Factors influencing the Landing Error Scoring System: systematic review with meta-analysis

Abstract

Objectives: Systematically review the literature addressing age, sex, previous injury, and intervention program as influencing factors of the Landing Error Scoring System (LESS).

Design: Systematic review with meta-analysis.

Methods: Three databases (PubMed, Web of Science®, and Scopus®) were searched on 1 April 2020. Original studies using the LESS as primary outcome and exploring age, sex, previous injury, and intervention program were included, assessed for risk of bias, and critically appraised. Three meta-analyses were performed using one random and two mixed effect models with dependent variables: sex, previous injury and intervention program, respectively. Grading of Recommendations Assessment, Development and Evaluation (GRADE) was used to evaluate the strength of the evidence. PROSPERO registration number CRD42018107210.

Results: Fifty-two studies were included. Pooled data indicated that females have higher LESS scores than males ($p < 0.001$, mean difference = 0.6 error). Participants with previous Anterior Cruciate Ligament (ACL) injury have higher LESS scores than healthy controls ($p = 0.004$, mean difference 1.2 error). Neuromuscular training programs lasting a minimum of 6 weeks and other intervention programs decrease LESS scores ($p < 0.001$, mean difference 1.2 error and $p = 0.042$, mean difference 0.5 error, respectively). There is limited evidence suggesting that age may influence LESS scores in clinically meaningful manner. Overall, GRADE ratings suggest very low strength of evidence.

Conclusions: History of ACL injury and undertaking neuromuscular training for a minimum of 6 weeks meaningfully altered LESS scores. These findings, however, should be interpreted cautiously considering the very low GRADE rating of the evidence.

Keywords: Anterior Cruciate Ligament injuries; athletic injuries; soft tissue injuries; risk assessment; movement screen; jump-landing

1 Introduction

The Landing Error Scoring System (LESS) is an easy and convenient field-based testing method that examines the presence of biomechanical movement patterns previously linked to non-contact Anterior Cruciate Ligament (ACL) injury[1]. The LESS involves the performance of a double-leg jump-landing task and relies on the use of two standard video cameras, one placed to capture the motion from front view and other to capture the motion from side view. Clinicians evaluate the frontal and sagittal plane videos from the LESS and visually evaluate aberrant lower extremity and trunk kinematics between initial ground contact (IC) and peak knee flexion and note the number of "movement errors" observed. The LESS consists of 17 items. Movement items 1 to 15 are scored as 0 (error absent) and 1 (error present). The last two items (16 and 17) of the LESS are subjective in nature and assess the overall sagittal plane displacement and quality of landing which are scored from 0 to 2 errors. The minimum LESS score is 0 and the maximum score is hypothetically 19 errors. However, it is unlikely that an individual presents a wide and narrow stance or an internal and external rotation of the foot simultaneously. Consequently, the real maximum score is 17 errors. A higher score means a greater number of landing errors, poorer landing biomechanics, and greater risk of non-contact lower extremity injuries[1].

A recent systematic review of the literature concluded that the overall LESS score has good to excellent intrarater (intraclass correlation coefficient [ICC], 0.82 to 0.99), interrater (ICC, 0.83 to 0.92), and intersession (ICC, 0.81) reliability[2]. Validity of the overall LESS score against 3-dimensional (3D) jump-landing biomechanics was good when individuals were divided into four quartiles based on LESS scores, although the validity of the individual LESS items was item dependent[2]. Poor agreement (10% to 42%) between 3D motion data and LESS ratings was found for knee flexion at IC, lateral trunk flexion at IC, and symmetric foot contact at IC. The remaining LESS items showed moderate to excellent agreement (68% to 100%)[3]. Padua et al.[4] concluded from a prospective investigation that LESS scoring had a good sensitivity (86%) and acceptable specificity (64%) to identify risk of non-contact or indirect-contact ACL injury. More specifically, the relative risk of ACL injury was 10.7 times greater when LESS scores were ≥ 5 errors. However, Smith et al.[5] did not find any significant relationship between

LESS and primary ACL injury incidence in their case-control analysis. Based on the recent review[2], the predictive value of the LESS for non-contact ACL injury and other non-contact lower extremity injury incidence is unclear. The reasons for the conflicting results are likely due to under-powered sample sizes and differences in sampled populations in terms of age, proportion of females and males, and injury history[2]. All of these factors can potentially influence LESS scores and explain between study differences in findings.

Due to its clinical-friendly focus and minimal use of equipment, space, and time; the LESS lends itself well to movement screening initiatives involving a large number of athletes and is often used in practice and research[6-8]. Therefore, it is important to understand what factors might impact LESS scores for the proper interpretation of outcomes. To date, there has been no systematic evaluation of factors that can influence LESS scores. Therefore, the aim of this systematic review with meta-analysis was to systematically review the literature addressing age, sex, previous injury, and intervention program as influencing factors of the LESS. The results of this systematic review with meta-analysis may assist in establishing thresholds defining injury risk for different sexes, age groups and previous injuries and may guide prevention effort in intervention programs with highest impact on gross movement jump-landing biomechanics.

2 Methods

2.1 Protocol and registration

A systematic review with meta-analysis was undertaken and followed the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines[9]. Literature review methods and inclusion criteria were specified in advance, and prospectively registered with PROSPERO (CRD42018107210).

2.2 Eligibility criteria

Studies using the LESS as main outcome measure and reported age, sex, previous injury, or intervention program were included regardless of participants, intervention, or study design. Only original research (excluding case reports) in the English language published in peer-reviewed journals were considered.

Studies using modified versions of the original LESS (e.g., real-time LESS[10], iLESS[11], automated quantification of the LESS[12], or LESS with additional items[13]) were excluded.

2.3 Search strategy and study selection

Three electronic databases [PubMed (1950-), Web of Science® (1965-) and Scopus® (1970-)] were searched using the key words "Landing Error Scoring System". The final search was undertaken on 1st April 2020, by one reviewer (IH). Titles, abstracts, and full-texts were screened sequentially for inclusion and exclusion criteria. In case of uncertainty regarding inclusion, a second reviewer (KHL) was consulted. Reference lists of included articles were hand-searched for additional records. 2.4 Data collection process

Data concerning study design, population (number, sex, age, and activity level), LESS scores, statistical analysis, and results concerning LESS were extracted from articles using a standardized template by one reviewer (IH), with the completeness of extraction verified by a second reviewer (KHL). We contacted seven authors by email to request additional information from ten studies[1,5-7,14-19]. Two authors responded[17,19], with one author[19] providing additional data for one study.

2.5 Risk of bias within studies

Three validated risk of bias assessment tools: Newcastle – Ottawa Assessment Scale adapted for cross-sectional studies (NOS)[20], revised tool for Risk of Bias in randomized trials (RoB 2.0)[21], and Risk Of Bias in Non-randomized Studies - of Interventions (ROBINS-I)[22] were used. Two reviewers (IH and KHL) independently assessed the risk of bias of included studies. Prior to assessment, the two reviewers met to discuss and familiarise themselves with the scales. All identifiable information (i.e., authors, affiliations, countries, and sources of publication) were removed from articles by a third party to blind the two reviewers (IH and KHL) and reduce the assessment bias. The risk of bias for each study was assessed specifically for the LESS outcome score as recommended[23]. Disagreements in the risk of bias assessment scores were resolved by discussion between the reviewers. Consensus scores are presented in this review article.

The RoB 2 assessed the risk of bias across six domains through which bias can be introduced into the results of randomized controlled trials[21]. The ROBINS-I assessed the risk of bias across seven domains through which bias might be introduced into non-randomized interventional studies[22]. Both the RoB2 and ROBINS-I tools have been rigorously developed and recommended to assess the risk of bias in sport and exercise medicine[23]. The risk of bias in outcomes from the observational studies were assessed using the NOS as it is a suitable alternative to the ROBINS-I[24]. Using the NOS star system, a maximum of two stars for each numbered item can be allocated, with an overall maximum of 10 stars. Therefore, more star indicates superior methodological quality and lower risk of bias. Reviewers agreed to award the highest score in the statistical test section for the reporting of confidence intervals, quartiles, limits of agreement, or standard errors.

In addition, the level of evidence for each study was determined using the Oxford Centre for Evidence-Based Medicine 2011 table. The level of evidence ranges from 1 to 5, with 1 indicating the highest level of evidence and 5 the lowest. Study design was categorized according to Parab and Bhalerao[25]. Furthermore, the outcomes of the meta-analysis were evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) scale[26]. No study was excluded based on risk of bias assessment, level of evidence, or study design.

2.6 Data analysis and synthesis

Descriptive statistics were computed using Microsoft® Office Excel 2016 and expressed in terms of means and standard deviations (mean ± SD) weighted based on sample size, minimum to maximum ranges (min to max), percentages (%), and counts (*n*). Note that for interventional studies, LESS score pre-intervention was included in calculating and analyzing study characteristics. Hedge's *g* was calculated as a measure of effect size when data were reported in sufficient detail. Thresholds for interpreting the magnitude of the effect were: $g < 0.20$ for trivial, $0.20 \leq g < 0.50$ for small, $0.50 \leq g < 0.80$ for medium, and $g \geq 0.80$ for large[27].

Five or more studies are needed to achieve reasonable power from a random effect model meta-analysis[28]. Therefore, meta-analysis was attempted when at least five studies reported results in sufficient detail. Three meta-analyses were undertaken exploring sex, previous injury, and intervention program as potential influencing factors of LESS scores. Heterogeneity was explored statistically using Cochrane Q and quantified using I^2. The Q test has a low power in meta-analysis when studies have small sample sizes or are few in numbers[29]. Therefore, statistical significance for Cochrane Q was set to $p < 0.10$. The I^2 was interpreted according Higgins et al.[29], with 0% to 40% indicating "heterogeneity might not be important", 30% to 60% "moderate heterogeneity", 50% to 90% "substantial heterogeneity" and 75% to 100% "considerable heterogeneity". When meta-analysis had one moderator and heterogeneity was significant, a random effect model was used to account for both within-study and between-study variance. For meta-analysis with two moderators, a mixed effect model was used. Raw mean difference between scores with associated 95% confidence intervals [CI] were calculated for all meta-analyses. Statistical significance was set at $p \leq 0.05$, and clinical meaningfulness of differences in LESS score means was set at one error based on Padua et al.[1] who identified one error change in total LESS score to be associated with moderate to large differences in biomechanical variables previously linked to ACL injury. Meta-analysis calculations were undertaken in RStudio® Version 1.1.456 with R version 3.5.1 using the metafor package[30]. Note, that if meta-analysis was not possible due to small number of studies, a qualitative analysis was undertaken.

2.7 Risk of bias across studies

Funnel plots were constructed for every meta-analysis to assess publication bias. Egger's test (model of weighted regression with multiplicative dispersion) was performed on the random effect model for each meta-analysis to assess funnel plot asymmetry as suggests metafor package[30].

3 Results

3.1 Study selection

The systematic database search generated 252 hits related to the Landing Error Scoring System. Following the removal of duplicates, 114 studies remained. An additional 63 studies were removed following title (not original research n = 6), abstract (not original research n = 35; not in English language *n* =5), and full-text screen (modified version of the LESS *n* = 13; age, sex, previous injury, or intervention program not explored *n* = 4), with 1 article subsequently identified via hand searching of reference lists. Fifty-two studies met inclusion and were reviewed (Figure 1).

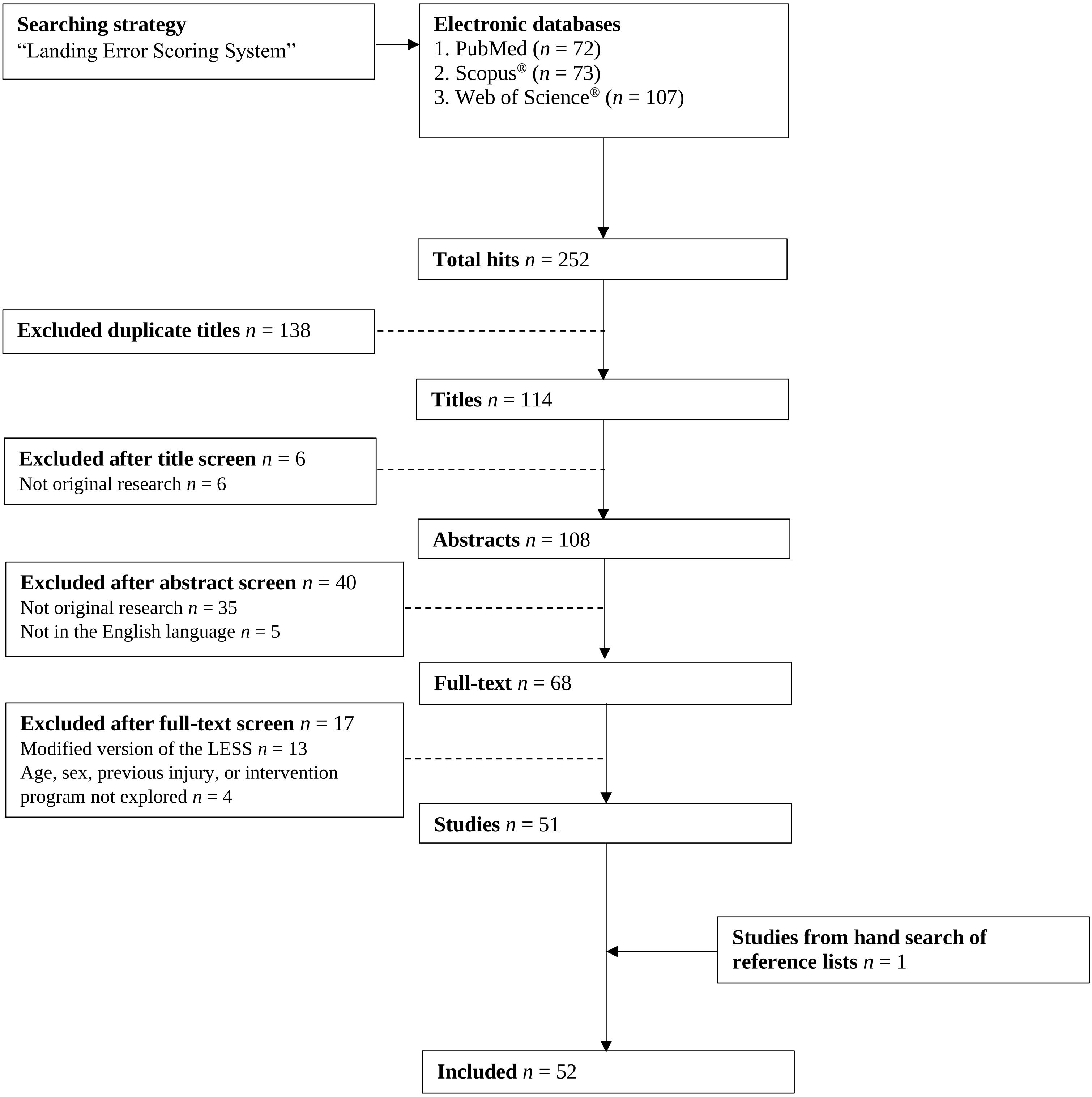


Figure 1. Flow chart of the search strategy and study selection process.

3.2 Study characteristics

All studies reported the number of participants tested with the LESS. The sample size ranged from 11[31] to 2,753[32] participants. A total of 11,672 participants were represented across the 52 studies. Four studies did not specify the activity levels of their cohorts[17,33-35]. All remaining studies (92%) tested individuals engaged in some level of physical activity (see Table 1). Sex distribution was described in 51 (98%) studies, totaling 6,925 males (59%) and 4,669 (40%) females, with the sex not reported for the remaining 78 participants (1%) in one study[36]. The mean age was reported in 46 (88%) studies (weighted mean: 16.2 ± 1.3 years), with the average ranging from 11[6] to 28[19] years.

The overall LESS score was reported in 47 (90%) studies. The calculated weighted mean for overall LESS score was 4.9 ± 1.7 errors using pre-intervention LESS scores for computations. The minimum reported mean LESS score for a group was 2.0[8] and maximum was 8.1[36] errors. Only four studies reported the range of individual LESS scores[18,19,37,38], with a minimum of 0.0[19,37] and maximum of 13.3[18] errors (average of three trials).

3.3 Risk of bias within studies

The NOS adapted for cross-sectional studies was used for 33 (64%) studies. Out of a maximum of 10 stars, 2 studies scored two stars[35,39], 4 studies four stars[40-43], 7 studies five stars[44-50], 10 studies six stars[1,18,32,37,38,51-55], 2 studies seven stars[56,57], 7 studies eight stars[4,5,19,33,58-60], and 1 study nine stars[6]. The RoB 2 was used for 9 (17%) studies. There was some concern regarding risk of bias in 3 studies[8,61,62], and a high risk of bias in the remaining 6 studies[7,14-16,36,63]. The ROBINS-I was used for 10 (19%) studies. Risk of bias was considered moderate in 4 of these studies[31,34,64,65] and serious in the remaining 6 studies[17,66-70]. The level of evidence ranged between 2 and 4 based on the Oxford Centre for Evidence-Based Medicine 2011 table. Studies were most often of level 3 (n = 30, 58%) and cross-sectional in design (n = 25, 48 %). Risk of bias scores, level of evidence, and study design of studies are presented in Appendix A. The risk of bias of the studies considered in examining each one of the influencing factors of the LESS is presented in Appendix B. Overall, GRADE ratings suggest that the strength of evidence in relation to LESS influential factors explored by meta-analysis is very low (Table 2).

3.4 Risk of bias across studies

The Egger's test for funnel plot asymmetry was not significant in any meta-analysis, suggesting that publication bias was not present (Appendix C). The *p*-values of Egger's test for meta-analysis exploring sex, previous injury, and intervention program were 0.757, 0.914, and 0.072, respectively.

3.5 Influencing factors

3.5.1 Age

Only Smith et al.[5] compared overall LESS scores between different age categories and reported significantly lower overall LESS scores in older college athletes compared to younger high school athletes. Seven studies[4,6,7,14,61,62,66] tested and reported overall LESS scores for 1,997 participants 15 years or younger; 17 studies[5,15,18,31,33,36,38,45,46,49,52,56,58,63,64,67,70] for 1,613 participants aged from 15 to 20 years inclusively; and 24 studies[8,17,19,32-35,37,39-44,47,48,51,55,57,59,60,65,67,68] for 4,566 participants older than 20 years. The weighted mean LESS scores for participants 15 years or younger was 6.1 ± 1.7, for participants aged from 15 to 20 years was 5.5 ± 1.9, and for participant older than 20 years was 5.1 ± 1.8 errors.

3.5.2 Sex

Fourteen studies compared LESS scores between males and females (Table 1). Six studies found females to have significantly higher overall LESS scores compared to males[1,32,40,46,52,56], six studies found no significant difference in overall scores between sexes[5,6,8,45,57,69], and the remaining two studies did not specify if the differences were significant[14,70]. Thirty studies reported overall LESS scores separately for males (n = 3294) and females (n = 1910), with resulting weighted mean scores for males of 5.0 ± 1.8 and 5.6 ± 1.7 errors for females.

Twelve studies testing 2,729 males and 1,656 females reported the results in sufficient detail for meta-analysis[5,8,14,32,40,45,46,52,56,57,69,70]. A random effect model was used given the significant and substantial heterogeneity (Q = 21.34, p = 0.030, I^2 = 66%, Figure 2A). Findings from the meta-analysis indicate statistically significant higher LESS scores in females than males ($p < 0.001$), but the mean difference of 0.6 [0.4, 0.8] errors was not clinically meaningful (i.e., less than 1 error, Figure 2A). The quality of evidence was very low according to the GRADE scale (Table 2).

3.5.3 Previous injury

Nine studies compared LESS scores between previously injured and control participants (Table 1). Five of these studies[4,17,33-35] reported significantly higher LESS scores for the previously injured groups compared with controls. The remaining four studies[5,18,45,55] reported no significant difference in scores between previously injured athletes compared with those with no injury history, as well as between athletes who suffered lower extremity injury during a season compared to those who remained injury free during the same season. Weighted mean LESS scores for all previously injured participants (n = 450) was 5.7 ± 2.3 errors. Weighted mean scores were 5.5 ± 2.3 for ACL injured or reconstructed (n = 338), 5.8 ± 2.4 for other types of injury (n = 110), and 4.4 ± 1.9 errors for uninjured controls (n = 100).

Eight studies were included in the meta-analysis exploring the difference in LESS scores between previously injured and uninjured participants[4,5,18,33-35,45,55], with two studies exploring two subgroups of injuries[18,45]. The meta-analysis compared the difference in LESS scores from 208 previously injured participants (98 ACL and 110 other injuries) and 1,692 uninjured controls. Given the presence of significant ($Q = 16.95$, $p = 0.031$, Figure 2B) moderate ($I^2 = 54\%$, Figure 2B) heterogeneity and two moderators (study-level variables: ACL and other injury), a mixed effect model was used to examine to what extent the type of injury (moderator) influenced the size of the average true effect. The results indicate that participants with a previous ACL injury have statistically significant higher LESS scores ($p = 0.004$), with a clinically meaningful mean difference of 1.2 [0.4, 2.0] errors. LESS scores of participants with other types of previous injury are similar to those of uninjured controls ($p = 0.441$), Figure 2B. The quality of evidence was very low according to the GRADE criteria (Table 2).A total of 14 studies explored the influence of intervention programs on LESS (Table 1). The explored interventions included diverse injury prevention, isolated resistance training, weight training, military movement course, aquatic training, static warm up, dynamic warm up, standard warm up, and internal, external, and video instruction programs.

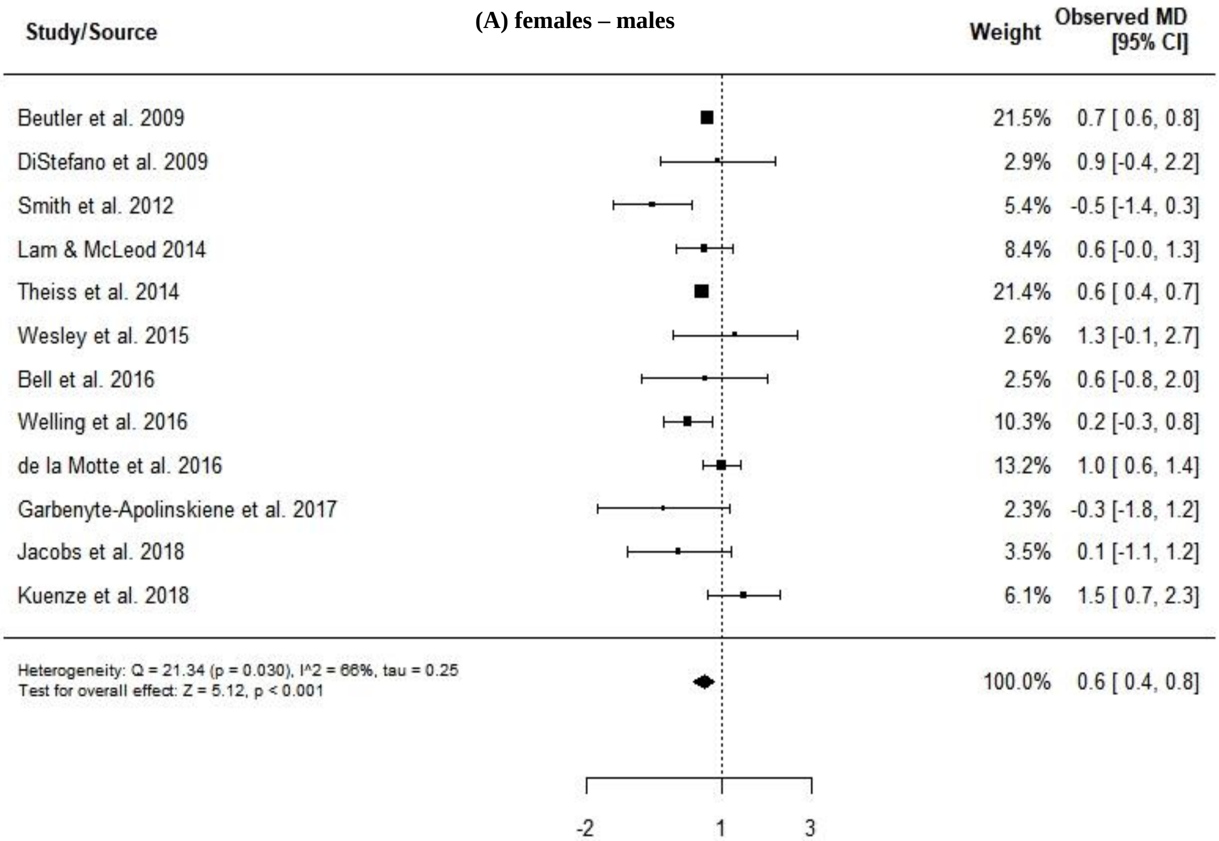
3.5.4 Intervention program

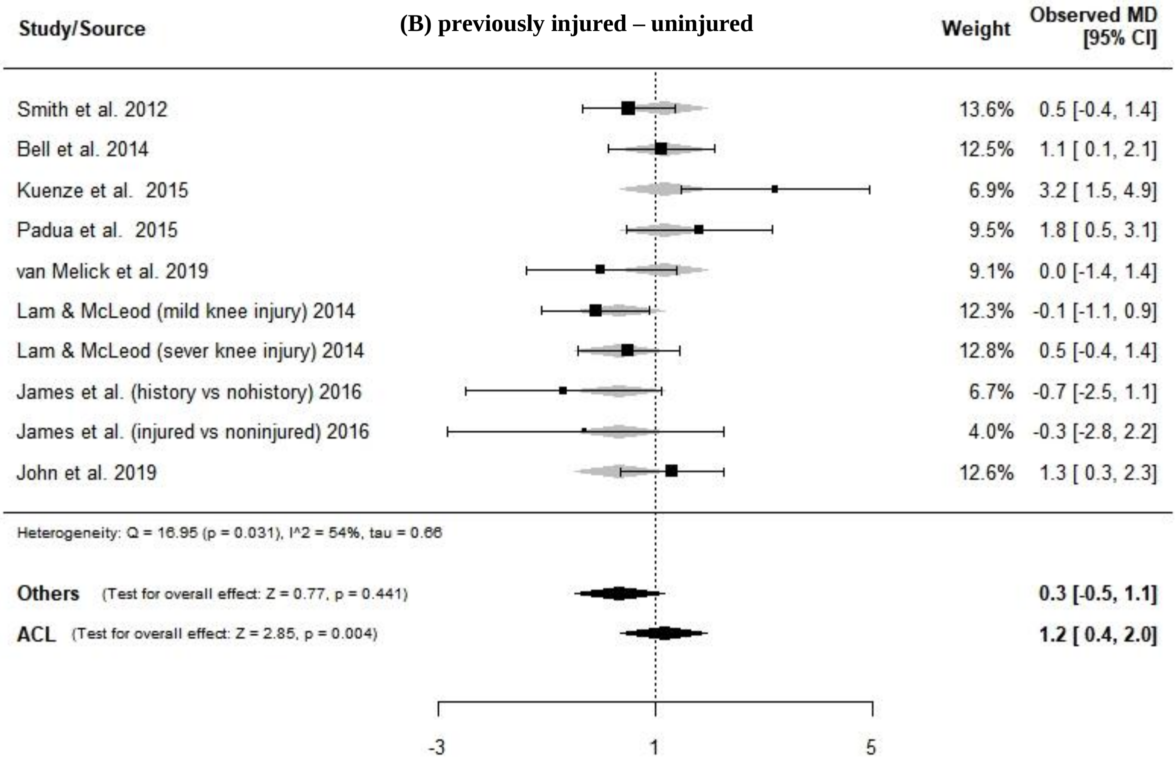
External focus and video instructions had significantly greater potential in decreasing LESS scores compared to internal focus instructions[8]. Two studies found that participants with poor landing technique improved the most with training[14,61]. Pryor et al.[7] showed that preventive training programs had a beneficial effect on decreasing LESS scores regardless of coaches and players previous experience with programs.

Four studies examined the persistence of LESS score improvements following intervention programs[16,31,65,66]. DiStefano et al.[16] reported that even when training programs improved LESS scores, changes were no longer apparent 6 months post-intervention cessation. Padua et al.[66] compared programs of 3 to 9 months in duration and found that improved scores remained 3 months post-intervention only in the 9-month group. Oppositely, a 6-week neuromuscular training program improved LESS scores, and improvements were sustained 4[65] and 9 months[31] post intervention cessation.

Thirteen studies involving 927 participants and 19 different interventions were included in the meta-analysis exploring the effect of intervention program on LESS scores by comparing differences between pre-intervention and post-intervention scores[7,8,14,15,31,36,61-63,65-67,70]. Note that LESS scores recorded several months post-intervention were not included into the meta-analysis to focus on the more immediate effects of training. Of the participants, 803 completed neuromuscular training programs with a minimum duration of 6 weeks and 124 completed "other" intervention programs. The 6-week threshold for neuromuscular training programs was selected as evidenced to reduce ACL injury rates[71]. Given the presence of significant (Q = 49.50, p < 0.001, Figure 2C) moderate (I^2 = 53%, Figure 2C) heterogeneity and two moderators (study-level variables: neuromuscular and other intervention program), a mixed effect model was used to determine to what extent the type of intervention program (moderator) influenced the size of the average true effect. Meta-analysis indicated that neuromuscular training programs with minimal duration of 6 weeks significantly and meaningfully decreased LESS scores by 1.2 [0.9, 1.5] error ($p < 0.001$). The "other" training programs significantly improved LESS scores from a statistical perspective ($p = 0.042$), however the 0.5 [0.0, 0.9] error difference was not clinically meaningful, Figure 2C. The quality of evidence was very low according the GRADE criteria (Table 2).

(A) females – males




Study/Source
(B) previously injured – uninjured
Weight
Observed MD [95% CI]
Smith et al. 2012 13.6% 0.5 [-0.4, 1.4]
Bell et al. 2014 12.5% 1.1 [0.1, 2.1]
Kuenze et al. 2015 6.9% 3.2 [1.5, 4.9]
Padua et al. 2015 9.5% 1.8 [0.5, 3.1]
van Melick et al. 2019 9.1% 0.0 [-1.4, 1.4]
Lam & McLeod (mild knee injury) 2014 12.3% -0.1 [-1.1, 0.9]
Lam & McLeod (sever knee injury) 2014 12.8% 0.5 [-0.4, 1.4]
James et al. (history vs nohistory) 2016 6.7% -0.7 [-2.5, 1.1]
James et al. (injured vs noninjured) 2016 4.0% -0.3 [-2.8, 2.2]
John et al. 2019 12.6% 1.3 [0.3, 2.3]
Heterogeneity: Q = 16.95 (p = 0.031), I^2 = 54%, tau = 0.66
Others (Test for overall effect: Z = 0.77, p = 0.441) 0.3 [-0.5, 1.1]
ACL (Test for overall effect: Z = 2.85, p = 0.004) 1.2 [0.4, 2.0]
-3
1
5

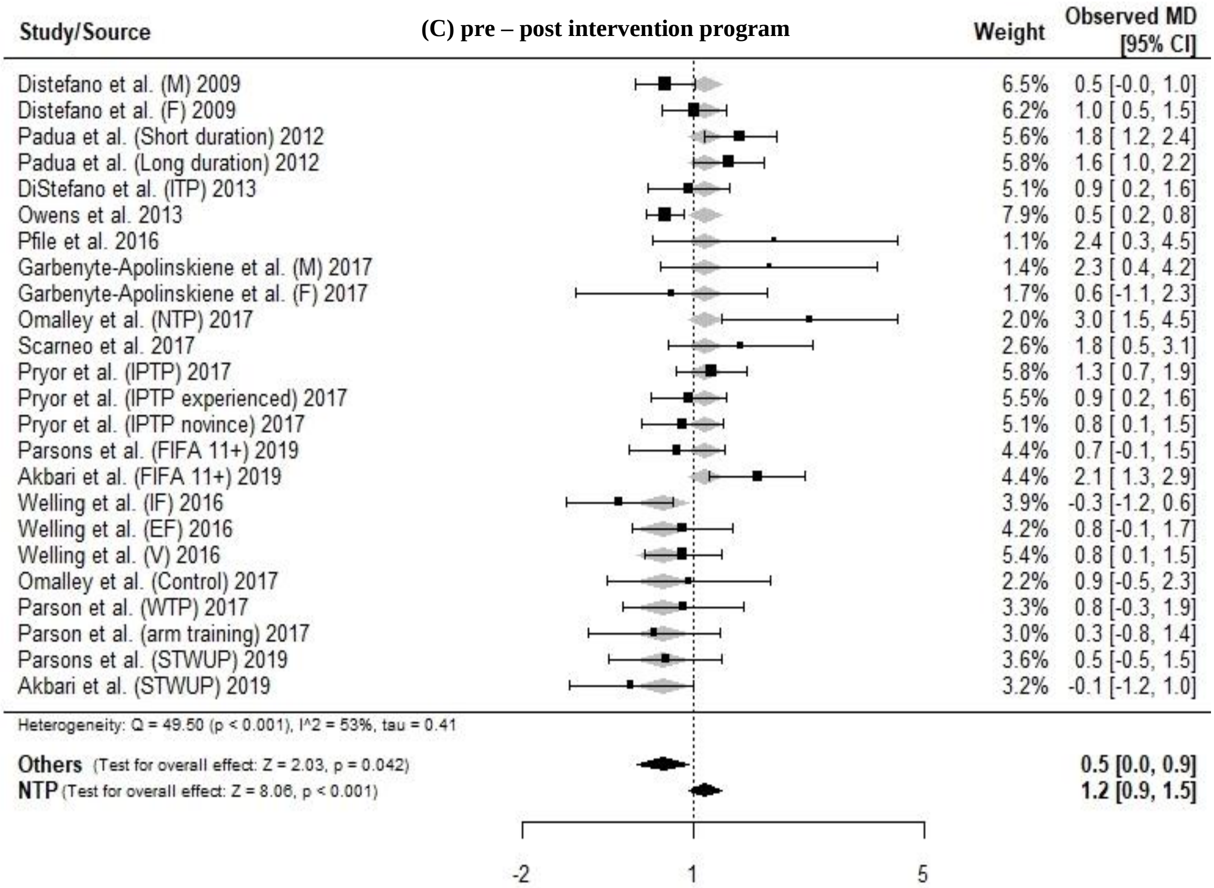

Study/Source
(C) pre – post intervention program
Weight
Observed MD [95% CI]
Distefano et al. (M) 2009 6.5% 0.5 [-0.0, 1.0]
Distefano et al. (F) 2009 6.2% 1.0 [0.5, 1.5]
Padua et al. (Short duration) 2012 5.6% 1.8 [1.2, 2.4]
Padua et al. (Long duration) 2012 5.8% 1.6 [1.0, 2.2]
DiStefano et al. (ITP) 2013 5.1% 0.9 [0.2, 1.6]
Owens et al. 2013 7.9% 0.5 [0.2, 0.8]
Pfile et al. 2016 1.1% 2.4 [0.3, 4.5]
Garbenyte-Apolinskiene et al. (M) 2017 1.4% 2.3 [0.4, 4.2]
Garbenyte-Apolinskiene et al. (F) 2017 1.7% 0.6 [-1.1, 2.3]
Omalley et al. (NTP) 2017 2.0% 3.0 [1.5, 4.5]
Scarneo et al. 2017 2.6% 1.8 [0.5, 3.1]
Pryor et al. (IPTP) 2017 5.8% 1.3 [0.7, 1.9]
Pryor et al. (IPTP experienced) 2017 5.5% 0.9 [0.2, 1.6]
Pryor et al. (IPTP novince) 2017 5.1% 0.8 [0.1, 1.5]
Parsons et al. (FIFA 11+) 2019 4.4% 0.7 [-0.1, 1.5]
Akbari et al. (FIFA 11+) 2019 4.4% 2.1 [1.3, 2.9]
Welling et al. (IF) 2016 3.9% -0.3 [-1.2, 0.6]
Welling et al. (EF) 2016 4.2% 0.8 [-0.1, 1.7]
Welling et al. (V) 2016 5.4% 0.8 [0.1, 1.5]
Omalley et al. (Control) 2017 2.2% 0.9 [-0.5, 2.3]
Parson et al. (WTP) 2017 3.3% 0.8 [-0.3, 1.9]
Parson et al. (arm training) 2017 3.0% 0.3 [-0.8, 1.4]
Parsons et al. (STWUP) 2019 3.6% 0.5 [-0.5, 1.5]
Akbari et al. (STWUP) 2019 3.2% -0.1 [-1.2, 1.0]
Heterogeneity: Q = 49.50 (p < 0.001), I^2 = 53%, tau = 0.41
Others (Test for overall effect: Z = 2.03, p = 0.042) 0.5 [0.0, 0.9]
NTP (Test for overall effect: Z = 8.06, p < 0.001) 1.2 [0.9, 1.5]
-2
1
5

Figure 2. Forest plots comparing mean difference (MD) in Landing Error Scoring System scores between (A) sexes (females – males), (B) previously injured and uninjured individuals (previously injured – uninjured), and (C) pre and post intervention programs (pre – post).

Abbreviations: ACL, Anterior Cruciate Ligament injury; CI, Confidential Intervals; EF, external focus instruction; F, females; FIFA, Federation International de Football Association IF, internal focus instruction; IPTP, injury prevention training program; ITP, integrated training program; M, males; NTP, neuromuscular training program; *Q*, Cochrane *Q*; STWUP, standard warm up; V, video instruction; WTP, weight training program.

Cochrane *Q* statistical significance set at $p < 0.10$; statistical significance for overall effect set at $p \leq 0.05$; clinical meaningful effect threshold set at one error. Shaded diamonds in the background represent the two moderators.

Table 1. Summary of studies (by year) comparing the influence of sex, previous injury, and training program on Landing Error Scoring System scores.

Sex						
Study (year)	**Sample size (*n*)**	**Population**	**Age (years)[a]**	**LESS score (errors)[a]**	**Hedge's g**	**Comparison M vs F**
Beutler et al. (2009)[32]	Total: 2753 M: 1707, F: 1046	Cadets of US military	18 – 24	M: 4.7 ± 1.7 F: 5.3 ± 1.5	0.37	$p < 0.001$
Padua et al. (2009)[1]	Total: 2691 M: 1655, F: 1036	US military freshmen	Not specified	Not specified		Females higher scores than males $p < 0.001$
DiStefano et al. (2009)[14]	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	M: 4.4 ± 1.7 F: 5.8 ± 1.9	0.78	Not specified
Smith et al. (2012)[5]	Total: 92 M: 29, F: 63	College and high school athletes	M: 18.5 ± 2.5 F: 18.0 ± 1.7	M: 5.5 ± 2.1[b] F: 5.0 ± 1.9[b]	0.26	Non-significant $p = 0.22$
Lam & McLeod (2014)[45]	Total: 215 M: 116, F: 99	Athletes competing in interscholastic sports	M: 19.4 ± 1.5 F: 19.1 ± 1.1	M: 5.1 ± 2.5 F: 5.8 ± 2.3	0.29	Non-significant $p > 0.05$
Theiss et al. (2014)[46]	Total: 277 M: 222, F: 55	Cadets of US military	19.3 ± 0.8	M: 5.1 ± 0.2[b] F: 5.6 ± 0.5[b]	1.75	$p = 0.05$
Wesley et al. (2015)[56]	Total: 36 M: 18, F: 18	Athletes	M: 19.4 ± 1.4 F: 19.2 ± 0.9	M: 5.0 ± 2.3 F: 6.3 ± 1.9	0.70	$p \leq 0.05$
Bell et al. (2016)[69]	Total: 39 M: 20, F: 19	Recreationally active population	M: 20.9 ± 1.2 F: 21.2 ± 1.4	M: 4.7 ± 2.3 F: 5.3 ± 2.1	0.27	Non-significant $p = 0.56$

Welling et al. (2016)[8]	Total: 40 M: 20, F:20	Ball team sport athletes	22.50 ± 1.62	M: 2.8 ± 1.0 [b] F: 3.1 ± 0.7 [b]	0.35	Non-significant *p* > 0.05
de la Motte (2016)[40]	Total: 521 M: 431, F: 90	Military applicants entering US army	M: 20.8 ± 3.0 F: 20.9 ± 3.2	M: 5.5 ± 2.1 F: 6.5 ± 1.8	0.49	*p* < 0.001
Garbenytė-Apolinskienė et al. (2018)[70]	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	M: 6.9 ± 2.3 F: 6.6 ± 1.8	0.13	Not specified
DiStefano et al. (2018)[6]	Total: 355 M: 122, F: 233	Soccer and basketball players	11.0 ± 2.0	Not specified	Not specified	Non-significant *p* > 0.05
Jacobs et al. (2018)[57]	Total: 40 M: 20, F: 20	Recreationally active population	M: 24.4 ± 1.8 F: 23.4 ± 2.8	M: 5.1 ± 2.2 F: 5.1 ± 1.5	0.01	Non-significant *p* = 0.624
Kuenze et al. (2018)[52]	Total: 168 M: 41, F: 127	Participants after ACL reconstruction	M: 20 (median) F: 19 (median)	M: 4.6 ± 2.3 F: 6.1 ± 2.3	0.65	*p* < 0.001

Previous injury

Study (year)	Sample size (*n*)	Population	Age (years)[a]	LESS score (errors)[a]	Hedge's g	Comparison injured vs uninjured
Smith et al. (2012)[5]	Total: 92 ACL: 28 Control: 64	College and high school athletes	18.3 ± 2.0	ACL: 5.5 ± 1.9 Control: 5.0 ±2.0	0.25	*p* = 0.32
Lam & McLeod (2014)[45]	Total: 215; Mild knee injury (MI): 31; Severe knee injury (SI): 36; No knee injury (control): 148	Athletes competing in interscholastic sports	19.3 ± 1.4[b]	MI: 5.3 ± 2.6 SI: 5.9 ± 2.6 Control: 5.4 ± 2.4	MI vs Control 0.04 SI vs Control 0.20	Non-significant

Bell et al. (2014)[33]	Total: 54 ACLR: 27 Control: 27	Not specified	ACLR: 19.9 ± 1.7 Control: 20.5 ± 1.6	ACLR: 6.7 ± 2.1 Control: 5.6 ± 1.5	0.60	$p = 0.04$
Gokeler et al. (2014)[17]	Total: 20 ACLR: 10 Control: 10	Not specified	ACLR: 27.4 ± 9.6 Control: 21.0 ± 0.8	ACLR: 6.5 Control: 2.5 (median)		Not specified
Kuenze et al. (2015)[34]	Total: 46 ACLR: 22 Control: 24	Not specified	ACLR: 22.5 ± 5.0 Control: 21.7 ± 3.6	ACLR: 6.0 ± 3.6 Control: 2.8 ± 2.2	1.08	$p = 0.002$
Padua et al. (2015)[4]	Total: 1217 ACL: 7 Control: 1210	Soccer players	ACL: 14.9 ± 0.70 Control: 13.9 ± 1.8	ACL: 6.2 ± 1.8 Control: 4.4 ± 1.7	1.06	$p < 0.005$
James et al. (2016)[18]	Total: 34 History of injury (HI): 13 No history of injury (NHI): 21 Injured during study (IDS): 10 Never injured (NI): 11	NCAA division I soccer players	HI: 19.7 ± 1.2 NHI: 19.6 ± 1.3 IDS: 19.6 ± 1.2 NI: 19.6 ± 1.4	HI 4.9 ± 2.4 NHI: 5.6 ± 2.9 IDS 5.5 ± 2.5 NI: 5.8 ± 3.4	HI vs NHI 0.26 IDS vs NI 0.10	HI vs NHI $p = 0.50$ IDS vs NI $p = 0.83$
van Melick et al. (2019)[55]	Total: 33 ACLR: 14 Control: 19	Recreational soccer players	ACLR: 23.2 ± 3.6 Control: 21.3 ± 3.0	ACLR: 4.0 ± 2.0 Control: 4.0 ± 2.0	0.00	Non-significant
John et al. (2019)[35]	Total: 40 CAI: 20 Control: 20	Students	CAI: 23.3 ± 3.3 Control: 25.5 ± 3.4	CAI: 7.4 ± 1.6 Control: 6.1 ± 1.5	0.80	$p = 0.010$

Training program

Study (year)	Sample size (*n*)	Population	Age (years)[a]	Intervention	Duration	Test times	LESS score (errors)[a]	Hedge's g	Comparison between groups

DiStefano et al. (2009)[14]	Total: 173 M: 90, F: 83	Soccer players	13.0 ± 2.0	Stratified and generalized injury prevention TP	10-15 minutes, 3-4 times/week for 3 months	Pre TP Post TP	Males Pre: 4.4 ± 1.7 Post: 3.9 ± 1.8 Females Pre: 5.8 ± 1.9 Post: 4.8 ± 1.7	Males 0.29 Females 0.55	Males vs Females $p = 0.35$
Padua et al. (2012)[66]	Total: 84 M: 20, F: 64 Short duration: 33 Long duration: 51	Soccer players	14.0 ± 2.0	Injury prevention TP short duration (3 months) vs Injury prevention TP long duration (9 months)	10-15 minutes, 3-4 times/week for 3 or 9 months	Pre TP Post TP 3months post TP	Short TP Pre: 5.2 ± 1.5 Post: 3.4 ± 1.1 3 months post: 4.7 ± 1.6 Long TP Pre: 5.7 ± 1.7 Post: 4.1 ± 1.4 3 months post: 4.2 ± 1.3	Short TP pre vs post 1.37 pre vs 3 months post 0.32 Long TP pre vs post 1.03 pre vs 3 months post 0.99	Short and long TP significantly lower scores pre vs post Long TP significantly lower scores 3 months post $p < 0.05$
DiStefano et al. (2013a)[15]	Total: 30 M: 25, F: 5 IRTP: 15 ITP: 15	Participants of weight training course	19.0 ± 1.0	Isolated resistance TP (IRTP) vs Integrated TP (ITP)	45 minutes, 2 times/week for 8 weeks	Pre TP Post TP	IRTP Not specify ITP Pre: 3.9 ± 1.0 Post: 3.0 ± 1.0	ITP 0.9	ITP Pre vs post $p = 0.02$

Owens et al. (2013)[67]	Total: 273 M: 158, F: 115	Participants of Military Movement course	17 to 25	Military movement course (MMC)	19 sessions of 50 minutes (8 weeks)	Pre MMC Post MMC	Pre MMC: 5.0 ± 1.8 Post MMC: 4.5 ± 2.0	0.26	Pre vs post $p < 0.001$
DiStefano et al. (2016)[16]	Total: 1104 M: 928, F: 176	US military freshmen	17 to 22	Standard warm up vs Dynamic integrated movement enhancement injury prevention TP	10-12 minutes, 2-3 times/week for 6 weeks	Pre TP Post TP 2, 4, 6, 8, months post TP	Not specified		Non-significant group differences in scores at all time point
Pfile et al. (2016)[31]	Total: 11 M: 0, F: 11	Division I basketball players	19.4 ± 1.4	Plyometrics and neuromuscular control TP	18 sessions of 30 min in 6 weeks	Pre TP Post TP 9 months post TP	Pre: 7.3 ± 3.4 Post: 4.9 ± 1.2 9 months post: 5.4 ± 1.8	Pre vs post 0.94 Pre vs 9 months post 0.70	Pre vs post $p = 0.024$ Pre vs 9 months post $p = 0.030$
Welling et al. (2016)[8]	Total: 40 M: 20, F: 20 IF: 10, EF: 10, V: 10, C: 10	Ball team sport athletes	22.5 ± 1.6	4 groups: Internal focus instruction (IF). External focus instruction (EF). Video instruction (V) and Control (C)	1 session	Pre TP Post TP 1 week (1W) post TP	IF Pre: 2.9 ± 1.0 Post: 3.2 ± 1.1 1W post: 3.1 ± 1.5 EF Pre: 3.1 ± 1.0 Post: 2.3 ± 1.0 1W post: 2.3 ± 0.5 V Pre: 2.8 ± 0.9 Post: 2.0 ± 0.6 1W post: 2.0 ± 0.6	IF pre vs post 0.29 IF pre vs 1W post 0.16 EF pre vs post 0.8 EF pre vs 1W post 1.01 V pre vs post 1.05 V pre vs 1W post 1.05	Males in V group Pre vs post $p < 0.05$ Pre vs 1W post $p < 0.05$ Female in V and EF group Pre vs post $p < 0.05$ Pre vs 1W post $p < 0.05$

							C Pre: 3.0 ± 0.6 Post: 3.1 ± 0.7 1W post: 2.9 ± 0.5	C pre vs post 0.15 C pre vs 1W post 0.18	
Garbenytė-Apolinskienė et al. (2018)[70]	Total: 31 M: 15, F: 16	Basketball players	15.4 ± 0.3[b]	Integrated exercise TP	Individual dosage, 5 times/week for 5 months	Pre TP Post TP	Males Pre: 6.9 ± 2.3 Post: 4.6 ± 2.9 Females Pre: 6.6 ± 1.8 Post: 6.0 ±2.9	Males 0.88 Females 0.25	Males pre vs post $p = 0.001$ Females pre vs post Non-significant
O´Malley et al. (2017)[36]	Total: 78 NTP: 41 Control: 37	Gaelic footballers and hurling athletes	18.5	Neuromuscular TP (NTP) vs Usual team training (Control)	15 minutes, 2 times/week for 8 weeks	Pre TP Post TP	NTP Pre: 7.1 ± 3.8 Post: 4.1 ± 3.2 Control Pre: 8.1 ± 3.3 Post: 7.2 ± 2.9	NTP 0.89 Control 0.29	NTP vs control $p < 0.001$
Parson et al. (2017)[61]	Total: 36 M: 0, F: 36 WTP: 19, Control: 17	Athletes	12.3 ± 1.4	Weight TP (WTP) vs Control (arm training)	60 minutes, 2 times/week for 12 weeks	Pre TP Post TP	WTP Pre: 6.8 ± 1.5 Post: 6.0 ± 1.8 Control Pre: 6.4 ± 1.6 Post: 6.1 ± 1.8	WTP 0.48 Control 0.18	WTP vs control Not-significant $p = 0.85$
Scarneo et al. (2017)[65]	Total: 15 M: 0, F: 15	Active population with real time LESS > 4	21.0 ± 2.0	Aquatic neuromuscular TP	7-10 minutes 3 times/week for 6 weeks	Pre TP Post TP 4 months post TP	Pre: 6.3 ± 1.8 Post: 4.5 ± 1.7 4 months post: 4.2 ± 1.7	Pre vs post 1.03 Pre vs 4 months post 1.20	Pre vs post $p < 0.01$ Pre vs 4 months post $p < 0.01$

Pryor et al. (2017)[7]	Total: 89 M: 41, F: 48 IPTP (experienced): 43 Control (novice): 46	Soccer players	8 to 14	2 stages: Stage 1: Injury prevention IP (IPTP) vs Control Stage 2: group with experience of IPTP vs novice group without experience of IPTP	10-12 minutes 3 times/week for 8 weeks	Pre TP Post TP	Stage 1: IPTP Pre: 6.2 ± 1.0 Post: 4.9 ±1.8 Stage 2: Experienced group Pre: 5.9 ± 1.6 Post: 5.0 ±1.5 Novice group Pre: 6.1 ± 1.6 Post: 5.3 ± 1.9	Stage 1: 1.02 Stage 2: Experienced 0.58 Novice 0.46	Stage 1: IPTP Pre vs post *p* = 0.01 Stage 2: Experienced Pre vs post *p* < 0.01 Novice Pre vs post *p* < 0.01
Parsons et al. (2019)[62]	Total: 43 M: 0, F: 43 FIFA 11+: 29, Standard warm up: 18	Soccer players	11.1	FIFA 11+ vs standard warm up	10-30 minutes 2 times/week for 5 months	Pre TP Post TP	FIFA 11+ Pre: 6.9 ± 1.6 Post: 6.2 ± 1.6 Warm up Pre: 6.6 ± 1.7 Post: 6.1 ± 1.3	FIFA 11+ 0.42 Warm up 0.31	FIFA 11+ vs Warm up *p* = 0.66
Akbari et al. (2019)[63]	Total: 24 M: 24, F: 0 FIFA 11+: 12, Standard warm up: 12	Elite soccer players	16.8 ± 1.2	FIFA 11+ vs standard warm up	20-25 minutes 3tiems/week for 8 weeks	Pre TP Post TP	FIFA 11+ Pre: 4.4 ± 0.7 Post: 2.3 ± 1.3 Warm up	FIFA 11+ 1.86 Warm up 0.07	FIFA 11+ vs Warm up *p* < 0.001

Pre: 4.6 ± 1.3

Post: 4.7 ± 1.4

Abbreviations: ACL, Anterior Cruciate Ligament; ACLR, Anterior Cruciate Ligament reconstruction; CAI, Chronic ankle instability; F, females; FIFA, Federation International de Football Association, LESS, Landing Error Scoring System; M, males; NCAA, National Collegiate Athletic Association; TP, training program; US, United States.
[a]Mean ± standard deviation values for age (years) and LESS score (errors).
[b]Mean ± standard deviation values weighted based on sample size.

Table 2. Summary of findings regarding influencing factors (sex, previous injury, intervention program) of the Landing Error Scoring System (LESS).

Outcome	**Certainty assessment**						**Summary of findings**		
	Studies (*n*)	**Study design**	**Risk of bias**	**Indirectness**	**Imprecision**	**Publication bias**	**Participants included in meta-analysis (*n*)**	**Results**	**Quality of the evidence (GRADE)**
Sex	12	Observational, randomized and non-randomized interventional studies	Very serious[1]	Serious[2]	Serious[3]	Undetected	Males: 2,729 Females: 1,656	▪Females 0.6 errors higher LESS scores than males	⊕○○○ Very low
Previous injury	8	Observational and non-randomized interventional studies	Very serious[1,4]	Serious[2,5]	Serious[6]	Undetected	Previously injured: 208 Uninjured: 1,692	▪ Participants with ACL injury had 1.2 errors higher LESS scores than uninjured controls ▪ Participants with other types of injury had 0.3 error higher LESS scores than control	⊕○○○ Very low
Intervention program	13	Randomized and non-randomized interventional studies	Serious[7]	Serious[2,8]	Not serious	Undetected	927	▪Compare to pre-preintervention, LESS score post-intervention decreased by 1.2 error for NTP and by 0.5 errors for other interventions	⊕○○○ Very low

Abbreviations: ACL, Anterior Cruciate Ligament; GRADE, Grading of Recommendations Assessment, Development and Evaluation; NTP, neuromuscular training program with minimal duration of 6 weeks.

[1] At least a half of observational studies did not justify sample size, describe response rate, blind assessment of outcome, and did not use appropriate statistical tests. At least a half of interventional studies had high or moderate risk of bias due confounding and in selection of the reported results (see Appendix B).

[2] The heterogeneity may be explained by the varying risk of bias of included studies, different age groups, and population (athletes participating in different sports and different sport levels) explored in the meta-analysis.

[3] Differences in age (pre versus post pubertal) in included studies may seriously affect the results of the meta-analysis.

[4] All observational studies had poor representativeness of the sample and a half of interventional studies had the high risk of bias due to missing data (see Appendix B).

[5] The heterogeneity may be explained by different types of injuries included in the meta-analysis.

[6] Participants with contact injuries were included into the meta-analysis.

[7] Majority of studies (n = 8) had high or moderate risk of bias due deviations from the intended intervention (adhering to intervention). Five studies had high or moderate risk of bias in selection of the reported results (see Appendix B).

[8] The heterogeneity may be explained by different intervention programs with varying duration included into the meta-analysis.

4 Discussion

4.1 Influencing factors

4.1.1 Age

A single study[5] compared overall LESS scores between younger high school and older college athletes, and found significantly better overall scores in the older athletes. When weighted means of LESS scores were calculated for three age groups (under 15, 15 to 20, and over 21 years), scores were seen to decrease with age. Padua et al.[4] stated that the natural decrease in LESS scores in older athletes could be an effect of maturation or selection in competitive sports that might limit the ability of LESS to predict ACL injury in older athletes. Smith et al.[5] who tested older participants (18.3 ± 2.0 years) compared to Padua et al.[4] (13.9 ± 1.8 years) did not find any predictive values for ACL injury incidence whereas Padua and colleagues[4] identified 5 errors as optimal cut point for distinguishing between athletes with low and high risk. There is strong evidence showing that females have higher risk of non-contact ACL injury compared to males[72]. However, there is no strong evidence of this sex difference in injury rate in prepubertal females[73]. Age also significantly influences the effectiveness of ACL injury prevention neuromuscular programs in females with greater knee injury reduction in those under 18 years compared to older[73]. These findings indicate that age is an important injury risk factor. More evidence is needed to conclude whether age influences LESS score and whether the same threshold is suitable to identify athletes at high risk of injury across different age categories.

4.1.2 Sex

It is well documented that on average, females have a four to six times higher incidence of knee injury than males participating in the same sport[72]. Specifically, the risk of non-contact ACL injury is more than double for females compared to males[72]. Several theories have emerged to explain these sex differences in injury rates that include sex-specific hormonal, anatomical, and neuromuscular abilities differences[74]. Despite hormonal involvement in injury incidence being a topic of considerable scientific interest, the overall strength of evidence for hormonal involvement in injury incidence remains still low[75]. Anatomical measures often do not correlate with dynamic injury mechanisms and are difficult to modify[74]. The higher incidence of knee injury seen in female athletes is clearly of multifactorial origin, with specific movement patterns and altered neuromuscular control playing an important role in this increased ACL injury risk[32].

Six studies[1,32,40,46,52,56] reported statistically significant difference in LESS scores ($p \leq 0.05$) between males and females. These studies together included 6,446 participants overall with a weighted mean age of 20.2 ± 2.2 years (two studies did not specify mean age). The six other studies who reported no significant difference in LESS scores between males and females[5,6,8,45,57,69] tested 781 participants altogether with a weighted mean age of 15.9 ± 1.5 years. The different mean age between studies reporting statistically significant and non-significant differences between sexes can be one of the underlying reasons for the discrepancy given that mechanics associated with increased risk of injury in females tend to emerge after the pubertal growth spurt (i.e., puberty commonly between 10 to 16 years)[76]. The significant differences found in some studies might have been linked to differences in sample sizes; and, albeit being statistically significant, these differences in LESS scores might not have been clinically meaningful. In fact, based on the weighted mean from all studies (mean difference between females and males of 0.6 errors) and results from our meta-analysis (mean difference between females and males of 0.6 errors), the finding of statistically significant higher overall LESS scores in females compared to males is substantiated. However, the difference is not clinically meaningful based on the one error threshold[1]. Risk of bias was high for a number of domains, and the overall GRADE rating suggests very low strength of evidence.

4.1.3 Previous injury

A prior systematic review[77] agrees that previous injuries are a strong risk factor of sustaining not only the same, but also another type, of injury. When dividing previous injury into two subgroups (ACL and others), our meta-analysis identified the ACL group as having meaningfully higher LESS scores from a clinical perspective (mean difference of 1.2 errors) than the control group. The LESS scores of the group with other types of injuries than ACL were not significantly different from control group ($p = 0.441$). One explanation for these findings may be that the LESS was developed to screen for risk of ACL injury, and therefore targets movements linked with this type of injury. That said, knee valgus and stiff landing are movement patterns linked with various non-contact lower extremity injuries[78], suggesting that the LESS should be a useful screening tool for a range of injuries other than ACL. Two out of three studies exploring the effect of other types of previous injury on LESS[18,45] did not differentiate between contact and non-contact mechanisms of injury (e.g., contusion was recorded as an injury), which could also explain why the meta-analysis identified no significant difference in LESS scores between the other injury and control groups. Furthermore, injures were self-reported in these two studies[18,45]. Research shows that only 61% of athletes accurately recall their 12 months injury history[79], which highlights the difficulty of using self-reported data in research. On the other hand, John et al.[35] concluded that individuals with chronical ankle instability have significantly higher LESS scores compared to a healthy controls with a meaningful difference of 1.3 errors between groups, suggesting that LESS may be a useful tool for identifying movement patterns linked with injury risk in individuals with ankle instability. Nonetheless, the strength of the evidence regarding the influence of injury on LESS scores was considered very low based on the GRADE scale, and there was high risk of bias in several domains.

4.1.4 Intervention program

The meta-analysis of meta-analysis provide evidence for the effectiveness of neuromuscular training in reducing the incidence of ACL injury[80]. It is therefore logical to expect that intervention programs influence LESS scores. Fourteen studies[7,14-16,31,36,61-63,65-67,70,81,82] together tested 2,031 participants and explored the influence of a variety of intervention programs on LESS scores. Seven training programs[7,31,36,63,65,66,70] meaningfully improved LESS scores (change ≥ 1 error), all of which implemented injury prevention training programs with neuromuscular components. O'Malley et al.[36] concluded that injury prevention training programs involving strength, core stability, balance, movement control, plyometric, and agility exercises are statistically significantly superior in decreasing

LESS scores compared to usual training methods that do not emphasize neuromuscular control. Training programs with meaningful decreased in LESS scores[7,31,36,63,65,66,70] were implemented in diverse cohort groups, including males and females from 8[7] to 21[65] years of age; soccer[7,63,66], basketball[31,70], Gaelic football[36], and hurling[36] players; and recreational[65] to elite[63] level of sport participation. Given this diversity, it is difficult to ascertain whether sex, age, sport, or sport level also contributed to LESS score improvements following these intervention programs.

From all programs tested, the most effective in improving LESS scores were: (1) plyometric and neuromuscular training programs (decreased scores by 2.4 errors[31]), and (2) neuromuscular training programs with strength, core stability, movement control, plyometric, and agility exercises (decreased scores by 3 errors[36]). Both training[31,36] programs emphasized landing technique, with only one having controls completing their usual training program for comparison[36]. The programs consisted of 2 to 3 session per week over 6 to 8 weeks, each lasting approximately 15 to 30 minutes. Meta-analysis exploring the effect of intervention on ACL injury incidence[71] highlighted the importance of plyometrics and technique feedback in intervention programs. Both of these components were present in the most effective training programs in improving LESS scores[31,36]. Noteworthy is that both studies involved cohorts with some of the highest pre-intervention mean LESS score (7.3 ± 3.4[31] and 7.1± 3.8[36] errors), which could have contributed to their higher relative LESS improvements given research indicating that individuals with the poorest landing technique improve the most with training[14,61]."

The results from our meta-analysis showed that neuromuscular training programs with a minimum duration of 6 weeks meaningfully reduced LESS scores (mean difference: 1.2 errors, $p < 0.001$). Different interventions or training programs with a shorter duration than 6 weeks did significantly reduce LESS scores ($p = 0.042$), but the mean difference of 0.5 error was not clinically meaningful. These finding are in agreement with meta-analysis showing 6 weeks as a minimum duration of intervention programs that can assist in reducing ACL injury incidence[71]. Based on our results, there is evidence that neuromuscular training programs with a minimum duration of 6 weeks can meaningfully influence LESS scores. However, studies disagree in regard to the persistence of the effect once the intervention program stops (e.g., improvements persist up to 9-months versus improvements no longer present at 3-

months or 6-months) and the training duration required (e.g., 3-week, 3-month, 9-month programs) for the most optimal and long-term effect[16,31,65,66]. Furthermore, the strength of the evidence was considered very low based on GRADE and high risk of bias was present, notably in relation to adherence, confounding, and selection of reported results.

4.2 Limitations

This systematic review with meta-analysis explored the influence of age, sex, previous injury, and intervention program on LESS scores. The main limitations of this review and associated findings are the varied study design and heterogeneity between studies, risk of bias of the included studies, indirectness and imprecision of outcomes which resulted in very low quality of evidence according to the GRADE scale (Table 2). We included all studies exploring LESS as a main outcome measure regardless of study design, population tested, or risk of bias to systematically review and analyze all the scientific literature available on the topic. However, the results and corresponding interpretations may differ if only randomized control trials with low risk of bias studies were included. Another limitation is the use of the NOS as a risk of bias assessment tool given that there are no specific tools to assess risk of bias in cross-sectional observation studies. Furthermore, the testing protocols (e.g., sampling frequency of the cameras[38,52], landing distance[64], and landing surface[57]) and calculations of total LESS score (mean of three jumps[66] versus the best jump[70]) varied across studies, which can influence LESS scores[83].

Based on this review of the literature, there is indication that the influence of sex on LESS scores may vary in different age groups (pre versus post puberty). Therefore, it is probable that multiple influencing factors interact with each other. For example, females in puberty age with a history of ACL injury who do not participate in injury prevention programs may have the greatest LESS scores, and males older than 20 years with no previous injury and who have adhered to a neuromuscular training program lasting over 6 weeks potentially exhibit the lowest LESS scores. However, we did not explore this assumption specifically, hence, it is not possible to make conclusions regarding interactions between influencing factors and specifically regarding the influence of sex on LESS scores across different age groups.

Moreover, studies that did not differentiate between contact and non-contact mechanisms of injury were included into the meta-analysis, which could explain the lack of significant difference in LESS scores between the other injury and control groups. Given the limited number of studies exploring other injury in this meta-analysis (*n* = 3), we did not explore how the results would change if we excluded those studies involving contact injuries (*n* = 2). Besides sex, age, previous injury, and intervention program, other factors (e.g., fatigue[17,56,69], sport and competition level[6,41,46], and strength levels[32,44,51]) may also influence LESS scores; however, these factors were not explored in this review.

5 Conclusion

The goal of this literature review was to critically appraise and summarize research addressing age, sex, previous injury, and intervention program as factors potentially influencing LESS scores. The meta-analysis results provide evidence that sex, previous ACL injury, and training programs significantly influence LESS scores. However, only previous ACL injury and neuromuscular training programs with a minimal duration of 6 weeks were associated with a clinically meaningful change of one error. Our qualitative analysis of the reviewed studies suggests that LESS scores may be influenced by age; however, more evidence is needed to confirm the potential influence of age on LESS scores. These findings, however, should be interpreted cautiously considering the very low GRADE rating of the evidence. Further research is required to enhance our certainty regarding which factors influence LESS scores.

6 Practical implications

- Age can influence Landing Error Scoring System (LESS) scores, indicating that the established thresholds defining injury risk may not apply across different age groups.
- Females have higher LESS scores than males; however, the difference of 0.6 errors is not clinically meaningful, indicating that differences in landing mechanics assessed by LESS are not the only factor contributing to the overall higher risk of anterior cruciate ligament (ACL) injury seen in females.

- Previous ACL injury meaningfully increases LESS scores likely due to residual long-term deficits in neuromuscular control or presence of compensatory strategies.
- Previous injuries other than ACL do not appear to affect LESS scores given that the existing research includes contact injuries, which the LESS was not designed to predict.
- Neuromuscular programs completed 2 to 3 times per week for at least 6 weeks incorporating plyometric exercise and landing technique feedback are currently shown to be the most effective in improving LESS scores in a meaningful manner. Other intervention programs significantly decreased LESS score, but the difference of 0.5 errors is not clinically meaningful.

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References

1. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE, Jr., Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: the JUMP-ACL study. *Am J Sports Med.* 2009;37(10):1996-2002.
2. Hanzlíková I, Hébert-Losier K. Is the Landing Error Scoring System reliable and valid? A systematic review. *Sports Health.* 2020;12(2):181-188.
3. Onate JA, Cortes N, Welch C, Van Lunen B. Expert versus novice interrater reliability and criterion validity of the Landing Error Scoring System. *J Sport Rehabil.* 2010;19(1):41-56.
4. Padua DA, DiStefano LJ, Beutler AI, de la Motte SJ, DiStefano MJ, Marshall SW. The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury-prevention program in elite-youth soccer athletes. *J Athl Train.* 2015;50(6):589-595.
5. Smith HC, Johnson RJ, Shultz SJ, et al. A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. *Am J Sports Med.* 2012;40(3):521-526.
6. DiStefano LJ, Beltz EM, Root HJ, et al. Sport sampling is associated with improved landing technique in youth athletes. *Sports Health.* 2018;10(2):160-168.
7. Pryor JL, Root HJ, Vandermark LW, et al. Coach-led preventive training program in youth soccer players improves movement technique. *J Sci Med Sport.* 2017;20(9):861-866.
8. Welling W, Benjaminse A, Gokeler A, Otten B. Enhanced retention of drop vertical jump landing technique: a randomized controlled trial. *Hum Movement Science.* 2016;45:84-95.
9. Moher D, Liberati A, Tetzlaff J, Altman DG. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Int J Surg.* 2010;8(5):336-341.
10. Schwartz O, Talmy T, Olsen CH, Dudkiewicz I. The Landing Error Scoring System Real-Time test as a predictive tool for knee injuries: a historical cohort study. *Clin Biomech.* 2020;73:115-121.
11. Schussler E, Chaudhari AM, Cortes N, et al. iLESS visual estimation is a valid measure of knee valgus during drop vertical jump. *Med Sci Sports Exerc.* 2014;46(5):407.
12. Mauntel TC, Padua DA, Stanley LE, et al. Automated quantification of the Landing Error Scoring System with a markerless motion-capture system. *J Athl Train.* 2017;52(11):1002-1009.
13. Pryor JL, Burbulys ER, Root HJ, Pryor RR. Movement technique during jump-landing differs between sex among athletic playing surfaces. *J Strength Cond Res.* 2020.
14. DiStefano LJ, Padua DA, DiStefano MJ, Marshall SW. Influence of age, sex, technique, and exercise program on movement patterns after an anterior cruciate ligament injury prevention program in youth soccer players. *Am J Sports Med.* 2009;37(3):495-505.
15. DiStefano LJ, DiStefano MJ, Frank BS, Clark MA, Padua DA. Comparison of integrated and isolated training on performance measures and neuromuscular control. *J Strength Cond Res.* 2013;27(4):1083-1090.
16. DiStefano LJ, Marshall SW, Padua DA, et al. The effects of an injury prevention program on landing biomechanics over time. *Am J Sports Med.* 2016;44(3):767-776.

17. Gokeler A, Eppinga P, Dijkstra PU, et al. Effect of fatigue on landing performance assessed with the Landing Error Scoring System (LESS) in patients after ACL reconstruction. A pilot study. *Int J Sports Phys Ther.* 2014;9(3):302-311.
18. James J, Ambegaonkar JP, Caswell SV, Onate J, Cortes N. Analyses of landing mechanics in division I athletes using the Landing Error Scoring System. *Sports Health.* 2016;8(2):182-186.
19. Dar G, Yehiel A, Cale' Benzoor M. Concurrent criterion validity of a novel portable motion analysis system for assessing the Landing Error Scoring System (LESS) test. *Sports Biomech.* 2019;4:426-436.
20. Modesti PA, Reboldi G, Cappuccio FP, et al. Panethnic differences in blood pressure in Europe: a systematic review and meta-analysis. *PLoS One.* 2016;11(1):e0147601.
21. Sterne JA, Savović J, Page MJ, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ.* 2019;366 :l4898.
22. Sterne JA, Hernán MA, Reeves BC, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. *BMJ.* 2016;355:i4919.
23. Büttner F, Winters M, Delahunt E, et al. Identifying the 'incredible'! Part 2: Spot the difference-a rigorous risk of bias assessment can alter the main findings of a systematic review. *Br J Sports Med.* 2020;54.
24. Sterne JA, Higgins J, Reeves BC, Savović J, Turner L. Review of the development of the risk of bias tool for nonrandomised studies for interventions – ROBINS-I https://methods.cochrane.org/methods-cochrane/robins-i-tool?fbclid=IwAR0I3TSpmUeEJ-8UcY5O7TTiVOTl3BrUAHfumVFf6I2b4zl2pPx06WtUgo8. Published 2017. Accessed 03.05., 2020.
25. Parab S, Bhalerao S. Study designs. *Int J Ayurveda Res.* 2010;1(2):128.
26. GRADE. Grading quality of evidence and strength of recommendations. *BMJ.* 2004;328(7454):1490.
27. Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol.* 2013;4:863.
28. Jackson D, Turner R. Power analysis for random-effects meta-analysis. *Res Synth Methods.* 2017;8(3):290-302.
29. Higgins JP, Green S. *Cochrane handbook for systematic reviews of interventions.* Vol 4: John Wiley & Sons; 2011.
30. Viechtbauer W. Conducting meta-analyses in R with the metafor package. *J Stat Softw.* 2010;36(3).
31. Pfile KR, Gribble PA, Buskirk GE, Meserth SM, Pietrosimone BG. Sustained improvements in dynamic balance and landing mechanics after a 6-week neuromuscular training program in college women's basketball players. *J Sport Rehabil.* 2016;25(3):233-240.
32. Beutler AI, de la Motte SJ, Marshall SW, Padua DA, Boden BP. Muscle strength and qualitative jump-landing differences in male and female military cadets: the jump-ACL study. *J Sport Sci Med.* 2009;8(4):663-671.
33. Bell DR, Smith MD, Pennuto AP, Stiffler MR, Olson ME. Jump-landing mechanics after anterior cruciate ligament reconstruction: a Landing Error Scoring System study. *J Athl Train.* 2014;49(4):435-441.
34. Kuenze CM, Foot N, Saliba SA, Hart JM. Drop-landing performance and knee-extension strength after anterior cruciate ligament reconstruction. *J Athl Train.* 2015;50(6):596-602.

35. John C, Stotz A, Gmachowski J, et al. Is an elastic ankle support effective in improving jump landing performance, and static and dynamic balance in young adults with and without chronic ankle instability? *J Sport Rehabil.* 2019:1-6.
36. O'Malley E, Murphy JC, Persson UM, Gissane C, Blake C. The effects of the gaelic athletic association 15 training program on neuromuscular outcomes in gaelic football and hurling players: a randomized cluster trial. *J Strength Cond Res.* 2017;31(8):2119-2130.
37. Fox AS, Bonacci J, McLean SG, Saunders N. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scand J Med Sci Sports.* 2017;27(5):525-534.
38. Hébert-Losier K, Hanzlíková I, Zheng C, Streeter L, Mayo M. The 'DEEP' landing error scoring system. *Appl Sci.* 2020;10(3).
39. DiFabio M, Slater LV, Norte G, Goetschius J, Hart JM, Hertel J. Relationships of functional tests following ACL reconstruction: Exploratory factor analyses of the lower extremity assessment protocol. *J Sport Rehabil.* 2018:1-7.
40. de la Motte SJ, Gribbin TC, Lisman P, Beutler AI, Deuster P. The interrelationship of common clinical movement screens: establishing population-specific norms in a large cohort of military applicants. *J Athl Train.* 2016;51(11):897-904.
41. Kraus K, Schutz E, Doyscher R. Construct validation of the FMS: relationship between a jump-landing task and FMS items. *J Strength Cond Res.* 2017.
42. Everard EM, Harrison AJ, Lyons M. Examining the relationship between the functional movement screen and the Landing Error Scoring System in an active, male collegiate population. *J Strength Cond Res.* 2017;31(5):1265-1272.
43. Arslan S, Ertat KA, Karamizrak SO, İŞleğen Ç, Arslan T. Soccer match induced fatigue effect on landing biomechanic and neuromuscular performance. *Acta Medica Mediterr.* 2019;35(1):391-397.
44. Lepley AS, Strouse AM, Ericksen HM, Pfile KR, Gribble PA, Pietrosimone BG. Relationship between gluteal muscle strength, corticospinal excitability, and jump-landing biomechanics in healthy women. *J Sport Rehabil.* 2013;22(4):239-247.
45. Lam KC, McLeod TCV. The impact of sex and knee injury history on jump-landing patterns in collegiate athletes: a clinical evaluation. *Clin J Sport Med.* 2014;24(5):373-379.
46. Theiss JL, Gerber JP, Cameron KL, et al. Jump-landing differences between varsity, club, and intramural athletes: the jump-ACL study. *J Strength Cond Res.* 2014;28(4):1164-1171.
47. Herman DC, Riveros D, Jacobs K, Harris A, Massengill C, Vincent HK. Previous high school participation in varsity sport and jump-landing biomechanics in adult recreational athletes. *J Athl Train.* 2019;54(10):1089-1094.
48. Kraus K, Schütz E, Doyscher R. The relationship between a jump-landing task and functional movement screen items: a validation study. *J Strength Cond Res.* 2019;33(7):1855-1863.
49. Scarborough DM, Linderman SE, Cohen VA, Berkson EM, Eckert MM, Oh LS. Neuromuscular control of vertical jumps in female adolescents. *Sports Health.* 2019;11(4):343-349.
50. Tran AA, Shen J, Wernecke C, Gatewood CT, Harris AHS, Dragoo JL. A comparison of the Functional Movement ScreenTM and the Landing Error Scoring System: a cohort study. *Curr Orthop Pract.* 2020;31(1):8-12.
51. Mohammadi MF, Shojaadin S, Letafatkar A, Ebrahimi E, Eslami M. The relationship of anatomical alignment and strength of some lower extremity muscles with jump-

landing biomechanics: a Landing Error Scoring System study. *J Kerman Univ Medical Sci.* 2017;24(3):237-245.

52. Kuenze CM, Trigsted S, Lisee C, Post E, Bell DR. Sex differences on the landing error scoring system among individuals with anterior cruciate ligament reconstruction. *J Athl Train.* 2018;53(9):837-843.
53. Welling W, Benjaminse A, Seil R, Lemmink K, Zaffagnini S, Gokeler A. Low rates of patients meeting return to sport criteria 9 months after anterior cruciate ligament reconstruction: a prospective longitudinal study. *Knee Surg Sports Traumatol Arthrosc.* 2018;26(12):3636-3644.
54. Šiupšinskas L, Garbenytė-Apolinskienė T, Salatkaitė S, Gudas R, Trumpickas V. Association of pre-season musculoskeletal screening and functional testing with sports injuries in elite female basketball players. *Sci Rep.* 2019;9(1).
55. van Melick N, van Rijn L, Nijhuis-van der Sanden MWG, Hoogeboom TJ, van Cingel REH. Fatigue affects quality of movement more in ACL-reconstructed soccer players than in healthy soccer players. *Knee Surg Sports Traumatol Arthrosc.* 2019;27(2):549-555.
56. Wesley CA, Aronson PA, Docherty CL. Lower extremity landing biomechanics in both sexes after a functional exercise protocol. *J Athl Train.* 2015;50(9):914-920.
57. Jacobs K, Riveros D, Vincent HK, Herman DC. The effect of landing surface on landing error scoring system grades. *Sports Biomech.* 2018:1-8.
58. Beese ME, Joy E, Switzler CL, Hicks-Little CA. Landing Error Scoring System differences between single-sport and multi-sport female high school-aged athletes. *J Athl Train.* 2015;50(8):806-811.
59. Everard EM, Lyons M, Harrison AJ. Examining the association of injury with the Functional Movement Screen and Landing Error Scoring System in military recruits undergoing 16 weeks of introductory fitness training. *J Sci Med Sport.* 2018;21(6):569-573.
60. Biese KM, Pietrosimone LE, Andrejchak M, Lynall RC, Wikstrom EA, Padua DA. Preliminary investigation on the effect of cognition on jump-landing performance using a clinically relevant setup. *Meas Phys Educ Exerc Sci.* 2019;23(1):78-88.
61. Parsons JL, Sylvester R, Porter MM. The effect of strength training on the jump-landing biomechanics of young female athletes: results of a randomized controlled trial. *Clin J Sport Med.* 2017;27(2):127-132.
62. Parsons JL, Carswell J, Nwoba IM, Stenberg H. Athlete perceptions and physical performance effects of the FIFA 11+ program in 9-11 year old female soccer players: a cluster randomized trial. *Int J Sports Phys Ther.* 2019;14(5):740-752.
63. Akbari H, Sahebozamani M, Daneshjoo A, Amiri-Khorasani M, Shimokochi Y. Effect of the FIFA 11+ on landing patterns and baseline movement errors in elite male youth soccer players. *J Sport Rehabil.* 2019:1-8.
64. Distefano LJ, Casa DJ, Vansumeren MM, et al. Hypohydration and hyperthermia impair neuromuscular control after exercise. *Med Sci Sports Exerc.* 2013;45(6):1166-1173.
65. Scarneo SE, Root HJ, Martinez JC, et al. Landing technique improvements after an aquatic-based neuromuscular training program in physically active women. *J Sport Rehabil.* 2017;26(1):8-14.
66. Padua DA, DiStefano LJ, Marshall SW, Beutler AI, de la Motte SJ, DiStefano MJ. Retention of movement pattern changes after a lower extremity injury prevention program is affected by program duration. *Am J Sports Med.* 2012;40(2):300-306.

67. Owens BD, Cameron KL, Duffey ML, et al. Military movement training program improves jump-landing mechanics associated with anterior cruciate ligament injury risk. *J Surg Orthop Adv.* 2013;22(1):66-70.
68. Stiffler MR, Pennuto AP, Smith MD, Olson ME, Bell DR. Range of motion, postural alignment, and LESS score differences of those with and without excessive medial knee displacement. *Clin J Sport Med.* 2015;25(1):61-66.
69. Bell DR, Pennuto AP, Trigsted SM. The effect of exertion and sex on vertical ground reaction force variables and landing mechanics. *J Strength Cond Res.* 2016;30(6):1661-1669.
70. Garbenytė-Apolinskienė T, Šiupšinskas L, Salatkaitė S, Gudas R, Radvila R. The effect of integrated training program on functional movements patterns, dynamic stability, biomechanics, and muscle strength of lower limbs in elite young basketball players. *Sport Sci Health.* 2018;14:245–250.
71. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med.* 2006;34(3):490-498.
72. Arendt E, Dick R. Knee injury patterns among men and women in collegiate basketball and soccer: NCAA data and review of literature. *Am J Sports Med.* 1995;23(6):694-701.
73. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med.* 2013;41(1):203-215.
74. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: part 1, mechanisms and risk factors. *Am J Sports Med.* 2006;34(2):299-311.
75. Herzberg SD, Motu'apuaka ML, Lambert W, Fu R, Brady J, Guise J-M. The effect of menstrual cycle and contraceptives on ACL injuries and laxity: a systematic review and meta-analysis. *Orthop J Sports Med.* 2017;5(7):2325967117718781.
76. Myer GD, Ford KR, Divine JG, Wall EJ, Kahanov L, Hewett TE. Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: a case report. *J Athl Train.* 2009;44(1):101-109.
77. McCall A, Carling C, Davison M, et al. Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the perceptions and practices of 44 football (soccer) teams from various premier leagues. *Br J Sports Med.* 2015;49(9):583-589.
78. Decker MJ, Torry MR, Wyland DJ, Sterett WI, Steadman JR. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech.* 2003;18(7):662-669.
79. Gabbe BJ, Finch CF, Bennell KL, Wajswelner H. How valid is a self reported 12 month sports injury history? *Br J Sports Med.* 2003;37(6):545-547.
80. Webster KE, Hewett TE. Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *J Orthop Res.* 2018;36(10):2696-2708.
81. Padua DA, DiStefano LJ, DiStefano M, Beutler AI, Marshall SW. Duration of training affects retention of movement pattern changes following an ACL injury prevention program. *Med Sci Sports Exerc.* 2011;43(5):14-15.
82. Root HJ, Beltz EM, Martinez JC, Scarneo SE, DiStefano LJ. Team-specific needs-based injury prevention program improves landing technique in youth female athletes. *Med Sci Sports Exerc.* 2016;48(5):741-741.
83. Hanzlíková I, Athens J, Hébert-Losier K. Clinical implications of Landing Error Scoring System calculation methods. *Phys Ther Sport.* 2020;44:61-66.