Utility of kinetic and kinematic jumping and landing variables as predictors of injury risk: a systematic review

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ABSTRACT

Purpose: Jump-landing assessments provide a means to quantify an individual's ability to attenuate ground reaction forces, generate lower limb explosive power and maintain joint alignment. In order to identify risk factors that can be targeted through appropriate training interventions, it is necessary to establish which (scalar) objective kinetic, kinematic, and performance measures are most associated with lower-extremity injury,

Methods: Online searches of MEDLINE, SCOPUS, EBSCOHost, SPORTDiscus and PubMed databases were completed for all articles published before March 2020 in accordance with PRISMA guidelines.

Results: 40 articles investigating nine jump-landing assessments were included in this review. 79% of studies using drop jump (n =14) observed an association with future injury, while only 8% of countermovement jump studies (n = 13) observed an association with injury risk. 57% of studies using unilateral assessments found associations with risk of injury (n = 14). Studies using performance measures (jump height/ distance) as outcome measure were only associated with injury risk in 30% of cases. However, those using kinetic and/or kinematic analyses (knee abduction moment, knee valgus angle, knee separation distance, peak ground reaction force) found associations with injury in 89% of studies.

Conclusion: The landing element of jump-landing assessments appears to be superior for identifying individuals at greater risk of injury; likely due to a closer representation of the injury mechanism. Consequently, jump-landing assessments that involve attenuation of impact forces such as the drop jump appear most suited for this purpose but should involve assessment of frontal plane knee motion and ground reaction forces.

INTRODUCTION

Lower extremity injuries account for a large proportion of time loss injuries in sports people and professional service men and women, with the knee and ankle being the primary site in many of these cases (Hootman et al. 2007; Read et al. 2018a; Teyhen et al. 2018). Knee and ankle injuries primarily occur within passive tissue such as ligament and tendon, which in part may be due to altered neuromuscular control resulting in undesirable magnitudes of force being transmitted to these structures rather than attenuated by the muscle-tendon unit (Beynnon and Fleming 1998). A large proportion of these injuries have non-contact mechanisms, which are predominantly a result of modifiable risk factors that can be corrected through appropriate training (Hootman et al. 2007; Noyes et al. 2005; Read et al. 2018a).

A systems-based approach to injury prevention which highlights the need to identify mechanisms of injury and risk factors for injury in order to tailor training interventions towards addressing these risk factors has been previously proposed (Bittencourt et al. 2016; Quatman et al. 2009; van Mechelen et al. 1992). Through highlighting the mechanism of injury, practitioners can design specific movement challenges for athletes to complete to assess an individual's level of risk. Cadaver simulations and match video analysis studies illustrate that stiff landings with aberrant movement strategies such as frontal plane medial knee displacement place excessive strain on passive joint restraints such as anterior cruciate ligament leading to tissue failure (Bates et al. 2015; Krosshaug et al. 2007; Walden et al. 2015). Recent commentary has suggested that using screening assessments to predict future injury is not a viable approach to support injury prevention strategies (Bahr 2016). However, analysis of the competency of future injured athletes in executing a movement challenge can be used to establish performance traits of high-risk individuals. To this end, since evidence highlights landing as a particularly common mechanism of injury (Hewett et al. 2010; Hewett et al. 2016; Krosshaug et al. 2007; Walden et al. 2015), numerous jump-landing assessments have been designed and investigated with respect to their ability to detect individuals at greater risk of injury (Dingenen et al. 2015; Hewett et al. 2005; Padua et al. 2009; Read et al. 2018b).

For a test to be useful, it needs to have good sensitivity in accurately identifying those at greater risk of injury versus those who are not, i.e. it needs to maximise the true positives while minimizing the number of false positives. Previous research has suggested performance markers can identify injury risk from a hop for distance test (Goossens et al. 2015), a standing broad jump (Taanila et al. 2010) and a countermovement jump (Visnes et al. 2013), while others have shown that kinetic and kinematic markers during rebound jump tasks can be significant predictors of injury (Hewett et al. 2005; Leppanen et al. 2017b; Verrelst et al. 2014). These assessments range in complexity from simply measuring jump heights and distances during these tasks to full-body, 3-dimensional motion analysis and consequently have a variety of cost and time implications.

Existing systematic reviews assessing the utility of jump-landing assessments have been limited in their scope so as to only address subjective assessments for a single type of injury such as anterior cruciate injury (ACL) rupture (Fox et al. 2016), have solely focused upon kinematic variables that can be assessed in a clinical setting (Aerts et al. 2013) or have assessed the utility of tests in distinguishing between injured people after the fact (Hegedus et al. 2015). None of these reviews required assessment methods to be validated by prospective cohort studies. Retrospective injury surveillance is undermined by the tendency for recall bias and misreporting (Gabbe et al. 2003). Additionally, studies using a design whereby previously injured participants are screened to identify differences with individuals who have suffered no injury are flawed because it is not known whether any kinematic differences that present are a result of, or the cause of the injury.

Simple assessments of jumping performance (e.g. height or distance) have provided conflicting findings in terms of their association with injury risk. Gabbett and Domrow (2005) reported that rugby league players with a reduced countermovement jump height were at greater risk of injury than those with better vertical jumping ability. In contrast, Visnes et al. (Visnes et al. 2013) found that greater vertical jumping ability increased the likelihood of overuse knee injury. Similarly, Hewett et al. (Hewett et al. 2005) found that knee abduction moment during a drop jump landing could predict ACL injury with 78% sensitivity and 73% specificity. However, Krosshaug et al. (Krosshaug et al. 2016a; Krosshaug et al. 2016b) found no significant relationship between knee abduction moment or medial knee displacement and risk of a first ACL injury. Though ACL injuries are one of the most severe time-loss lower extremity injuries, they are also relatively infrequent (Hootman et al. 2007). Practitioners would be well advised to screen for other more common, albeit less severe, knee and ankle injuries too since their mechanism of injury has also been linked to aberrant landings (Bengtsson et al. 2013; Ekstrand et al. 2011; Hägglund et al. 2013; Lundblad et al. 2013; Waldén et al. 2013).

Several jump-landing screening protocols have been utilised to identify risk factors for lower limb injury in athletes. The body of literature has investigated numerous jumping tasks and measured a breadth of variables to create a considerable body of knowledge. In order to progress this area of research, a consensus is required on the most valid screening protocols and measures that are currently available and to highlight appropriate avenues for future research. The breadth of jumping tasks, variables, methods of measurement and populations that have been studied have created controversy and inconsistency that makes synthesis of the findings challenging for a practitioner. Therefore, a study that systematically reviews and critically analyzes the currently available prospective evidence regarding the utility of kinetic and kinematic jumping and landing variables as injury risk factors in athletic populations seems to be warranted in order to shed light regarding this issue.

METHODS

Literature Search

This review was conducted in accordance with the PRISMA guidelines (Moher et al. 2009) and registered in the PROSPERO register of systematic reviews (CRD42020169776). A literature search was performed to retrieve articles using jump-landing assessments to prospectively identify biomechanical risk factors for lower extremity injury in athletes. The following search terms were entered into PubMed, MEDLINE, EBSCOHost, SPORTDiscus and SCOPUS online databases on 13th March 2020 without any publishing date restrictions: 'injur*', 'jump*' and 'prospective'. All terms were searched for in the title and/or abstract of articles. The search outcomes were subjected to a preliminary screening of their title and abstract to remove duplicates, clearly irrelevant studies, non-English language publications and studies utilising non-human participants.

Literature Selection

The full text of the remaining articles were reviewed for final inclusion in the review by the first author based upon the following inclusion criteria: (1) a full text of an article was available, excluding abstract only articles and conference presentations; (2) a unilateral or bilateral baseline jump-landing assessment must have been performed and assessed in isolation for any relationship to injury risk; studies using jump assessments to contribute to a composite score for a testing battery and that did not report statistics for the jump assessment alone were excluded; (3) prospective injury surveillance monitoring the frequency of at least one lower-extremity injury must have been conducted; (4) participants were required to be free of injury at the time of the study commencing with no known history of the injury of interest prior to engaging in the study; (5) only objective assessment tools to measure jump-landing performance were permitted, with any subjective assessments involving an assessor rating of performance being excluded; (6) studies needed to present statistics indicating injury risk. Studies were included if they reported hazard ratios, risk ratios or odds ratios with sensitivity and specificity also reported in cases where it was provided. Where studies did not report any of these ratios, they were excluded unless they provided sufficient information (specificity, sensitivity, numbers of injured and uninjured participants, cut-off value) to calculate an odds ratio ± 95% confidence interval using the method of Altman (Altman 1991).

Methodological Quality Assessment

All included studies were reviewed for methodological quality and risk of assessment using a modified version of the Cochrane Group on Screening Diagnostic Test Methodology quality assessment tool as previously utilised by Fox et al. (Fox et al. 2016). Two reviewers, including the first author screened the included studies against the 11 criteria that were previously deemed most relevant to prospective cohort studies. In the event of disagreement, discussion with a third reviewer was conducted and a decision reached by vote.

Data Extraction and Analysis

The remaining articles were screened and tabulated to collate the following information:

1) Which jump-landing assessment was deployed in the study?
2) Did analysis of the test involve kinetic and/or kinematic methods and what equipment and sampling rate was used?
3) Which variables were assessed and reported?
4) What was the age group of the study cohort?
5) What was the sample size of the study cohort?
6) What was the duration of follow-up injury surveillance?
7) Which injuries were investigated?

8) How many injuries were reported during the study?
9) Key findings relating to injury risk identification
10) Was a link between performance in the test and injury reported (yes/no)?
11) Were predictive statistics provided or sufficient information to calculate this *post hoc*?

RESULTS

Search Findings and Study Selection

The online database searches returned 999 results. A summary of the review process and screening strategy is shown in **Error! Reference source not found.**. Duplicates within each database's results were removed to leave 798 papers. The preliminary search of the titles and abstracts removed 719 articles due to the irrelevance of the study, language of publication, and use of non-human participants. The full texts of the remaining 79 studies were screened for eligibility; a further 45 were removed due to insufficient statistical information (*n* = 13), use of a subjective jump screen (*n* = 5), absence of any baseline jump assessment (*n* = 10), no prospective injury surveillance conducted (*n* = 11), or implementation of a training study (*n* = 5). The reference lists of the remaining 34 studies that met the inclusion criteria were screened for relevant articles that had been missed by the online database search. This yielded a further 12 studies of which 6 were excluded for insufficient statistical information leaving a final list of 40 studies to be included in the systematic review (Table 1). The 40 articles revealed that nine jump-landing assessments had been investigated in prospective cohort studies to determine injury risk factors. The prospective injury surveillance period following initial baseline screening varied from eight weeks to six years, using sample sizes ranging from 43 up to 3893. There was a bias towards studies investigating injuries in younger populations, with 29 of the 40 studies included using populations with a mean age of <20 yrs. A relatively even split of studies examined female (*n* = 15) and male (*n* = 14) populations while 11 studies examined mixed-sex samples. Most papers investigated a broad but loosely defined range of injuries (all injuries, *n* = 12; all lower extremity injuries, *n* = 9). Knee injuries were investigated by 13 studies (all knee, *n* = 1; patellofemoral pain syndrome, *n* = 5; non-contact ACL rupture, *n* = 7) while ankle injuries were only investigated in 4 studies. Muscular strains and medial tibial stress syndrome were the focus of one study each. Research studies were heavily biased towards acute injuries (*n* = 33) rather than chronic onset injuries (*n* = 7).

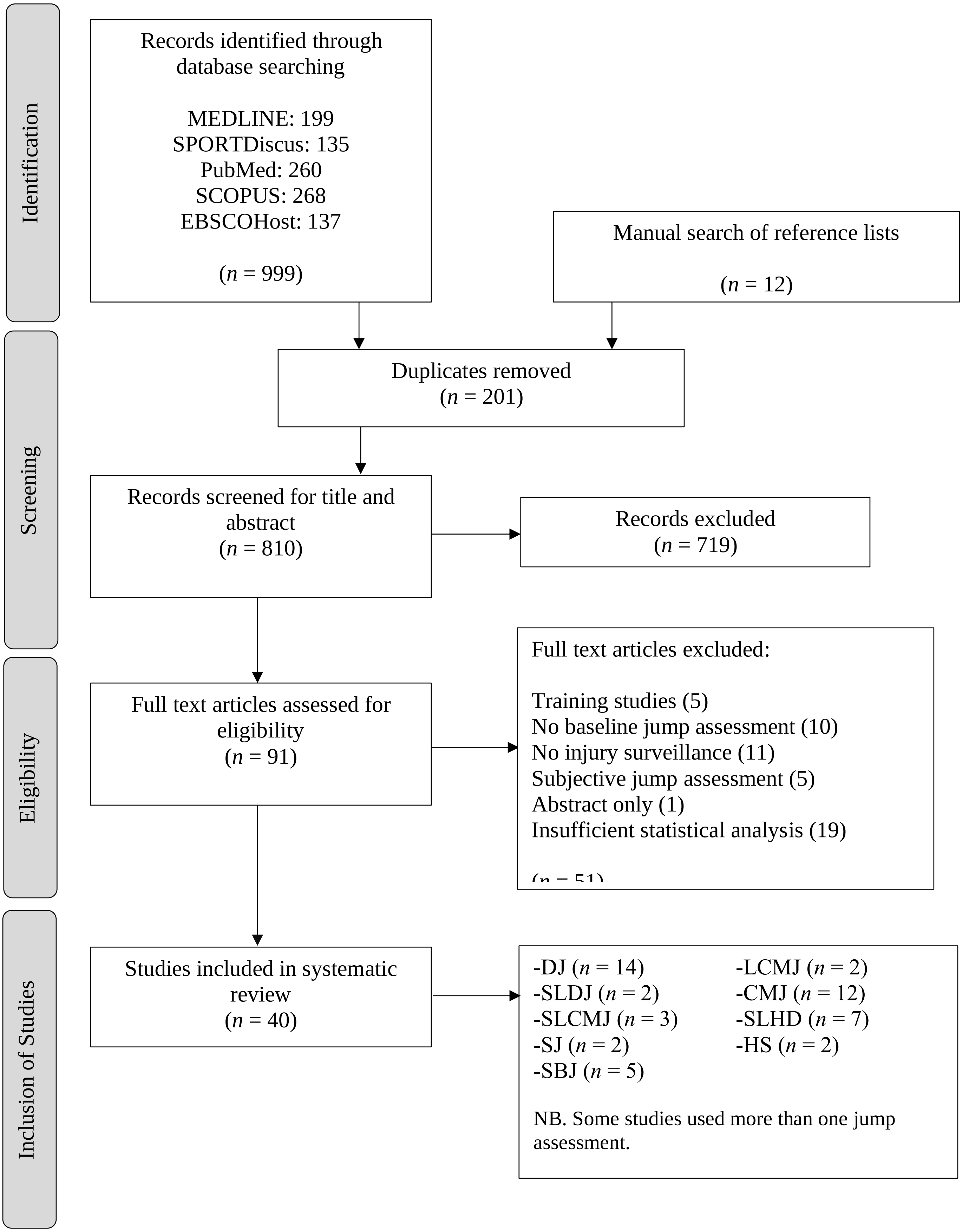

Figure 1 Summary flowchart of literature search, screening process and outcomes. DJ- drop jump; SLDJ- single-leg drop jump; CMJ- countermovement jump; SLCMJ- single-leg countermovement jump; SJ- squat jump; SBJ- standing broad jump; LCMJ- loaded countermovement jump; SLHD- single-leg hop for distance; HS- hop and stick.

Table 1 Summary of studies investigating jump-landing tasks as indicators of injury risk through prospective analysis of objective variables.

SJ Squat Jump, **CMJ** Countermovement Jump, **SLCMJ** Single Leg Countermovement Jump, **DJ** Drop Jump, **SLDJ** Single Leg Drop Jump, **SBJ** Standing Broad Jump, **SLHD** Single Leg Hop for Distance, **LCMJ** Loaded Countermovement Jump, **HS** Hop and Stick, **F** Female, **M** Male, **SD** Standard Deviation, **ACL** Anterior Cruciate Ligament.

Citation	Test(s) used	Population characteristics				Follow up period	Injuries investigated	Injuries reported
		Age (yr) (Mean ±SD)	Sex	Sport	Sample size (*n*)			
Ambegaonkar et al. (2018)	SLHD	18.0 ± 0.7	Female	Dancers	43	16 weeks	All lower extremity	51
Arnason et al. (2004)	SJ CMJ	24 (range 16-38)	Male	Soccer	217	1 playing season	All injuries	193 lower limb
Attenborough et al. (2017)	CMJ	21.5 ± 6.3	Female	Netball	96	1 playing season	Lateral, medial or syndesmotic ankle sprains	11
Boling et al. (2009)	DJ	Not reported	M: 806 F: 513	US Navy Freshmen	1319	1-3 years	Patellofemoral pain	40
Boling et al. (2019)	DJ	18.8 ± 0.9	M: 2448 F: 1445	US Navy Freshmen	3893	4 years	Patellofemoral pain	188
Brumitt et al. (2018)	SBJ SLHD	19.1 ± 1.1	Female	Multisports	106	1 playing season	All lower back and lower extremity	32
Brumitt et al. (2013)	SBJ SLHD	19.3 ± 1.2	F: 110 M: 83	University multisport	193	1 playing season	All lower back and lower extremity	63

Brumitt et al. (2016)	SBJ SLHD	20.2 ± 1.9	Male	Basketball	71	1 playing season	All lower back and lower extremity	29
DuPrey et al. (2016)	HS	18.5	M: 166 F: 112	Multisports	278	4 years	ACL	9
Emery et al. (2005)	CMJ	14.8 ± 0.3	M: 153 F: 164	Soccer	317	13 weeks	All injuries	78
Fransz et al. (2018)	SLDJ	16.0 ± 3.6	Male	Soccer	190	3 years	Lateral ankle sprains	45
Frisch et al. (2011)	SLHD SJ CMJ	15 ± 2.0	Male	Soccer	67	44 weeks	All injuries	142 lower limb
Gabbett et al. (2012)	LCMJ CMJ	23.2 ± 4.0	Male	Rugby League	66	1 playing season	All contact	154
Gabbett and Domrow (2005)	CMJ	Not reported	Male	Rugby league	153	4 playing seasons	All injuries	185
Gastin et al. (2015)	LCMJ	22.8 ± 3.6	Male	Australian rules football	57	4 competitive seasons	All injuries	152 lower limb
Goetschius et al. (2012)	DJ	18.0 ± 1.9	Female	University multisports	65	3 years	ACL	20
Goossens et al. (2015)	SLHD	18.2 ± 1.0	M: 61 F: 41	Physical education students	102	1 academic year	Hamstring strains	16

Henry et al. (2016)	SLCMJ	18.9 ± 3.5	Male	Soccer	210	1 playing season	Noncontact ankle	14
Hewett et al. (2005)	DJ	16.1 ± 1.7	Female	Soccer and basketball	205	2 playing seasons	Noncontact ACL	9
Holden et al. (2017)	DJ	12.9 ± 0.4	Female	High school multisports	76	2 years	Patellofemoral pain	8
Knapik et al. (2001)	CMJ	21.4 ± 3.7	M: 182 F: 168	US military recruits	350	8 weeks	All injuries	128
Krosshaug et al. (2016)	DJ	21.4 ± 4.0	Female	Handball and soccer	710	6 years	ACL	53
Leppanen et al. (2017b)	DJ	15.4 ± 1.9	Female	Basketball and floorball	171	1-3 years	Noncontact ACL	15
Leppanen et al. (2017a)	DJ	15.4 ± 1.9	Female	Basketball and floorball	171	3 years	Noncontact ACL	15
Ling et al. (2020)	CMJ	19.6 ± 1.2	Female	Gymnastics	100	1 year	All injuries	160
MacDonald et al. (2018)	CMJ	Median 20 (range 18-25)	Male	Volleyball	50	1 competitive season	Knee injuries	18

Myer et al. (2010)	DJ	13.3 ± 1.5	Female	Basketball	145	1 competitive season	Patellofemoral pain	14
Muller et al. (2017)	DJ	11.5 ± 1.5	M: 50 F: 31		81	2 competitive seasons	All injuries	69
Nilstad et al. (2014)	DJ	21.5 ± 4.1	Female	Soccer	173	8 months	Lower extremity	171
O'Kane et al. (2017)	DJ	Range 12-15	Female	Soccer	351	4 years	Lower extremity overuse	83
O'Kane et al. (2016)	DJ	Range 11-14	Female	Soccer	351	1-2 years	Lower extremity	173
Quarrie et al. (2001)	CMJ	20.6 ± 3.7	Male	Rugby union	258	23 weeks	All injuries	83/1000hrs
Raschner et al. (2012)	DJ	Range 14-19	M: 195 F: 175	Skiers	370	1 year	ACL ruptures	57
Read et al. (2018)	SLHD HS SLCMJ	Range 11-18	Male	Soccer	356	10 months	Noncontact lower extremity	99
Sman et al. (2014)	CMJ THD	21.0 ± 3.3	Male	Rugby league and Australian rules football	202	1 playing season	Ankle syndesmosis	12

Taanila et al. (2015)	SBJ	19.0 (median)	Male	Finnish military conscripts	1411	180 days	All injuries	550
Taanila et al. (2010)	SBJ	19.0 (median)	Male	Finnish military conscripts	944	6 months	All injuries	1629
van Seters et al. (2017)	CMJ SLCMJ	18.6 ± 1.1	M: 17 F: 28	Dance students	45	1 year	Lower extremity	31
Visnes et al. (2013)	CMJ	16.7 ± 0.8	M: 68 F: 82	Volleyball	150	1 year	Patella Tendonitis	28
Verrelst et al. (2014)	SLDJ	19.4 ± 0.9	Female	Physical education students	79	1-2 years	Exertional medial tibial pain	22

Study Methodology Screening Outcomes

All studies received a rating of five or greater from the methodological screening tool and the median and mode score was eight out of a possible 11. There was 97.7% agreement ($\kappa = 0.948$; $p < 0.001$) between the first two reviewers with nine instances of disagreement. There was 100% agreement for eight of the 11 criteria. Of the nine disagreements, four were resolved through discussion between reviewer one and reviewer two, whilst a third reviewer was required to resolve the remaining five instances of disagreement. No study was excluded from the review on the basis of the screening outcome. A summary of the methodological assessment for all studies included in the review is available in Supplementary Table 1.

Screening Methods Identified

A mixture of vertical (drop jump, countermovement jump, squat jump, loaded countermovement jump, single leg drop jump, single-leg countermovement jump) and horizontal (standing broad jump, single-leg hop for distance, hop and stick) unilateral and bilateral screening assessments were identified utilising performance measures and/or kinetic and/or kinematic analysis. The most frequently investigated jump landing assessments were the bilateral countermovement jump and drop jump (**Error! Reference source not found.**). From the bilateral assessments, drop jump had the greatest proportion of studies showing a relationship with injury (79%; 14 studies). There were fewer studies investigating the individual unilateral assessments (n = 14) though when pooled, unilateral assessments (single-leg drop jump, single-leg countermovement jump, single-leg hop for distance and hop and stick) were associated with injury risk in 57% of studies.

Across the 40 studies, screening tests were examined 49 times owing to the fact that some studies utilised more than one assessment. Performance metrics (jump/hop height, jump/hop distance, reactive strength index) were outcome measures for 33 of these test investigations; only 9 of those 33 (30.3 %) reported an association between the outcome of the test and risk of lower extremity injury. Within these 9 test investigations, the direction of causality between injury and performance was inconsistent with seven investigations showing poorer performance in a single leg-hop for distance (Ambegaonkar et al. 2018; Brumitt et al. 2018; Goossens et al. 2015), single-leg countermovement jump (Henry et al. 2016), drop jump (Raschner et al. 2012) or standing broad jump (Taanila et al. 2010; Taanila et al. 2015) was

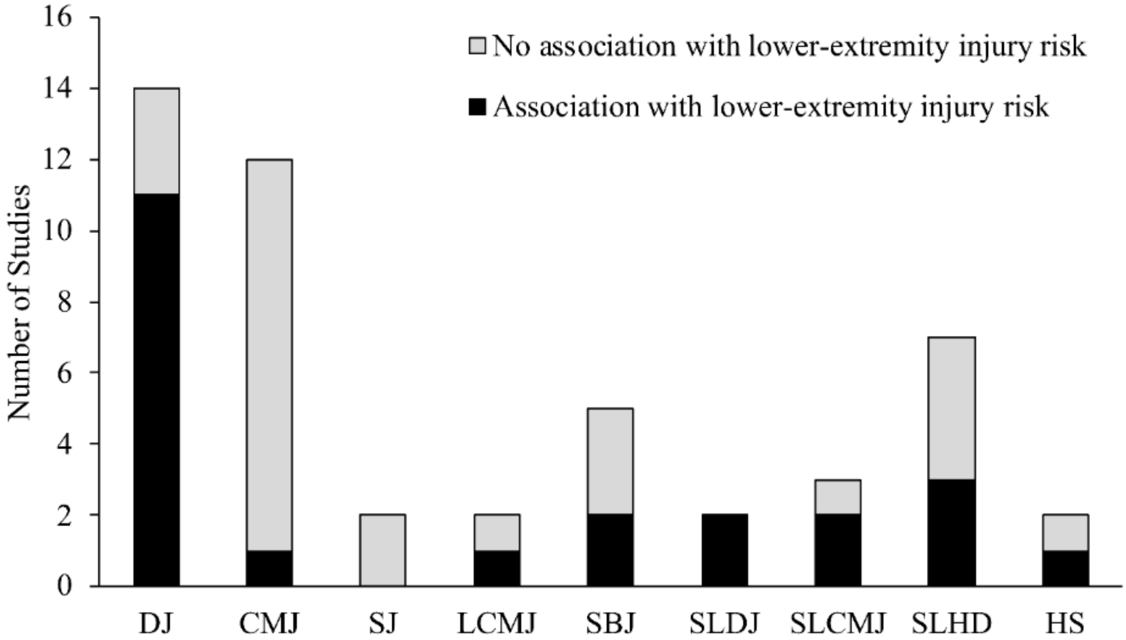

Figure 2 Summary of frequency of jump-landing assessment research studies. **DJ** Drop Jump; **SLDJ** Single Leg Drop Jump; **SMH** Submaximal Hopping; **CMJ** Countermovement Jump; **SJ** Squat Jump; **SLCMJ** Single Leg Countermovement Jump; **LCMJ** Loaded Countermovement Jump; **SBJ** Standing Broad Jump; **HS** Hop and Stick.

associated with greater risk of injury and two showing greater performance in a single leg hop for distance (Brumitt et al. 2013) or countermovement jump (Visnes et al. 2013) elevated injury risk. Tests utilising kinetic and/or kinematic assessment of movement were administered 18 times of which 16 found an association with injury (89%). Of the 24 test investigations demonstrating an association with injury risk, 50% utilised a drop jump. From test investigations identifying a significant association with injury risk, those using an assessment that did not involve a rebound jump found associations with landing forces rather than elements of the jump take-off (DuPrey et al. 2016; Read et al. 2018b; Verrelst et al. 2014).

Drop Jump

Drop jump was the most frequently investigated jump assessment. One study failed to report the drop height used (Muller et al. 2017) while the remaining studies all used a 30 cm / 12 inch drop height (Boling et al. 2019; Boling et al. 2009; Goetschius et al. 2012; Hewett et al. 2005; Holden et al. 2017; Krosshaug et al. 2016b; Leppanen et al. 2017a; Leppanen et al. 2017b; Myer et al. 2010a; Nilstad et al. 2014; O'Kane et al. 2017; O'Kane et al. 2016) and a single study used a drop height of 40 cm (Raschner et al. 2012). Boling et al. (2009), Boling et al. (2019) and Goetschius et al. (2012) included the jump technique used in the Landing Error

Scoring System (LESS) (Padua et al. 2009) which involves jumping forward 50% of standing height from the top of the box, but then used objective assessment techniques rather than using the subjective screening criteria of the LESS. All studies collected kinematic data and 11 of these 14 analysed the association of kinematic variables with risk of injury without the addition of kinetic data. Of these 11 studies, nine reported significant associations with injury risk (Boling et al. 2019; Boling et al. 2009; Holden et al. 2017; Leppanen et al. 2017a; Leppanen et al. 2017b; Nilstad et al. 2014; O'Kane et al. 2017; O'Kane et al. 2016; Raschner et al. 2012) while two studies found no association with risk of injury (Krosshaug et al. 2016b; Muller et al. 2017). Only seven of the 14 studies utilising drop included kinetic data in their assessment (Boling et al. 2009; Goetschius et al. 2012; Hewett et al. 2005; Krosshaug et al. 2016b; Leppanen et al. 2017a; Leppanen et al. 2017b; Myer et al. 2010a). This was usually processed along with kinematic data to calculate joint moments; the only ground reaction force variable analysed by any drop jump study was peak vertical ground reaction force (**Error! Reference source not found.**). Studies using the drop jump as an injury screening tool have predominantly investigated the relationship of these variables with knee injury (patellofemoral pain *n* = 4 studies; ACL rupture *n* = 6 studies) while four studies examined the risk of suffering all lower extremity injuries (Muller et al. 2017; Nilstad et al. 2014; O'Kane et al. 2017; O'Kane et al. 2016).

Six of the seven drop jump studies gathering kinetic variables utilised 3D motion-analysis technology alongside ground reaction force data. Goetschius et al. (2012) utilised two-dimensional video analysis in both the frontal and sagittal plane to predict knee abduction moment using an algorithm devised and validated by Myer et al. (2010b). Peak knee abduction moment was analysed by five studies with two finding an association with risk of suffering a knee injury (Hewett et al. 2005; Myer et al. 2010a) and three failing to observe such a relationship (Goetschius et al. 2012; Krosshaug et al. 2016b; Leppanen et al. 2017b). Myer et al. (Myer et al. 2010a) identified a knee abduction moment of > 15 N·m as the threshold that caused a two-fold increase in the risk of sustaining patellofemoral pain (OR = 2.34; CI 1.07-4.65). Meanwhile, Hewett et al. (Hewett et al. 2005) identified that a cut-off point of > 25.25 N·m could detect female athletes who would suffer an ACL rupture with 78% sensitivity and 73% specificity (OR = 9.38; CI 1.89-46.58). Peak vertical ground reaction force was investigated by 3 studies, with Leppänen et al. (Leppanen et al. 2017b) (HR = 1.26; CI 1.09-1.45) and Boling et al. (Boling et al. 2009) (RR = 3.57; CI 1.26-10.0) finding a significant association with risk of ACL rupture and patellofemoral pain syndrome respectively (**Error!**

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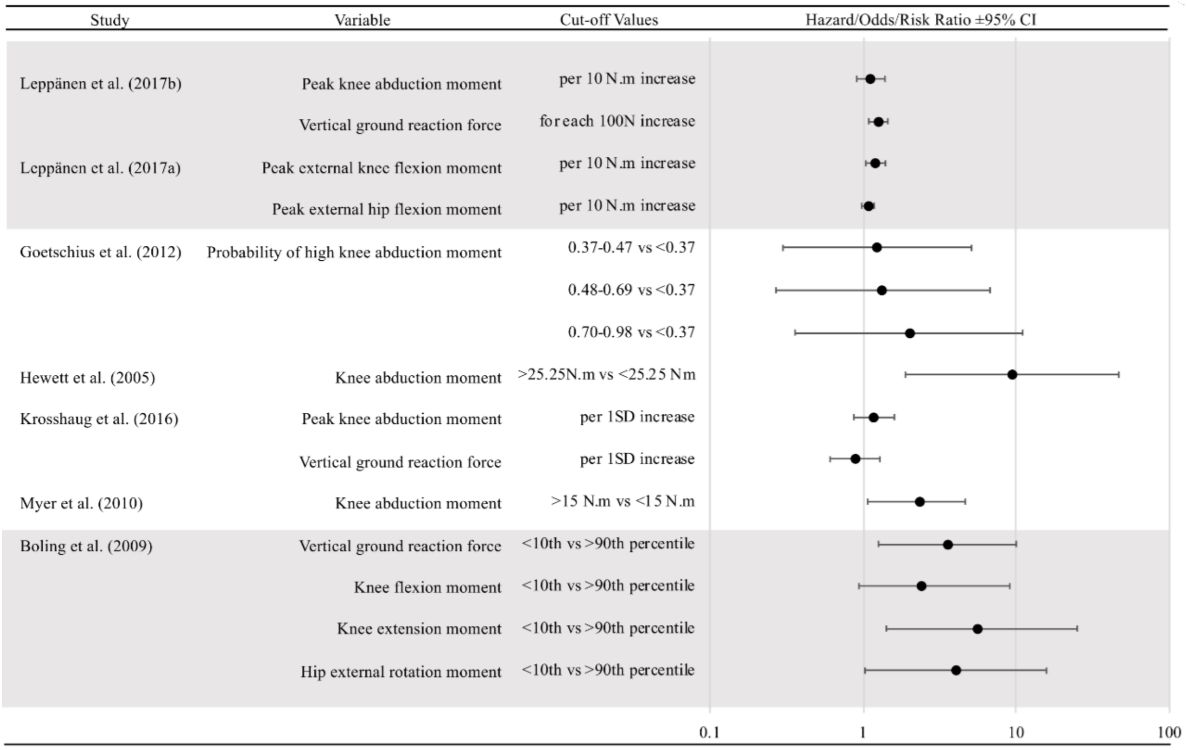

Figure 3 Likelihood of lower extremity injury in relation to kinetic drop jump variables studied in prospective cohort studies. Studies in the upper grey area present Hazard Ratios, in the lower grey area Risk Ratios and in the white area Odds Ratios. **SD** Standard Deviation.

vertical ground reaction force and risk of ACL rupture. Boling et al. (Boling et al. 2009) observed a significant association between knee flexion moment and the development of patellofemoral pain (RR = 5.55; CI 1.42-25.0). Likewise, Leppänen et al. (Leppanen et al. 2017a) reported a similar association with risk of ACL rupture (HR = 1.21; CI 1.04-1.40).

Three dimensional motion-analysis was employed by six of the 11 drop jump studies performing kinematic analysis (Boling et al. 2019; Boling et al. 2009; Krosshaug et al. 2016b; Leppanen et al. 2017a; Leppanen et al. 2017b; Nilstad et al. 2014) while three studies used frontal plane two-dimensional video analysis (Holden et al. 2017; O'Kane et al. 2017; O'Kane et al. 2016) and two utilised a force plate to derive jump height (Muller et al. 2017; Raschner et al. 2012).

Analysis of associations between kinematic variables and risk of lower extremity injury were conducted by 11 of the 14 drop jump studies (**Error! Reference source not found.**). Variables that indicate frontal plane knee motion such as knee valgus angle, medial knee displacement, valgus displacement and normalized knee separation distance were analysed by seven studies, with five observing an association with risk of injury. Two studies found an association between normalized knee separation distance at peak knee flexion and risk of lower extremity injury (RR= 3.62; 1.18-11.09) (O'Kane et al. 2016) and lower extremity overuse injury (RR= 2.24; 1.20-4.19) (O'Kane et al. 2017) when comparing the 10th percentile to the 90th percentile in populations of female adolescent soccer players. Holden et al. Holden et al. (2017) showed that a frontal plane knee valgus displacement of greater than 10.6º increased the risk of patellofemoral pain syndrome eleven-fold (OR= 11.60; 2.93-45.89). Nilstad et al. (2014) was the only study that observed that an increase in knee valgus angle decreased the risk of ankle injury (OR= 0.64; 0.41-1.00). Neither Krosshaug et al. (2016b) or Leppanen et al. (2017b) observed a significant association between knee valgus at initial ground contact and the risk of suffering an ACL rupture. Peak knee flexion angle was investigated by three studies with two finding an association with risk of injury (Boling et al. 2009; Leppanen et al. 2017b) and the remaining study seeing no association (Krosshaug et al. 2016b). Leppanen et al. (2017b) observed an increase in risk of ACL injury for each 10º decrease in knee flexion during ground contact (HR= 1.81; 1.13-2.94). Boling et al. Boling et al. (2009) also observed a three-fold increase in risk of patellofemoral pain syndrome if knee flexion angle was above 99.5º compared to below 63.2º (RR= 3.01; 1.16-8.33). Furthermore, Boling et al. (2019) observed a two-fold (OR = 2.13; 1.30-3.45) increase in risk of patellofemoral pain syndrome with reduced knee flexion at initial contact and greater knee external rotation at 50% of ground contact (OR = 1.92; 1.01-3.70) in male military recruits. In female recruits, Boling et al. (2019) reported that females landing with less than 10º of hip abduction (OR = 1.86; 1.06-3.26) were twice as likely to suffer patellofemoral pain while individuals landing with more than 10º of knee internal rotation were also more likely to suffer patellofemoral pain (OR = 1.71; 1.08-2.73) than those with less than 10º of knee internal rotation. Leppanen et al. (2017a) was the only study to investigate hip flexion range of motion and found significant associations with risk of injury. A reduced range of motion during ground contact was associated with greater risk of ACL injury (HR= 1.64; 1.01-2.62).

Other Bilateral Jump Assessments

The other bilateral assessments included countermovement jump, loaded countermovement jump and standing broad jump. All 12 studies that used a countermovement jump as a screening tool utilised jump height as the sole variable of interest and only a single study demonstrated a relationship with lower extremity injury risk (Visnes et al. 2013). Visnes et al. (2013) reported a two-fold increase in risk of developing patellar tendonitis with each 1 cm increase in jump

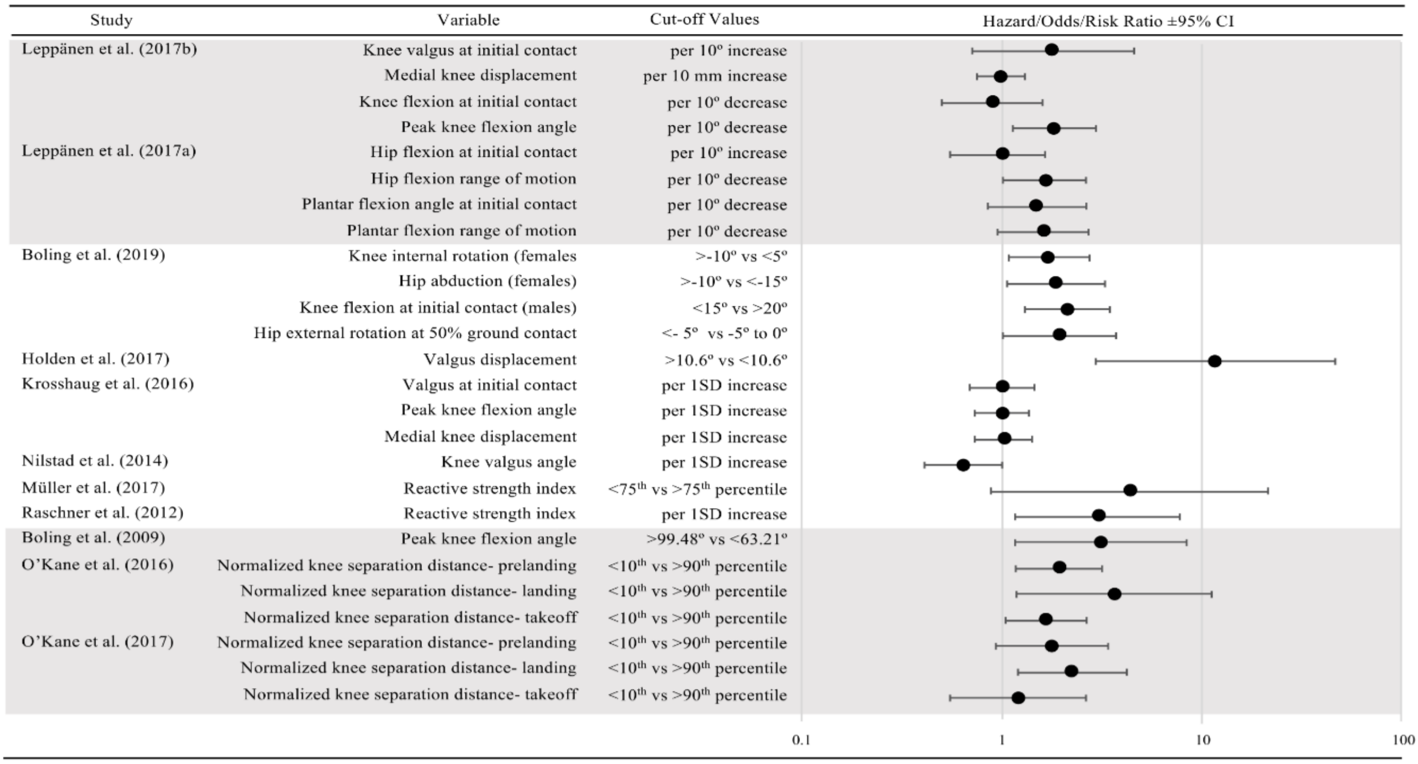

Figure 4 Likelihood of lower extremity injury in relation to kinematic drop jump variables studied in prospective cohort studies. Studies in the upper grey area present Hazard Ratios, in the lower grey area Risk Ratios and in the white area Odds Ratios. **SD** Standard Deviation.

height above the asymptomatic group (OR = 2.09; CI 1.03-4.25). All other studies investigating the relationship between countermovement jump height and risk of hamstring/groin strain (Arnason et al. 2004), ankle sprain (Attenborough et al. 2017; Sman et al. 2014), all knee injuries (MacDonald et al. 2018), or lower extremity injury in general (Emery et al. 2005; Frisch et al. 2011; Gabbett and Domrow 2005; Knapik et al. 2001; Ling et al. 2020; Quarrie et al. 2001; van Seters et al. 2017) failed to find a significant association (**Error! Reference source not found.**). Two studies investigated the relationship between squat jump height and lower-extremity injury risk with neither showing a relationship between lower extremity injury and jump height (Arnason et al. 2004; Frisch et al. 2011). Two studies also used loaded countermovement jump protocols to assess injury risk (Gabbett et al. 2012; Gastin et al. 2015). Gabbett et al. (2012) used incremental loading to determine peak power and found no relationship with future contact injury in rugby league players. Using a repeated jump protocol, Gastin et al. (2015) found that shorter ground contact times (OR = 4.08, CI 1.19-14.08) but not concentric or eccentric power was associated with increased risk of injury (Figure 6).

The only horizontal bilateral jump-land assessment identified by the search was a standing broad jump (**Error! Reference source not found.**). All five studies using a standing broad jump used either absolute jump distance or jump distance as a function of standing height as their outcome metric (Brumitt et al. 2016; Brumitt et al. 2018; Brumitt et al. 2013; Taanila et al. 2010; Taanila et al. 2015). Of these five studies, only Taanila et al. (2010) observed a relationship between absolute jump distance and risk of lower extremity musculoskeletal injury (HR = 1.6; CI 1.2-2.0). Only one study investigating any of the bilateral jump assessments

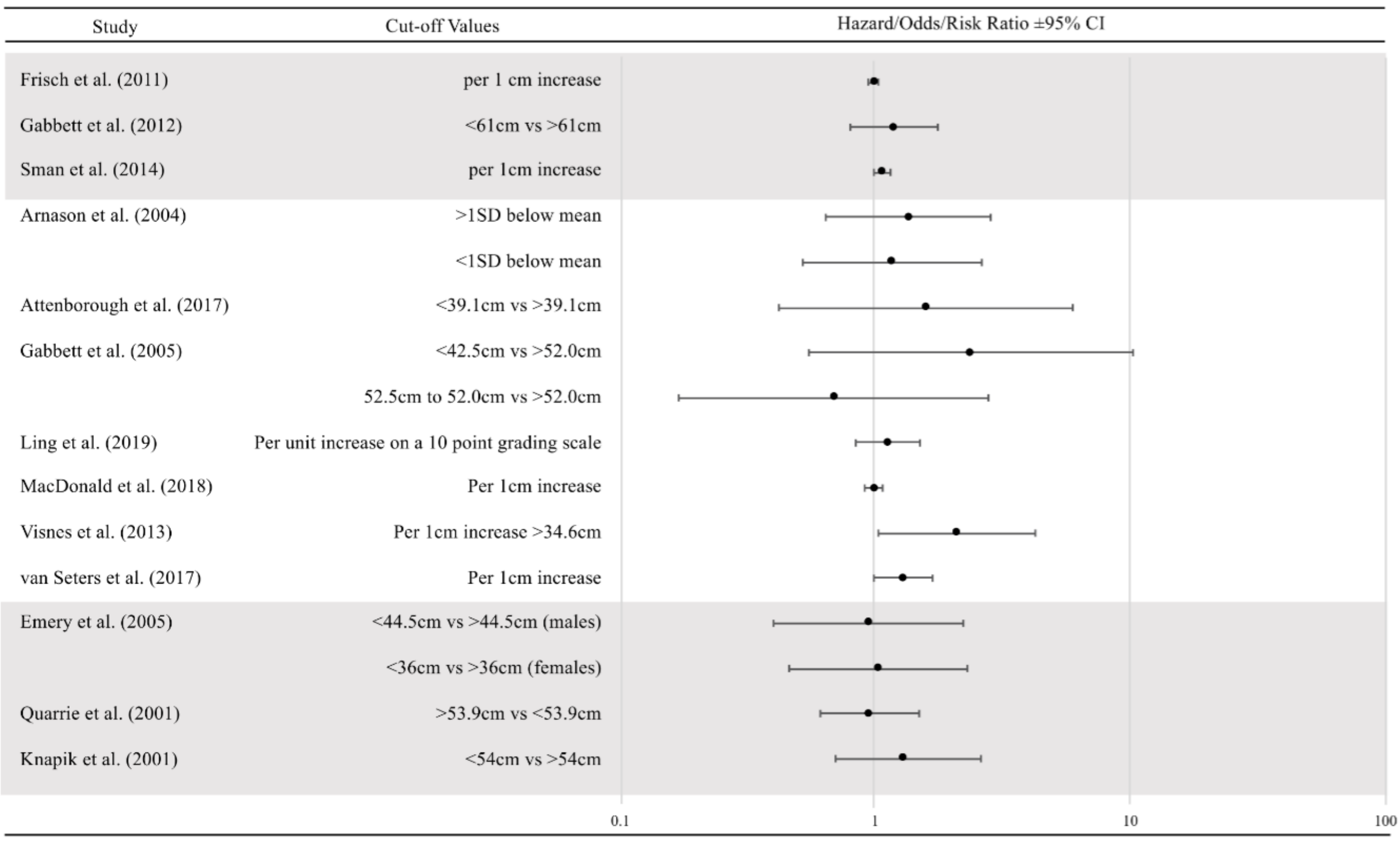

Figure 5 Likelihood of lower extremity injury in relation to countermovement jump height studied in prospective cohort studies. Studies in the upper grey area present Hazard Ratios, in the lower grey area Risk Ratios and in the white area Odds Ratios. **SD** Standard Deviation.

reported sensitivity and specificity. Brumitt et al. (2018) reported that a cut-off of value of <80% of standing height could predict lower extremity injury with 58% sensitivity and 39% specificity (OR = 1.1; CI 0.4-2.8).

Unilateral Jump Assessments

Four unilateral assessment tools were identified; two horizontal (single-leg hop for distance and hop and stick) and two vertical (single-leg drop jump and single-leg countermovement jump). Two studies investigated the relationship between landing variables in a hop and stick test. DuPrey et al. (DuPrey et al. 2016) found that backward hop time to stabilization was the only significant predictor of ACL injury risk in a multi-directional hop protocol (OR = 2.95; CI 1.28-6.77) and a cut-off of > 1.19 s could identify individuals who would go on to sustain

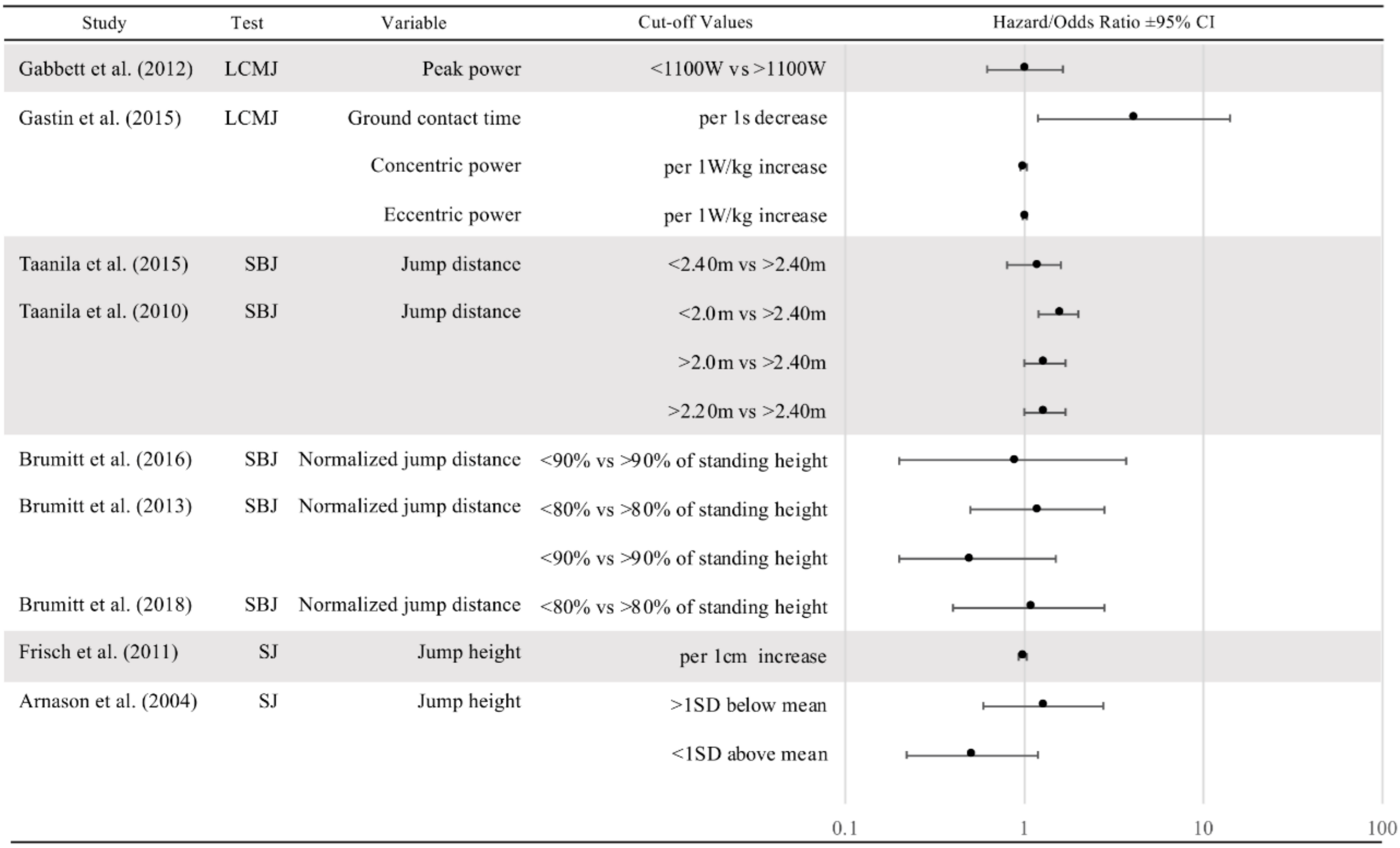

Figure 6 Likelihood of lower extremity injury in relation to a selection of variables in bilateral jump-land assessments. Studies in the grey areas presented Hazard Ratios, studies in the white areas presented Odds Ratios. **SD** Standard Deviation; **LCMJ** Loaded Countermovement Jump; **SBJ** Standing Broad Jump; **SJ** Squat Jump.

an ACL rupture with 89% sensitivity and 79% specificity. Read et al. (Read et al. 2018b) also used a hop and stick protocol whereby participants were required to hop 75% of their maximal single leg hop distance and then stabilise as rapidly as possible. The authors found no significant difference in peak vertical ground reaction force between participants who did and did not suffer a lower limb injury. The most widely investigated unilateral horizontal jump-land assessment was the single leg hop for distance. Of the 7 studies using this test, 3 observed a relationship with injury. Brumitt et al. (Brumitt et al. 2013) showed that females with a single leg hop asymmetry of greater than 10% were 4.4 (1.2-15.4; 95% CI) times more likely to suffer a foot or ankle injury. The authors also observed that males who could not hop more than 75% of their standing height were at significantly greater risk of thigh and knee injuries (OR = 3.3; CI 1.1-10.0). In a follow up study, the same authors found no significant relationship between asymmetry and risk of thigh or knee injury and could only predict the injured athletes with 30% sensitivity and 76% specificity (Brumitt et al. 2018). Goossens et al. (Goossens et al.

2015) observed that participants who suffered a hamstring injury had a significantly shorter single hop distance and the risk of injury was 13% greater for every standard deviation decrease in hop length (OR = 1.13; CI 1.03-1.23). The remaining four studies failed to observe any significant relationship between single leg hop distance or asymmetry between left and right leg and risk of lower extremity injury.

Two unilateral vertical assessment tools used in prospective cohort studies were identified; the single leg countermovement jump and single leg drop jump. Three studies applied a single-leg countermovement jump protocol prior to prospective injury surveillance (Henry et al. 2016; Read et al. 2018b; van Seters et al. 2017). Read et al. (Read et al. 2018b) observed that peak landing force asymmetry was a significant predictor of lower extremity injury in elite youth soccer players with a 10% increase in the risk of injury for each percentage increase in asymmetry (OR = 1.10; CI 1.03-1.16). Henry et al. (Henry et al. 2016) observed that amateur soccer players had a nine-fold increase in risk of suffering a non-contact ankle injury when lower limb power output was below 30 $W \cdot kg^{-1}$ (OR = 9.20; CI 1.13-75.09). Conversely, van Seters et al. (van Seters et al. 2017) found no association between single-leg countermovement jump height and risk of lower extremity injury in dance students.

Two studies investigated the relationship between single-leg drop jump variables and the risk of lower extremity injury. Verrelst et al. (Verrelst et al. 2014) found a selection of 3D kinematic variables were significant predictors of injury. Thorax rotation in the transverse plane between first ground contact and maximal knee flexion was a significant predictor of exertional medial tibial pain (OR = 10.20; CI 3.10-33.58) and a cut-off value of > 12.27° could identify the symptomatic group with 53% sensitivity and 89% specificity (**Error! Reference source not found.**). Similarly, thorax rotation during the concentric phase of the drop jump landing was significantly associated with greater risk of overuse injury (OR = 5.88; CI 1.77-19.52) and a cut-off point of > 13.24° predicted the injured participants with 39% sensitivity and 89% specificity. Hip internal rotation between ground contact and maximum knee flexion identified the injured participants with 76% sensitivity and 64% specificity when using a cut-off of >8.93° (OR = 5.83; CI 1.87-18.10). Furthermore, hip internal rotation during the concentric component of the ground contact phase was significantly associated with risk of injury (OR = 9.69; CI 1.21-77.77); with a cut-off point of > 6.12° predictive of injury with 95% sensitivity and 32 specificity. Fransz et al. (2018) analysed multiplanar time to stabilization in the second landing of a single leg drop jump and observed increased root mean square of mediolateral ground reaction force during the first 0.4s after landing reduced risk of lateral ankle sprain by

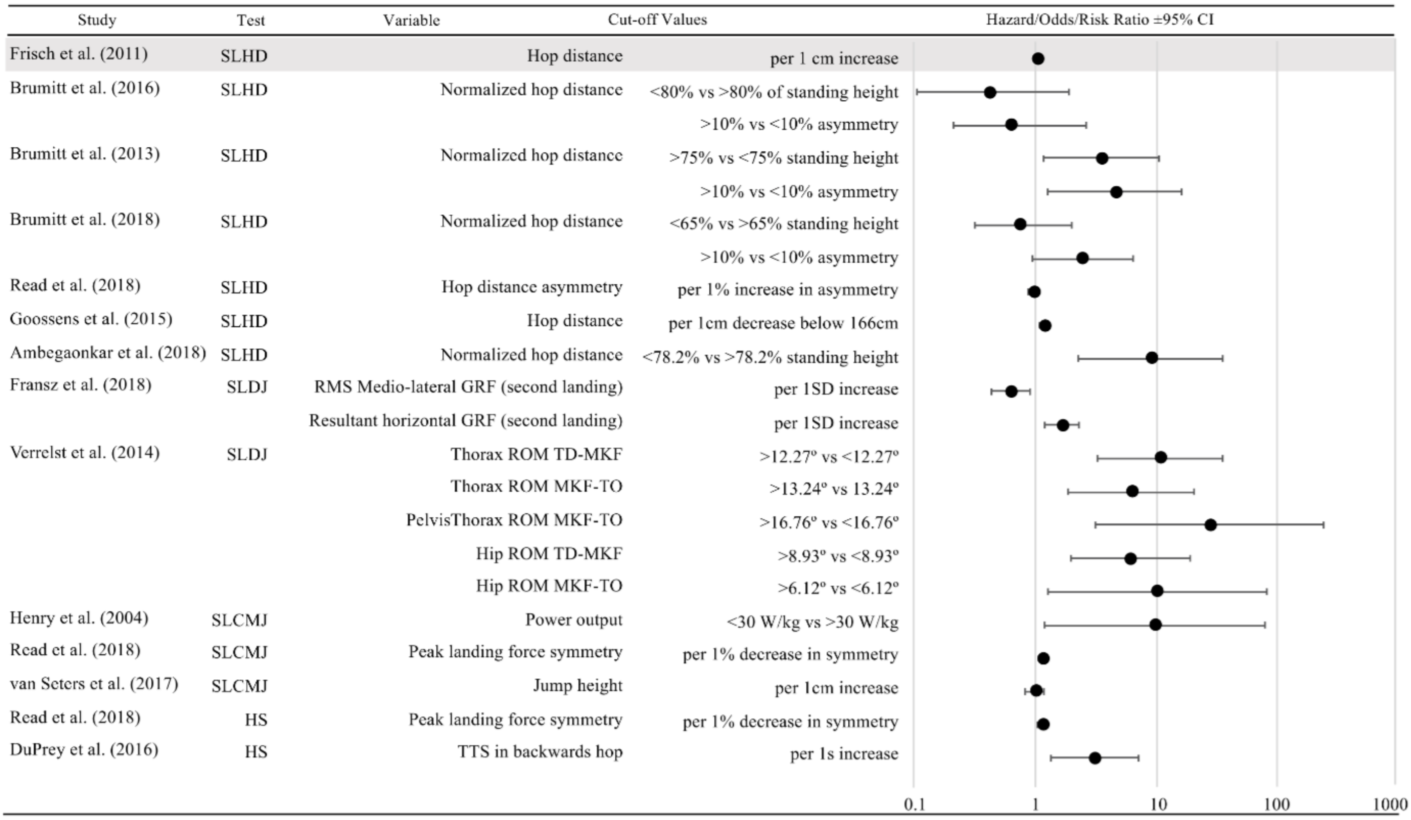

Figure 7 Likelihood of lower extremity injury in relation to a selection of variables in unilateral jump-land assessments. Studies in the grey area presented Hazard Ratios, studies in the white area presented Odds Ratios. **SLHD** Single Leg Hop for Distance; **SLDJ**; Single Leg Drop Jump; **SLCMJ** Single Leg Countermovement Jump; **HS** Hop and Stick; **ROM** Range of Motion; **TD** Touchdown; **MKF** Maximum Knee Flexion; **TO** Take-off; **TTS** Time to Stabilization.

40% (OR = 0.60; 0.41-0.86). Further, increased mean resultant horizontal force 3.0 - 5.0s after landing elevated injury risk by 57% (OR = 1.57; 1.13-2.18).

DISCUSSION

The aim of this review was to systematically summarise the existing body of literature relating to jump-landing assessments for the purposes of identifying risk factors for lower extremity injury in athletic populations. A consistent trend across all studies and jumping tasks was the poor association of performance outcome measures, such as jump height. Countermovement jump and drop jump were the most commonly investigated jump landing assessments for injury screening purposes with some kinetic and kinematic variables associated with a higher risk of injury in the latter. A variety of unilateral assessments were identified however each assessment was only used by a small number of studies

Drop Jump

A drop jump requires large force attenuation and production within short timeframes (typically < 250 ms), underpinned by a number of strength parameters and neuromuscular recruitment strategies (Pedley et al. 2017). Dysfunction of these feedforward strategies are reported to be key lower extremity injury risk factors (Read et al. 2016). Acute traumatic injuries such as ACL rupture are reported to occur within the first 56 ms of ground contact (Walden et al. 2015). Impact forces experienced during this time can exceed 2.5 x BW with an average loading rate of up to 60 $BW \cdot s^{-1}$ (Quatman et al. 2006); feedforward strategies that prepare the neuromuscular system to attenuate force effectively could help to mitigate the risk of injury from such loading. Consequently, the drop jump provides a controlled environment to assess an athlete's capacity to tolerate high vertical loading whilst maintaining dynamic joint stability. A number of kinematic variables (knee internal rotation, valgus displacement, normalized knee separation distance, knee flexion angles) (Boling et al. 2019; Boling et al. 2009; Holden et al. 2017; Leppanen et al. 2017b; O'Kane et al. 2017; O'Kane et al. 2016) (**Error! Reference source not found.**) and kinetic drop jump variables (knee abduction moment, knee flexion moment, peak vertical ground reaction force) (Boling et al. 2009; Hewett et al. 2005; Leppanen et al. 2017a; Leppanen et al. 2017b; Myer et al. 2010a) appear to be significantly associated with risk of lower-extremity injury.

Goetschius et al. (2012) used a clinic-based algorithm developed by Myer et al. (2010b) to predict knee abduction moment. The algorithm was shown to be ineffective at determining which athletes would go on to sustain an ACL rupture. However, it should be noted that the algorithm was developed based upon data from vertical drop jumps, but Goetschius et al. (2012) utilised a drop jump technique that includes a horizontal element as is used in the LESS (Padua et al. 2009). This subtle change in technique would have a substantial effect on the ground reaction forces, the kinetic chain and associated movement pattern as a result of the forward momentum of the body upon ground contact, which would likely invalidate a predictive tool based on data from a different movement pattern (Cruz et al. 2013). Goetschius et al. (2012) also had participants perform the assessment barefoot which in running gait studies has been demonstrated to change kinetics and kinematics and would not be representative of landing strategies used in gameplay when wearing footwear (Divert et al. 2005). Krosshaug et al. (2016b) used a vertical drop jump and kinetic and kinematic analyses to screen 710 female soccer and handball players and following reanalysis of their data set found no relationship between any variable and risk of ACL injury (Krosshaug et al. 2016a). Two of the three studies that did not observe any relationship with injury risk, focused on a single injury; ACL rupture (Goetschius et al. 2012; Krosshaug et al. 2016b). The remaining study only used a performance measure as the predictor variable (Muller et al. 2017). It is extremely unlikely that an athlete displaying aberrant landing mechanics is only at high-risk for an ACL injury but no other lower-extremity injuries. Myer et al. (2015) demonstrated that those at high risk of ACL injury might only represent the extreme end of a continuum and observed that a lower threshold for knee abduction moment was also predictive of those that went on to suffer from patellofemoral pain, an overuse injury. Consequently, a broader assessment of injury risk that encompasses acute and overuse injuries might be appropriate in future drop jump studies while non-standardization of protocols may lead to inconsistent results, and more standardized protocols should be adopted.

Other Bilateral Jump Assessments

Only a single study using a bilateral countermovement jump identified a relationship with injury risk (Visnes et al. 2013). Across the 15 studies identified for this review, the only variable investigated for a relationship to injury was jump height. Visnes et al. (2013) observed that athletes with a greater vertical jump were more likely to develop patellar tendonitis. Both studies investigating the association between squat jump performance and injury risk used jump height as the sole outcome variable and neither observed an association with risk of injury.

Jump height as a risk factor for injury presents a paradox since jumping higher suggests greater lower limb strength and power which has frequently been shown to be advantageous in reducing injury incidence (see (Lauersen et al. 2014) for a review). However, it could be that greater jump height results in greater magnitudes of force and velocity to be attenuated upon landing which have both been shown to be injurious (Hewett et al. 2006; Quatman et al. 2006; Read et al. 2016). From this perspective, further investigation into landing variables utilising both kinetic and kinematic analysis and their associations with risk of lower extremity injury risk should be pursued. Recent research into countermovement jump performance has highlighted the importance in assessing the force application strategy that an individual deploys in order to achieve a given performance outcome (Baumgart et al. 2017a; Baumgart et al.

2017b; Chavda et al. 2018; Gathercole et al. 2015; McMahon et al. 2018). These variables may provide greater insight into any potential relationship between countermovement jump performance and injury risk and subsequently further research is required in assessing these variables in prospective cohort studies.

Two studies conducted on samples of elite male Rugby League and Australian Football players used loaded countermovement jump protocols (Gabbett et al. 2012; Gastin et al. 2015). Gastin et al. (2015) demonstrated that longer ground contact times were associated with a reduced risk of injury and reduced injury severity, while larger concentric power was also associated with reduced injury severity. These findings suggest that when external load is applied and forces placed on the system exceed the capacity of the kinetic chain to absorb force safely and utilise the stretch-shortening cycle, the ability to decelerate over a wider range of movement and longer time frames is a useful skill in order to reduce injury risk. Previous research from injury risk in drop jumps supports the notion that stiff landings can be injurious (Leppanen et al. 2017b). Conversely, from a performance perspective, stiffer landings with less compliance at the point of ground contact are essential in achieving high reactive strength scores (Kipp et al. 2018). Once again this highlights the limitations of assessing kinematic variables in isolation and emphasises that it is not necessarily that stiff landings are dangerous but rather how that stiffness is achieved which is important with respect to injury risk. Gabbett et al. (2012) also assessed the relationship between injury risk and loaded countermovement jump performance. Their study found no relationship between peak power and injury risk though it must be highlighted that the authors only addressed contact injuries that are also influenced by multiple external factors.

Standing broad jump was the only bilateral horizontal jump assessment returned by the search. Across the five studies investigating a relationship with injury, all five used jump distance as the only variable for analysis, with two studies observing a relationship with injury (Taanila et al. 2010; Taanila et al. 2015). Both of these studies showed that military recruits were more likely to suffer a lower extremity injury during basic training if they had a standing broad jump distance of < 2 m. In contrast, the remaining three studies failed to observe a similar relationship, even when using different cut-off values (Brumitt et al. 2016; Brumitt et al. 2018; Brumitt et al. 2013). As with countermovement jump height, the standing broad jump distance provided inconsistent relationships as an indicator of injury risk. Injuries to the lower extremity during horizontal movement tasks are more likely to occur during the landing phase rather than the propulsive phase of ground contact (Krosshaug et al. 2007; Leppanen et al. 2017a; Leppanen et al. 2017b; Walden et al. 2015). Consequently, it is likely that landing variables in the standing broad jump might offer more insight into injury risk than a surrogate indicator of take-off force. In light of these considerations, future research should investigate braking forces and 2D and 3D motion analysis of the lower limb during landing from a horizontal jump.

Unilateral Jump Assessments

Seven studies used the single leg hop for distance test of which three found a significant relationship with injury risk. Goossens et al. (2015) showed that physical education students with a shorter single leg hop distance were at greater risk of hamstring strain. The single leg hop test requires participants to stick the landing and stabilize on the standing leg in order for a trial to be successful. Decelerating in a forward direction requires a large eccentric action by the quadriceps muscle group; concurrently, a counter moment must be produced by the hamstrings group to maintain knee joint stability. Individuals with weak hamstrings or large quadriceps-to-hamstring strength imbalances might be incapable of producing sufficient force to counter large moments produced at the knee and subsequently hop distance must be shortened. In contrast, Brumitt et al. (2013) found that an increased single leg hop distance increased risk of lower extremity injury in males. The remaining five studies investigating single leg hop for distance failed to observe a relationship between hop distance and risk of lower extremity injury (Ambegaonkar et al. 2018; Brumitt et al. 2016; Brumitt et al. 2018; Frisch et al. 2011; Read et al. 2018b). These inconsistent trends serve to emphasise the limitations of solely using a performance outcome to identify high risk individuals. Brumitt et al. (2013) observed that females with single leg hop distance asymmetry between legs of > 10% were at increased risk of lower extremity injury. No other study examined single leg hop distance asymmetry but asymmetry has been demonstrated to be an injury risk factor in a variety of biomotor tasks (Bishop et al. 2018; Fort-Vanmeerhaeghe et al. 2016; Hewit et al. 2012; Read et al. 2016) and therefore warrants further investigation.

The hop and stick test is very similar to the single leg hop for distance; however, hop distance is constrained so the effort is submaximal. Read et al. (2018b) showed no relationship between peak vertical ground reaction force when landing and risk of non-contact lower extremity injury in male youth soccer players. In contrast, DuPrey et al. (2016) found that time to stabilization when performing a backwards hop was a significant predictor of ACL injury risk.

Due to only two studies meeting all inclusion criteria using this jump-landing assessment, and these studies investigated different variables in distinctly separate tasks, it is difficult to draw firm conclusions on the validity of these assessments for identifying individuals at high risk of injury.

Three studies investigated the relationship between single leg countermovement jump performance and lower extremity injury risk. van Seters et al. (2017) assessed jump height and found no relationship with injury risk. In contrast, Henry et al. (2016) showed that individuals with a relative peak power < 30 $W \cdot kg^{-1}$ were 9.2 times more likely to incur a non-contact ankle injury than those above this threshold. This could potentially be due to the requirement for greater force attenuation as a result of greater jump height. Alternatively, this relationship could be a result of a bias in exposure as a result of the more powerful players experiencing more competitive match time. Read et al. (2018b) observed that vertical ground reaction force asymmetry was a significant predictor of lower extremity injury risk in elite male youth soccer players. Leg asymmetries have been suggested to preferentially load the stronger leg, which with repeated exposures may exceed its force tolerating capacity and result in injury (Bishop et al. 2018). Further research is required to determine what should be considered ‘normal’ magnitudes of asymmetry in single leg countermovement jump landing forces.

Verrelst et al. (2014) found that trunk rotation and hip internal rotation during a single leg drop jump was associated with lower extremity overuse injury. These findings serve to emphasise the extra challenge of unilateral assessments, as the movement of body segments more distal from the ground have an influence on the stability of the lower limb as a result of the narrower base of support. Consequently, assessments using performance metrics will not likely detect these aberrant movement patterns and kinematic analysis of the whole body might be essential when using unilateral assessments to take account for control of the largest proportion of body mass; the trunk. Fransz et al. (2018) was notably the only study to assess multi-planar ground reaction forces in a jump-landing assessment. They observed that greater medio-lateral forces immediately after ground contact reduced the risk of lateral ankle sprain in footballers. They speculated that the non-injured players made greater effort to stabilize in the frontal plane upon landing and this protected the ankle from injury. Single leg drop jump studies present interesting avenues for future research with promising prelimary results. However, with only two studies meeting the inclusion criteria for this review further research is required to fully understand the value of this assessment in determining an individual's risk of lower extremity injury.

The findings of the current review indicate that kinetic and kinematic variables collected during drop jump and unilateral assessments present the best opportunity for injury risk screening based upon the existing literature. However, further research is required to more clearly elucidate the influence of drop jump ground reaction force variables on the risk of suffering a lower extremity injury. All of the studies using unilateral assessments alongside kinetic or kinematic analyses that were included in the current review observed associations with injury risk, though the magnitude of these associations varied substantially. Due to the aforementioned limitations of performance metrics in predicting risk of injury, future research using unilateral jump performance and landing assessments should report limb asymmetries and analyse joint stability since these seem to be the primary advantages of unilateral assessments.

A limitation of the current review is the bias for authors to only report significant associations with injury. An inclusion criterion for the current study was the publication of predictive statistics (or sufficient data to calculate these *post hoc*). Many studies that were included in this review evaluated variables where there was no significant association with risk of injury but did not then report the associated statistics for these null findings. Finally, a meta-analysis of the findings of this review was not performed due to the variation in the reporting of the risk of injury across the 40 studies that were included. Studies reported a range of hazard ratios, risk ratios, and odds ratios and while these statistics are related they are not synonymous. Furthermore, in order to calculate a single standardised odds ratio for the purpose of a meta-analysis, the sensitivity, specificity and numbers of injured and uninjured participants are needed. Only six of the 40 studies included in this systematic review reported these statistical measures. It is recommended that future prospective injury screening studies report these statistics to allow meta-analysis of findings and extrapolation of conclusions beyond single study populations.

Practitioners are advised that performance measures of jumping and hopping height might provide valuable insights into performance improvement but offer little insight into an athlete's risk of injury. A broad range of assessment protocols are available for athletic trainers to screen their athlete's for lower limb injury risk but regardless of the jump assessment chosen, kinetic and kinematic variables measured during the landing phase of the test will provide the greatest insight of an athlete's risk of injury. The drop jump and unilateral assessments present the best opportunity for injury risk screening based upon the existing literature while the drop vertical jump remains the most valid evidence-based screening assessment for lower-extremity injury risk. Athletic trainers choosing to utilise a drop jump screening protocol should endeavour to measure a combination of frontal plane (knee valgus, valgus displacement, normalized knee separation distance) and sagittal plane (knee flexion at initial contact and peak knee angular displacement) kinematic variables and kinetic variables (knee abduction moment, peak vertical ground reaction force) to give a holistic view of an athlete's competency. Future research using unilateral jump performance and landing assessments should report limb asymmetries and analyse postural control since these seem to be the primary advantages of unilateral assessments. Researchers are advised to broaden the scope of injuries that are investigated in future research studies in the hope of identifying injury risk factors for other types of injury provided that the task presents some degree of similarity to the mechanism of injury.

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REFERENCES

Aerts I, Cumps E, Verhagen E, Verschueren J, Meeusen R (2013) A systematic review of different jump-landing variables in relation to injuries J Sports Med Phys Fitness 53:509-519

Altman DG (1991) Practical statistics for medical research. Chapman and Hall, London

Ambegaonkar JP, Caswell SV, Cortes N (2018) Lower Extremity Horizontal Work, But Not Vertical Power, Predicts Balance Performance in Female Collegiate Dancers J Dance Med Sci 22:75-80 doi:10.12678/1089-313X.22.2.75

Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R (2004) Risk factors for injuries in football Am J Sports Med 32:5S-16S doi:10.1177/0363546503258912

Attenborough AS, Sinclair PJ, Sharp T, Greene A, Stuelcken M, Smith RM, Hiller CE (2017) The identification of risk factors for ankle sprains sustained during netball participation Phys Ther Sport 23:31-36 doi:10.1016/j.ptsp.2016.06.009

Bahr R (2016) Why screening tests to predict injury do not work-and probably never will...: a critical review Br J Sports Med 50:776-780 doi:10.1136/bjsports-2016-096256

Bates NA, Nesbitt RJ, Shearn JT, Myer GD, Hewett TE (2015) Relative strain in the anterior cruciate ligament and medial collateral ligament during simulated jump landing and sidestep cutting tasks: implications for injury risk Am J Sports Med 43:2259-2269 doi:10.1177/0363546515589165

Baumgart C, Hoppe MW, Freiwald J (2017a) Phase-Specific Ground Reaction Force Analyses of Bilateral and Unilateral Jumps in Patients With ACL Reconstruction Orthop J Sports Med 5:2325967117710912 doi:10.1177/2325967117710912

Baumgart C, Schubert M, Hoppe MW, Gokeler A, Freiwald J (2017b) Do ground reaction forces during unilateral and bilateral movements exhibit compensation strategies following ACL reconstruction? Knee Surg Sports Traumatol Arthrosc 25:1385-1394 doi:10.1007/s00167-015-3623-7

Bengtsson H, Ekstrand J, Hagglund M (2013) Muscle injury rates in professional football increase with fixture congestion: an 11-year follow-up of the UEFA Champions League injury study Br J Sports Med 47:743-747 doi:10.1136/bjsports-2013-092383

Beynnon BD, Fleming BC (1998) Anterior cruciate ligament strain in-vivo: a review of previous work J Biomech 31:519-525

Bishop C, Turner A, Read P (2018) Effects of inter-limb asymmetries on physical and sports performance: a systematic review J Sports Sci 36:1135-1144 doi:10.1080/02640414.2017.1361894

Bittencourt NFN, Meeuwisse WH, Mendonca LD, Nettel-Aguirre A, Ocarino JM, Fonseca ST (2016) Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition-narrative review and new concept Br J Sports Med 50:1309-1314 doi:10.1136/bjsports-2015-095850

Boling MC, Nguyen AD, Padua DA, Cameron KL, Beutler A, Marshall SW (2019) Gender-Specific Risk Factor Profiles for Patellofemoral Pain Clin J Sport Med doi:10.1097/JSM.0000000000000719

Boling MC, Padua DA, Marshall SW, Guskiewicz K, Pyne S, Beutler A (2009) A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort Am J Sports Med 37:2108-2116 doi:10.1177/0363546509337934

Brumitt J, Engilis A, Isaak D, Briggs A, Mattocks A (2016) Preseason Jump and Hop Measures in Male Collegiate Basketball Players: An Epidemiologic Report Int J Sports Phys Ther 11:954-961

Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, Mattocks A, Rauh MJ (2018) Preseason Functional Test Scores Are Associated With Future Sports Injury in Female Collegiate Athletes J Strength Cond Res 32:1692-1701 doi:10.1519/JSC.0000000000002243

Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, Rauh MJ (2013) Lower extremity functional tests and risk of injury in division iii collegiate athletes Int J Sports Phys Ther 8:216-227

Chavda S et al. (2018) Force-time characteristics of the countermovement jump: analyzing the curve in Excel Strength and Conditioning Journal 40:67-77

Cruz A, Bell D, McGrath M, Blackburn T, Padua D, Herman D (2013) The effects of three jump landing tasks on kinetic and kinematic measures: implications for ACL injury research Res Sports Med 21:330-342 doi:10.1080/15438627.2013.825798

Dingenen B, Malfait B, Nijs S, Peers KH, Vereecken S, Verschueren SM, Staes FF (2015) Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study Clin Biomech (Bristol, Avon) 30:781-787 doi:10.1016/j.clinbiomech.2015.06.013

Divert C, Mornieux G, Baur H, Mayer F, Belli A (2005) Mechanical comparison of barefoot and shod running Int J Sports Med 26:593-598 doi:10.1055/s-2004-821327

DuPrey KM, Liu K, Cronholm PF, Reisman AS, Collina SJ, Webner D, Kaminski TW (2016) Baseline Time to Stabilization Identifies Anterior Cruciate Ligament Rupture Risk in Collegiate Athletes Am J Sports Med 44:1487-1491 doi:10.1177/0363546516629635

Ekstrand J, Hägglund M, Waldén M (2011) Injury incidence and injury patterns in professional football: the UEFA injury study Br J Sports Med 45:553-558 doi:10.1136/bjsm.2009.060582

Emery CA, Meeuwisse WH, Hartmann SE (2005) Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system Am J Sports Med 33:1882-1891 doi:10.1177/0363546505279576

Fort-Vanmeerhaeghe A, Gual G, Romero-Rodriguez D, Unnitha V (2016) Lower Limb Neuromuscular Asymmetry in Volleyball and Basketball Players J Hum Kinet 50:135-143 doi:10.1515/hukin-2015-0150

Fox AS, Bonacci J, McLean SG, Spittle M, Saunders N (2016) A Systematic Evaluation of Field-Based Screening Methods for the Assessment of Anterior Cruciate Ligament (ACL) Injury Risk Sports Med 46:715-735 doi:10.1007/s40279-015-0443-3

Fransz DP, Huurnink A, Kingma I, de Boode VA, Heyligers IC, van Dieen JH (2018) Performance on a Single-Legged Drop-Jump Landing Test Is Related to Increased Risk of Lateral Ankle Sprains Among Male Elite Soccer Players: A 3-Year Prospective Cohort Study Am J Sports Med 46:3454-3462 doi:10.1177/0363546518808027

Frisch A, Urhausen A, Seil R, Croisier JL, Windal T, Theisen D (2011) Association between preseason functional tests and injuries in youth football: a prospective follow-up Scand J Med Sci Sports 21:e468-476 doi:10.1111/j.1600-0838.2011.01369.x

Gabbe BJ, Finch CF, Bennell KL, Wajswelner H (2003) How valid is a self reported 12 month sports injury history? Br J Sports Med 37:545-547

Gabbett TJ, Domrow N (2005) Risk factors for injury in subelite rugby league players Am J Sports Med 33:428-434 doi:10.1177/0363546504268407

Gabbett TJ, Ullah S, Finch CF (2012) Identifying risk factors for contact injury in professional rugby league players--application of a frailty model for recurrent injury J Sci Med Sport 15:496-504 doi:10.1016/j.jsams.2012.03.017

Gastin PB, Meyer D, Huntsman E, Cook J (2015) Increase in injury risk with low body mass and aerobic-running fitness in elite Australian football Int J Sports Physiol Perform 10:458-463 doi:10.1123/ijspp.2014-0257

Gathercole R, Sporer B, Stellingwerff T, Sleivert G (2015) Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue Int J Sports Physiol Perform 10:84-92 doi:10.1123/ijspp.2013-0413

Goetschius J et al. (2012) Application of a clinic-based algorithm as a tool to identify female athletes at risk for anterior cruciate ligament injury: a prospective cohort study with a nested, matched case-control analysis Am J Sports Med 40:1978-1984 doi:10.1177/0363546512456972

Goossens L, Witvrouw E, Vanden Bossche L, De Clercq D (2015) Lower eccentric hamstring strength and single leg hop for distance predict hamstring injury in PETE students Eur J Sport Sci 15:436-442 doi:10.1080/17461391.2014.955127

Hägglund M, Waldén M, Ekstrand J (2013) Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study Am J Sports Med 41:327-335 doi:10.1177/0363546512470634

Hegedus EJ, McDonough S, Bleakley C, Cook CE, Baxter GD (2015) Clinician-friendly lower extremity physical performance measures in athletes: a systematic review of measurement properties and correlation with injury, part 1. The tests for knee function including the hop tests Br J Sports Med 49:642-648 doi:10.1136/bjsports-2014-094094

Henry T, Evans K, Snodgrass SJ, Miller A, Callister R (2016) Risk Factors for Noncontact Ankle Injuries in Amateur Male Soccer Players: A Prospective Cohort Study Clin J Sport Med 26:251-258 doi:10.1097/JSM.0000000000000240

Hewett TE, Ford KR, Hoogenboom BJ, Myer GD (2010) Understanding and preventing acl injuries: current biomechanical and epidemiologic considerations - update 2010 N Am J Sports Phys Ther 5:234-251

Hewett TE et al. (2005) Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study Am J Sports Med 33:492-501 doi:10.1177/0363546504269591

Hewett TE, Myer GD, Ford KR, Paterno MV, Quatman CE (2016) Mechanisms, prediction, and prevention of ACL injuries: Cut risk with three sharpened and validated tools J Orthop Res 34:1843-1855 doi:10.1002/jor.23414

Hewett TE, Myer GD, Ford KR, Slauterbeck JR (2006) Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex Clin J Sport Med 16:298-304

Hewit J, Cronin J, Hume P (2012) Multidirectional leg asymmetry assessment in sport Strength and Conditioning Journal 34:82-86

Holden S, Boreham C, Doherty C, Delahunt E (2017) Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females Scand J Med Sci Sports 27:188-194 doi:10.1111/sms.12633

Hootman JM, Dick R, Agel J (2007) Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives J Athl Train 42:311-319

Kipp K, Kiely MT, Giordanelli MD, Malloy PJ, Geiser CF (2018) Biomechanical Determinants of the Reactive Strength Index During Drop Jumps Int J Sports Physiol Perform 13:44-49 doi:10.1123/ijspp.2017-0021

Knapik JJ, Sharp MA, Canham-Chervak M, Hauret K, Patton JF, Jones BH (2001) Risk factors for training-related injuries among men and women in basic combat training Med Sci Sports Exerc 33:946-954

Krosshaug T et al. (2007) Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases Am J Sports Med 35:359-367 doi:10.1177/0363546506293899
Krosshaug T et al. (2016a) Corrigendum Am J Sports Med 45:NP28-29 doi:10.1177/0363546515625048
Krosshaug T et al. (2016b) The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes Am J Sports Med 44:874-883 doi:10.1177/0363546515625048
Lauersen JB, Bertelsen DM, Andersen LB (2014) The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials Br J Sports Med 48:871-877 doi:10.1136/bjsports-2013-092538
Leppanen M et al. (2017a) Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study Orthop J Sports Med 5:2325967117745487 doi:10.1177/2325967117745487
Leppanen M et al. (2017b) Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players Am J Sports Med 45:386-393 doi:10.1177/0363546516665810
Ling D, Sleeper M, Casey E (2020) Identification of Risk Factors for Injury in Women's Collegiate Gymnastics With the Gymnastics Functional Measurement Tool PM R 12:43-48 doi:10.1002/pmrj.12184
Lundblad M, Waldén M, Magnusson H, Karlsson J, Ekstrand J (2013) The UEFA injury study: 11-year data concerning 346 MCL injuries and time to return to play Br J Sports Med 47:759-762 doi:10.1136/bjsports-2013-092305
MacDonald K, Palacios-Derflingher L, Kenny S, Emery C, Meeuwisse WH (2018) Jumper's Knee: A Prospective Evaluation of Risk Factors in Volleyball Players Using a Novel Measure of Injury Clin J Sport Med doi:10.1097/JSM.0000000000000638
McMahon JJ, Jones PA, Suchomel TJ, Lake J, Comfort P (2018) Influence of the Reactive Strength Index Modified on Force- and Power-Time Curves Int J Sports Physiol Perform 13:220-227 doi:10.1123/ijspp.2017-0056
Moher D, Liberati A, Tetzlaff J, Altman DG, Group P (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement Ann Intern Med 151:264-269, W264
Muller L, Hildebrandt C, Muller E, Fink C, Raschner C (2017) Long-Term Athletic Development in Youth Alpine Ski Racing: The Effect of Physical Fitness, Ski Racing Technique, Anthropometrics and Biological Maturity Status on Injuries Front Physiol 8:656 doi:10.3389/fphys.2017.00656
Myer GD et al. (2010a) The incidence and potential pathomechanics of patellofemoral pain in female athletes Clin Biomech (Bristol, Avon) 25:700-707 doi:10.1016/j.clinbiomech.2010.04.001
Myer GD, Ford KR, Di Stasi SL, Foss KD, Micheli LJ, Hewett TE (2015) High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? Br J Sports Med 49:118-122 doi:10.1136/bjsports-2013-092536
Myer GD, Ford KR, Khoury J, Succop P, Hewett TE (2010b) Development and validation of a clinic-based prediction tool to identify female athletes at high risk for anterior cruciate ligament injury Am J Sports Med 38:2025-2033 doi:10.1177/0363546510370933
Nilstad A, Andersen TE, Bahr R, Holme I, Steffen K (2014) Risk factors for lower extremity injuries in elite female soccer players Am J Sports Med 42:940-948 doi:10.1177/0363546513518741
Noyes FR, Barber-Westin SD, Fleckenstein C, Walsh C, West J (2005) The drop-jump screening test: difference in lower limb control by gender and effect of neuromuscular

training in female athletes Am J Sports Med 33:197-207 doi:10.1177/0363546504266484
O'Kane JW, Neradilek M, Polissar N, Sabado L, Tencer A, Schiff MA (2017) Risk Factors for Lower Extremity Overuse Injuries in Female Youth Soccer Players Orthop J Sports Med 5:2325967117733963 doi:10.1177/2325967117733963
O'Kane JW, Tencer A, Neradilek M, Polissar N, Sabado L, Schiff MA (2016) Is Knee Separation During a Drop Jump Associated With Lower Extremity Injury in Adolescent Female Soccer Players? Am J Sports Med 44:318-323 doi:10.1177/0363546515613076
Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett WE, Jr., Beutler AI (2009) 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 37:1996-2002 doi:10.1177/0363546509343200
Pedley JS, Lloyd RS, Read PJ, Moore IS, Oliver JL (2017) Drop jump: a technical model for scientific application Strength and Conditioning Journal 39:36-44
Quarrie KL, Alsop JC, Waller AE, Bird YN, Marshall SW, Chalmers DJ (2001) The New Zealand rugby injury and performance project. VI. A prospective cohort study of risk factors for injury in rugby union football Br J Sports Med 35:157-166
Quatman CE, Ford KR, Myer GD, Hewett TE (2006) Maturation leads to gender differences in landing force and vertical jump performance: a longitudinal study Am J Sports Med 34:806-813 doi:10.1177/0363546505281916
Quatman CE, Quatman CC, Hewett TE (2009) Prediction and prevention of musculoskeletal injury: a paradigm shift in methodology Br J Sports Med 43:1100-1107 doi:10.1136/bjsm.2009.065482
Raschner C, Platzer HP, Patterson C, Werner I, Huber R, Hildebrandt C (2012) The relationship between ACL injuries and physical fitness in young competitive ski racers: a 10-year longitudinal study Br J Sports Med 46:1065-1071 doi:10.1136/bjsports-2012-091050
Read PJ, Oliver JL, De Ste Croix MB, Myer GD, Lloyd RS (2016) Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in Male Youth Soccer Players Sports Med 46:1059-1066 doi:10.1007/s40279-016-0479-z
Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS (2018a) An audit of injuries in six english professional soccer academies J Sports Sci 36:1542-1548 doi:10.1080/02640414.2017.1402535
Read PJ, Oliver JL, De Ste Croix MBA, Myer GD, Lloyd RS (2018b) A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players Scand J Med Sci Sports 28:1244-1251 doi:10.1111/sms.13013
Sman AD et al. (2014) Predictive factors for ankle syndesmosis injury in football players: a prospective study J Sci Med Sport 17:586-590 doi:10.1016/j.jsams.2013.12.009
Taanila H, Suni J, Pihlajamaki H, Mattila VM, Ohrankammen O, Vuorinen P, Parkkari J (2010) Aetiology and risk factors of musculoskeletal disorders in physically active conscripts: a follow-up study in the Finnish Defence Forces BMC Musculoskelet Disord 11:146 doi:10.1186/1471-2474-11-146
Taanila H, Suni JH, Kannus P, Pihlajamaki H, Ruohola JP, Viskari J, Parkkari J (2015) Risk factors of acute and overuse musculoskeletal injuries among young conscripts: a population-based cohort study BMC Musculoskelet Disord 16:104 doi:10.1186/s12891-015-0557-7
Teyhen DS et al. (2018) Incidence of Musculoskeletal Injury in US Army Unit Types: A Prospective Cohort Study J Orthop Sports Phys Ther 48:749-757 doi:10.2519/jospt.2018.7979

van Mechelen W, Hlobil H, Kemper H (1992) Incidence, severity, aetiology and prevention of sports injuries. A review of concepts. Sports Med 14

van Seters C, van Rijn RM, van Middelkoop M, Stubbe JH (2017) Risk Factors for Lower-Extremity Injuries Among Contemporary Dance Students Clin J Sport Med doi:10.1097/JSM.0000000000000533

Verrelst R, De Clercq D, Vanrenterghem J, Willems T, Palmans T, Witvrouw E (2014) The role of proximal dynamic joint stability in the development of exertional medial tibial pain: a prospective study Br J Sports Med 48:388-393 doi:10.1136/bjsports-2012-092126

Visnes H, Aandahl HA, Bahr R (2013) Jumper's knee paradox--jumping ability is a risk factor for developing jumper's knee: a 5-year prospective study Br J Sports Med 47:503-507 doi:10.1136/bjsports-2012-091385

Waldén M, Hägglund M, Ekstrand J (2013) Time-trends and circumstances surrounding ankle injuries in men's professional football: an 11-year follow-up of the UEFA Champions League injury study Br J Sports Med 47:748-753 doi:10.1136/bjsports-2013-092223

Walden M, Krosshaug T, Bjorneboe J, Andersen TE, Faul O, Hagglund M (2015) Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases Br J Sports Med 49:1452-1460 doi:10.1136/bjsports-2014-094573

Table S 1 Outcomes of methodological quality assessment performed on included studies.

Study	1	2	3	4	5	6	7	8	9	10	11	Total (/11)
Ambegaonkar et al. (2018)	0	1	1	1	1	N/A	0	1	0	1	1	7
Arnason et al. (2004)	1	1	1	1	1	N/A	0	1	1	1	1	9
Attenborough et al. (2017)	1	1	1	1	1	N/A	0	1	0	1	1	8
Boling et al. (2009)	1	1	1	0	1	N/A	0	1	1	1	1	8
Boling et al. (2019)	1	1	1	1	1	N/A	0	1	0	1	1	8
Brumitt et al. (2018)	1	1	1	1	1	N/A	0	1	1	1	1	9
Brumitt et al. (2016)	1	1	1	1	1	N/A	0	1	1	1	1	9
Brumitt et al. (2013)	1	1	1	1	1	N/A	0	1	0	1	1	8
DuPrey et al. (2016)	1	1	1	1	1	N/A	0	1	0	1	1	8
Emery et al. (2005)	0	1	1	1	1	N/A	0	1	0	1	1	7
Fransz et al. (2018)	0	1	1	1	1	N/A	0	1	0	1	1	7
Frisch et al. (2011)	1	1	1	1	1	N/A	0	1	0	1	1	8
Gabbett et al. (2012)	1	1	1	1	1	N/A	0	1	1	1	1	9
Gabbett and Domrow (2005)	0	1	1	0	1	N/A	0	0	1	1	1	6
Gastin et al. (2015)	0	1	1	1	1	N/A	0	1	0	1	1	7
Goetschius et al. (2012)	1	1	1	1	1	1	0	1	1	1	1	10
Goossens et al. (2015)	0	1	1	1	1	N/A	0	1	0	1	1	7
Henry et al. (2016)	1	1	1	1	1	N/A	0	0	1	1	1	8

Hewett et al. (2005)	0	1	1	1	1	N/A	0	0	0	1	1	6
Holden et al. (2017)	1	1	1	1	1	N/A	0	1	0	1	1	8
Knapik et al. (2001)	0	1	1	1	0	N/A	0	1	0	1	1	6
Krosshaug et al. (2016)	0	1	1	1	1	N/A	0	1	1	1	1	8
Leppanen et al. (2017b)	1	1	1	1	1	N/A	0	1	0	1	1	8
Leppanen et al. (2017a)	1	1	1	1	1	N/A	0	1	0	1	1	8
Ling et al. (2020)	0	1	1	1	0	N/A	0	0	1	1	1	6
MacDonald et al. (2018)	1	1	1	1	1	N/A	0	1	1	1	1	9
Myer et al. (2010)	1	1	1	1	1	1	0	0	0	1	1	8
Muller et al. (2017)	1	1	1	1	1	N/A	0	0	0	1	1	7
Nilstad et al. (2014)	1	1	1	1	1	N/A	0	1	1	1	1	9
O'Kane et al. (2016)	0	1	1	1	1	N/A	0	1	1	1	1	8
O'Kane et al. (2017)	0	1	1	1	1	N/A	0	1	0	1	1	7
Quarrie et al. (2001)	0	1	1	1	0	N/A	0	1	0	0	1	5
Raschner et al. (2012)	1	1	1	1	1	N/A	0	1	1	1	1	9
Read et al. (2018)	1	1	1	1	1	N/A	0	0	1	1	1	8
Sman et al. (2014)	1	1	1	1	1	N/A	0	1	1	1	1	9
Taanila et al. (2015)	1	1	1	1	1	N/A	0	1	0	1	1	8
Taanila et al. (2010)	1	1	1	1	1	N/A	0	1	0	1	1	8
van Seters et al. (2017)	1	1	1	1	1	N/A	0	1	1	1	1	9
Verrelst et al. (2014)	1	1	1	1	1	N/A	0	1	1	1	1	9
Visnes et al. (2013)	1	1	1	1	1	N/A	0	1	0	1	1	8

1= Subject inclusion/exclusion criteria clearly described (1 point)

2= Enough information to identify setting (1 point)

3= Study design- prospective (1 point) or retrospective (0 points) collection of data

4= Age (mean/median and SD/range) and gender reported (1 point)

5= Description of screening method had sufficient detail to permit replication of the test. Test device or instruments, protocol of screening method reported (1 point)

6= Groups were comparable at baseline, including all major confounding and prognostic factors (1 point)

7= Investigators were kept blind to important confounding and prognostic factors

8= For variable/s of interest, details given on mean/median, standard deviation/ confidence intervals and predictive value (1 point)

9= Reliability reported (1 point)

10= All included subjects measured and, if appropriate missing data or withdrawals from study reported or explained (1 point)

11= Outcome clearly defined and method of examination of outcome adequate (1 point)

A score of zero was given for criteria if insufficient information was available for accurate assessment

N/A- criteria not applicable