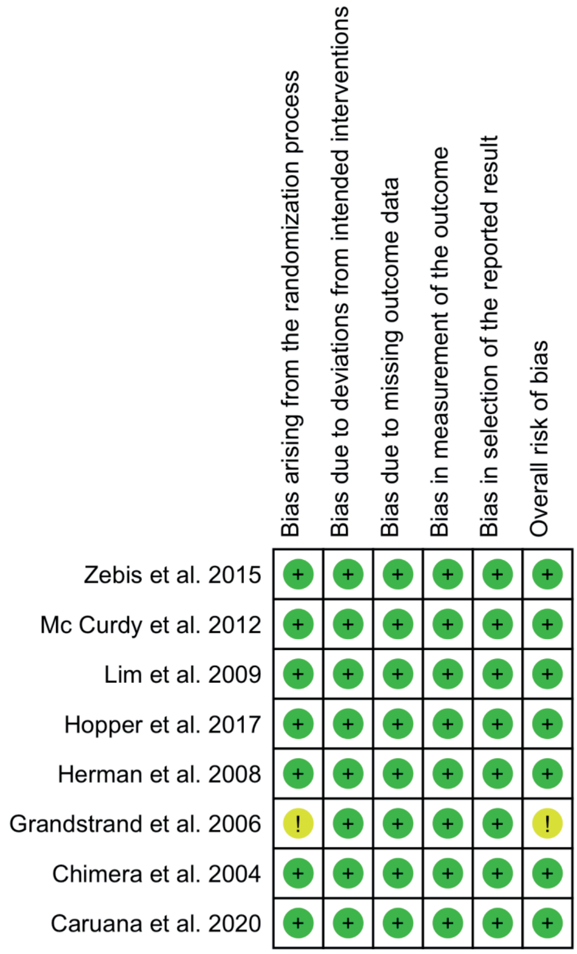
Effect of strength training on peak landing flexion angle during drop vertical (DPV) jump. For the three trials reporting the peak landing knee flexion angle during DPV (Ferri-Caruana, et al., 2020; Hopper, et al., 2017; McCurdy, et al., 2012), strength training significantly increased the peak landing knee flexion angle during DPV (MD 13.92 confidence interval [CI] 9.31 to 18.52) and moderate



* As there was a low number of studies, the authors chose to open the full texts when necessary, in the same phase of titles and abstract screening.

Figure 1. Identification of studies via databases and registers.

Table 3. Risk of bias within studies



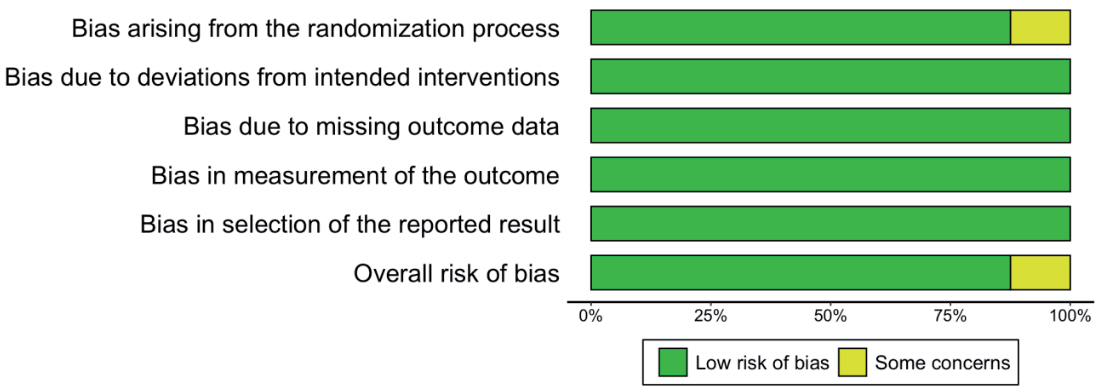


Figure 2. Risk of bias graph: review authors' judgements about each risk of bias item presented as percentages across all the included trials.

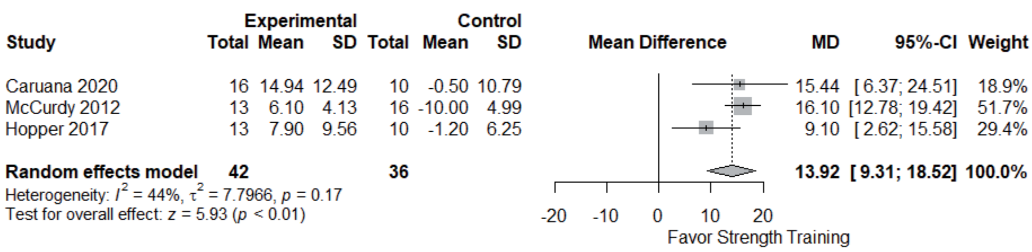


Figure 3. Peak landing knee flexion angle during drop vertical jump (DPV).

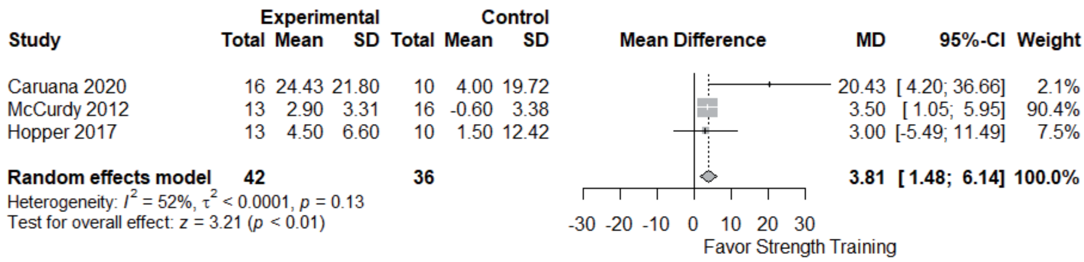


Figure 4. Peak landing hip flexion angle during drop vertical jump (DPV).

heterogeneity (Figure 3). This result has a clinically relevant effect.

On the other hand, the peak landing hip flexion angle during DPV (Ferri-Caruana, et al., 2020; Hopper, et al., 2017; McCurdy, et al., 2012) was not affected by strength training (MD 3.81, CI: 1.48 to 6.14) showing moderate heterogeneity (Figure 4). Hence, this result is not clinically relevant.

Discussion and conclusions

This systematic review with meta-analysis shows that strength training has a clinically relevant effect on peak landing knee flexion angle during DPV on athletes. Based on high quality of evidence, those who did strength training showed about 14º larger knee flexion during landing compared to the control group. On the other hand, despite a forest plot showing a tendency of strength training to increase the peak hip landing flexion angle during DPV, these results were not clinically relevant and were based on low quality of evidence.

Due to heterogeneity in study designs, only three out of the eight original articles met the inclusion criteria for this meta-analysis. The peak landing knee flexion angle during DPV has shown a significant change. Three studies (Ferri-Caruana, et al., 2020; Hopper, et al., 2017; McCurdy, et al., 2012) presented moderate heterogeneity and high effect, however, this clinically relevant result should be interpreted with caution because of the limited number of studies included. Even among the meta-analyzed studies, despite selecting the same outcomes, the frequency and type of training varied considerably. Ferri-Caruana et al. (2020) implemented core and pelvic strengthening exercises using resistance bands, performed twice a week for eight weeks. Similarly, McCurdy et al. (2012) applied the same training frequency and duration but focused on lower limb exercises using body weight. In contrast, Hopper et al. (2017) investigated a three-times-per-week regimen over six weeks, incorporating plyometric exercises for the lower limbs. Despite the high incidence and substantial costs generated by ACL injuries, few high-quality studies have investigated its prevention, making it challenging to meta-analyze them and synthesize robust evidence. In fact, current literature lacks standardization in terms of intervention type, volume, intensity, population and outcomes measures.

Sex significantly influences the risk for ACL injuries in athletes, with female athletes being 2-8 times more likely to sustain an ACL injury compared to their male counterparts in the same sport (Arendt-Nielsen, Graven-Nielsen, Svarrer, & Svensson, 1996; Hewett, et al., 2005; Myklebust, et al., 2003). A meta-analysis examining ACL tear incidence by gender and sport reported female-to-male injury ratios of 2.67 in soccer, 3.5 in basketball and 4.05 in wrestling (Prodromos, Han, Rogowski, Joyce, & Shi, 2007). This disparity likely explains why all articles included in our study focused exclusively on female athletes as participants. The notion that higher injury rates among females are due to a lack of experience in sports has been disproved (Sutton & Bullock, 2013). Instead, unique anatomical factors in females, such as a greater Q angle, smaller ACL size, narrower intercondylar notch, and increased medial posterior tibial slope (PTS) are among the potential static contributors to their higher injury rates (Sutton & Bullock, 2013). Biomechanicaly, women tend to land with less knee and hip flexion compared to men (Hewett, et al., 2005; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004). Although this is not the only biomechanical risk factor in ACL injury, greater lower limb joint flexion promotes softer landings, reduces ground reaction forces, enhances energy absorption by muscles and lowers stress on the ACL (McCurdy, et al., 2012). Our findings indicate that strength training effectively increases knee flexion during landing, supporting its potential for mitigating ACL injury risk.

Considering the increase in knee flexion in our meta-analysis, the next question is how this change relates to an increase in quadriceps force for impact absorption during DPV and its potential for lowering the risk of an ACL injury. However, on a broader scale, hip flexion did not change significantly, with the examined subjects maintaining an upright landing posture—a position already associated with higher ground reaction force and increased quadriceps electromyographic activity and elevated risk factor of ACL injury (Blackburn

& Padua, 2009). These findings suggest that the load on the ACL is unlikely to have changed significantly following strength training.

The main finding of this study is that one of the most serious and common sports injuries remains not only understudied but also characterized by sparse and inconsistent literature, highlighting how little is known about such an important topic. This systematic review exposed the limited number and the methodological fragility of studies investigating strength training aiming to prevent ACL injuries. The diversity of biomechanical parameters analyzed in the included articles allowed us to do the meta-analysis of only three of them. While the number of studies is small, the moderate heterogeneity and high quality of these studies point to strength training as a promising tool in ACL injury prevention.

Based on these results, strength training should be further investigated as a contributor to reducing the risk of ACL injury, a present, harmful and costly issue for athletes. Articles published in peer-reviewed journals have demonstrated favorable results of strength training lowering the ACL injury risk but significant differences among experimental designs, volume and intensity of interventions, population and outcomes do not allow a better understanding on how strengthening influences landing mechanics, reduces knee overload, and decreases the risk of these injuries.

Evaluating sports programs in scientific studies presents several challenges due to the complexity and variability inherent to sports settings. Firstly, sports environments are dynamic, with multiple factors such as team dynamics, individual performance, and coaching strategies influencing outcomes, making it difficult to isolate the effects of a specific program. Secondly, adherence and compliance to intervention protocols can vary widely among athletes and teams, impacting the consistency and reliability of the data collected.

Another significant challenge is that sports clubs often have their own agendas and pre-established training programs. These programs are meticulously planned to optimize performance, leaving little room for external modifications or experimental interventions. This lack of receptiveness to changes in their schedules and methods can hinder the implementation of scientifically designed programs within real-world settings.

We suggest that future studies should analyze more ACL injury-related movements in a more standardized way, i.e., using comparable biomechanical outcomes, as well as training interventions of comparable intensity and volume. Biomechanical factors related to injury risk also deserve greater attention. Addressing these challenges requires innovative study designs (which may facilitate adherence and implementation in competitive teams), standardized evaluation frameworks (which will increase generalizability and study reproducibility), and collaboration between researchers, coaches, and sports organizations to bridge the gap between science and practice.

This systematic review and meta-analysis showed that strength training results in an increase in peak landing knee flexion angle during drop vertical jump, a change that can be seen as optimistic to lower ACL stress.

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