RISK FACTORS FOR LOWER LIMB INJURY IN FEMALE TEAM FIELD AND COURT
SPORTS: A SYSTEMATIC REVIEW, META-ANALYSIS, AND BEST EVIDENCE
SYNTHESIS

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Word count: 4257/10000

Abstract word count: 303

ABSTRACT

Background: Identifying risk factors for lower limb injury is an important step in developing injury risk reduction training and testing for player monitoring. Female athletes are distinct from male athletes, warranting separate investigation into risk factors.

Objective: To systematically review the literature and synthesise the evidence for intrinsic risk factors for lower limb injury in female team field and court sports.

Method: Five online databases were searched from inception to April 2020. To be eligible for inclusion, studies were required to be a prospective study presenting intrinsic risk factors for lower limb injury in female team field or court sport athletes. Risk of bias was assessed using the Quality of Prognosis Studies tool.

Results: Sixty-nine studies, capturing 2902 lower limb injuries in 14,492 female athletes, and analysing 80 distinct factors met the inclusion criteria. Risk factors for any lower limb injury included greater body mass (standardised mean difference [SMD]=0.24, 95% confidence interval [95%CI]=0.18-0.29), greater body mass index (BMI) (SMD=0.22, 95%CI=0.05-0.40), older age (SMD=0.20, 95%CI=0.09-0.31), greater star excursion balance test (SEBT) anterior reach distance (SMD=0.18, 95%CI=0.12-0.24), and smaller single-leg hop distance (SMD=-0.09, 95%CI=-0.12- -0.06). Lower knee injury and osteoarthritis outcome score (KOOS) increased the risk of knee injury. Anterior cruciate ligament (ACL) injury risk factors included prior ACL injury (odds ratio [OR]=3.94, 95%CI=2.07-7.50), greater double-leg postural sway (SMD=0.58, 95%CI=0.02-1.15), and greater body mass (SMD=0.25, 95%CI=0.12-0.39). Ankle injury risk factors included smaller SEBT anterior reach distance (SMD=-0.13, 95%CI=-0.14- -0.13), greater single-leg hop distance asymmetry (OR=3.67, 95%CI=1.42-9.45), and slower agility course time (OR=0.20, 95%CI=0.05-0.88). Remaining factors were not associated with injury or had conflicting evidence.

Conclusion: Prior injury, older age, greater body mass, and greater BMI are risk factors for lower limb injury in female athletes. Limited evidence showed an association between KOOS, SEBT anterior reach, single-leg hop distance and asymmetry, double-leg postural sway, agility and lower limb injury. PROSPERO ID: CRD42020171973.

Key points

- Prior injury, older age, greater body mass, greater body mass index, and lower KOOS are risk factors for lower limb injury in female athletes.
- Performance tests associated with injury include star excursion balance test anterior reach, single-leg hop distance and asymmetry, double-leg postural sway, and agility course time.
- The majority of test/factors commonly proposed to be associated with injury have limited evidence, predominantly due to conflicting results between studies.

1 Introduction

Female team field and court sport athletes have a high incidence rate of lower limb injuries [1], resulting in sporting time-loss [1], high medical costs [2], a reduction in team performance [3], and long-term health issues [4]. Females tend to sustain more severe (greater time-loss) lower limb injuries than males [5], possibly due to anatomical [6], hormonal [7], and/or biomechanical differences [8]. Socio-cultural factors unique to females may also contribute to different training and competition exposure (e.g. girls participate in less physical activity than boys [9]) that, in turn, increases injury risk. Given the potential sex differences in injury rates and their underlying causes, it is important that injury risk mitigation strategies are targeted towards the specific needs of female athletes.

A critical step in an evidence-based injury prevention process is to first identify risk factors for injury [10, 11]. Intrinsic factors such as strength, biomechanics, physical performance, balance, and mobility are of particular interest because they are modifiable with training, unlike non-modifiable intrinsic risk factors such as age and prior injury [12]. Understanding modifiable intrinsic injury risk factors is needed to inform the design of targeted risk mitigation strategies. This knowledge may also aid in the development of tests to accurately and reliably measure risk factors, an essential tool for practitioners to perform injury screening, monitor athletes over time, and assess the efficacy of training programmes [13]. Understanding the intrinsic risk factors specific to females is a critical first step in reducing the rate and burden of lower limb injuries in female athletes. The aim of this paper is to systematically review the literature and synthesise the evidence for intrinsic risk factors for lower limb injury in female team field and court sports.

2 Methods

This review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [14], and was pre-registered with PROSPERO (ID: CRD42020171973) on 28th April 2020.

2.1 Literature search

A systematic search of online databases was performed using PubMed (MEDLINE), Scopus, EBSCOhost (SPORTDiscus and CINAHL), and EMBASE from inception to 8th April 2020. A comprehensive search strategy was developed using the PICO framework for prognostic studies [15]. *Population*: female team sport athletes, *problem*: lower limb musculoskeletal injuries, *prognostic factor*: intrinsic injury risk factors, *comparison*: prospective comparison of injured and uninjured groups, and *outcome*: lower limb injury and associated risk estimates. The final search strategy incorporated a combination of keywords, synonyms, and Medical Subject Headings or the database equivalent, and was refined through pilot testing to maximise the chance of returning all relevant studies (see Electronic Supplementary Material Appendix S1 for search strategy). Article reference lists and citation tracking on Google Scholar were also inspected for any further relevant articles.

2.2 Study inclusion/exclusion criteria

Articles were included if they: (1) had a prospective cohort design; (2) presented the association between one or more intrinsic risk factors and future injury to the hip/groin, thigh, knee or ankle/foot regions; and (3) included female athletes between the age of 13 and 40 playing a team field or court sport (e.g. soccer, futsal, rugby, Australian Football, Gaelic Football, basketball, handball, volleyball, netball, field hockey, lacrosse or floorball). All injury definitions (time-loss, non time-loss, contact, and non-contact) and reporting methods (medical staff or self-report) were included.

Studies were excluded if they: (1) were not written in English; (2) were a review article, abstract, conference proceeding or non-peer reviewed journal article; (3) had a cross-sectional, retrospective or case control study design; (4) only included extrinsic risk factors; (5) did not present an analysis of risk factors, or data were unable to be extracted; (6) only included male participants or did not present female data independent of male participants; (7) were predominately individual sport athletes; (8) only included water, ice or snow sport athletes; or (9) were a secondary analysis of an intervention study. Non-team field and court sports were excluded to limit the amount of heterogeneity in physical demands between sports studied.

2.3 Article screening

Articles were imported into EndNote (version X9.2, Clarivate Analytics, Boston, US) for eligibility screening. Duplicates were removed using autodetection by EndNote and manual removal. Article screening was performed independently by three reviewers (TC, WD and MB), with at least two reviewers screening each article. The initial screening of articles was performed by checking the title and abstract, and articles that did not meet the inclusion criteria were removed (Figure 1). Articles passing the first round of screening were subsequently pooled, and a second round of independent screening was performed using the full-text articles. Consensus on the final articles included was achieved through discussion between reviewers. Full-text articles that did not meet the inclusion criteria were removed and the reason for exclusion was recorded. Agreement/inter-rater reliability between reviewers for the final included articles was assessed using Cohen's Kappa statistic [16].

2.4 Risk of bias assessment

Eligible articles were assessed independently for methodological quality by two reviewers (TC and JH) using the Quality of Prognosis Studies (QUIPS) tool [17]. QUIPS provides criteria to assess each study for risk of potential bias in six areas of study design: study participation, study attrition, prognostic factor, outcome measurement, study confounding factors, and statistical analysis and reporting [17]. Each potential area of bias contains three

to six individual questions, which were answered with ‘not likely to increase bias’ or ‘may increase bias’. The complete QUIPS criteria and standards used to interpret these criteria are presented in Electronic Supplementary Material Appendix S2. For each of the six areas, ‘low risk’ was awarded if 75% of the questions were considered to not likely increase bias, otherwise the area of bias was deemed to be ‘high risk’ [18, 19]. Finally, to determine an overall risk of bias, a study was awarded ‘low risk’ if five out of the six areas of bias were marked as low risk. Otherwise, the study was awarded a rating of ‘high risk’ overall [19, 18]. This method of interpreting the QUIPS criteria provides an objective approach to determining risk of bias and was chosen for consistency with similar previous systematic reviews [18, 19]. Consensus on final ratings between reviewers was determined by discussion and where needed, consultation with a third reviewer (MB). No studies were excluded based on methodological quality or risk of bias.

2.5 Data extraction

Study characteristics and risk factor data were extracted by one reviewer (TC) and entered into a spreadsheet database (Microsoft Excel; Washington, US). Extracted study characteristics included: first author name, year of publication, country, playing level, participants’ age, sport, total number of participants, length of injury follow up period, number of injuries observed, method of recording injuries, and injury definition.

Extracted risk factor data included either continuous data (injured and uninjured group means and standard deviations [SD], number of participants injured and uninjured, and p-values) or binary frequency data (number of injured and uninjured athletes, with and without a risk factor present [e.g. contingency table]). Where frequency data were not presented, the unadjusted odds ratio (OR), relative risk (RR) or incident rate ratio (IRR), the associated p-value and 95% confidence interval (95% CI) were extracted. To facilitate comparison of

findings between studies, univariate model estimates of risk were extracted in favour of multivariate model analyses.

Data were synthesised across studies using injury groups that were selected and defined by the included articles. These groups were predominately based on anatomical regions instead of specific injuries and included: (1) knee injury, (2) anterior cruciate ligament (ACL) injury, (3) anterior knee pain, (4) ankle injury, (5) thigh injury, (6) hip/groin injury, and (7) any lower limb injury. Each of these groups were potentially comprised of a combination of acute, overuse, time loss or non-time loss injuries, depending on the injury definition provided (Table 1).

2.6 Meta-analysis

Data analysis was performed using R studio (version 1.2.1, Boston, US). Individual random effects model meta-analyses were performed using the ‘meta’ package for R [20]. A random effects model was selected to account for potential heterogenous populations due to the inclusion of studies with large variation in participant age, demographics, and sports [18, 21, 22]. Heterogeneity between studies was quantified using I^2 statistics. Meta-analyses of continuous data were performed using standardised mean differences (SMD) (Hedges’ g unbiased estimates for low sample sizes) [23], mean differences in original units of measurement, and 95% CI. Where SD were not presented, confidence intervals were used to determine the SD with the equation $SD = SE \times \sqrt{n}$ [24]. Where possible, odds ratios and 95% CI were calculated from binary frequency data [25]. Interpretation of SMD was as follows: 0 to 0.2 = trivial, 0.2 to 0.5 = small, 0.5 to 0.8 = medium, and 0.8 or higher = large [26]. For meta-analysis of SMDs or mean difference, study weighting was determined using the inverse-variance method and 95% CI for overall effect were calculated using the Hartung-

Knapp-Sidik-Jonkman method [27]. For meta-analyses of odds ratios, data were log-transformed [20].

For a risk factor to be included in a meta-analysis, data had to be reported by ≥ 2 independent studies with consistent analysis and reporting methods [28]. Inconsistent analysis and reporting methods included: different units, normalisation methods, expressions of risk estimates (e.g. group means, odds ratios, or relative risk), or use of different cut-off values to determine odds ratios/relative risk.

2.7 Best evidence synthesis

A best evidence synthesis was used to synthesise comparable risk factors that lacked the methodological consistency required for inclusion in a meta-analysis [29]. A best evidence synthesis provides a systematic approach for summarising the level of evidence, and strength of association between risk factors and lower limb injury risk [19, 30]. All factors with a minimum of two studies were included in the best evidence synthesis, regardless of whether they were included in a meta-analysis. The following criteria were used to establish levels of evidence for an association with injury: *strong evidence*: consistent results in two or more low risk of bias studies, with generally consistent findings in $\geq 75\%$ of studies; *moderate evidence*: one low risk of bias study and one or more high risk of bias study provide consistent findings, or consistent findings reported in two or more high risk of bias studies with consistent results in $\geq 75\%$ studies; *limited evidence*: single study findings from either a high risk or low risk of bias study; and *conflicting evidence*: multiple studies (either high or low risk of bias) with consistent results in $< 75\%$ studies [19, 29]. Study bias was based on the overall rating (low or high risk) assigned using the QUIPS risk of bias assessment. Risk factors were considered ‘associated’ or ‘not associated’ based on the reported statistical significance at $p < 0.05$. Where no p-value was reported, the 95% CI was used where a

significant association for SMD was indicated by a 95% CI that did not contain zero, or for odds ratios when the lower and upper limit of the 95% CI was greater and less than one, respectively. For findings to be considered ‘consistent’, both the association (significant/not significant) and the direction of the risk factor (increase/decrease value associated with injury) was required to be the same.

3 Results

3.1 Study characteristics

Agreement between reviewers for the independent screening of full-text articles was high ($\kappa = 0.73$, 95% CI = 0.62 – 0.83), with 100% agreement achieved after discussion. A total of 69 articles including 2902 lower limb injuries in 14,492 athletes met the inclusion criteria, including 373 knee injuries, 436 ACL injuries, 109 case of anterior knee pain, 340 ankle injuries, 128 thigh injuries, and 32 hip/groin injuries. Characteristics of the included studies are presented in Table 1. The median number of study participants was 123 (range = 23-1558, interquartile range = 133). The unweighted average age of participants was 18.3 years (mean age range = 12.0-24.8 years). The sports most frequently included in studies were soccer (41), basketball (34), volleyball (23), and handball (13). Fifty-five percent of studies included participants competing in high school or college leagues, 29% were elite/national league athletes, 12% were in other competitive leagues, and 4% were recreational athletes. The majority of injury follow up periods were one season/year (58%), 14% were 2 seasons/years, 16% were 3 seasons/years, and 12% were 3-9 years.

1 **Table 1.** Study characteristics, participant information, and data collection methods of included studies.

Reference	n	Age (SD)	Sport(s)	Level	Follow up	Injury type (n)	Injury definition	Reporting method
Attenborough et al. ^[84]	94	20.3 (3.4)	NB	Recreational	2 seasons	Ankle (11)	TL, LIG	Medical, self
Barber Foss et al. ^[31]	248	12.8 (1.1)	BB	Middle school	2 seasons	Anterior knee pain (39)	PFP, AKP	Medical
Beynnon et al. ^[86]	67	—	S,FH,L	College	1 season	Ankle (13)	LIG	Medical
Blokland et al. ^[60]	114	22.4 (3.3)	S	National	1 season	Any (179), thigh (45), knee (42), ankle (22), hip/groin (15)	TL	Medical
Brumitt et al. ^[89]	106	19.1 (1.1)	—	College	1 season	Any (32)	TL	Medical
Brumitt et al. ^[62]	106	19.1 (1.1)	S,VB,BB,L,+	College	1 season	Any (24)	TL	Medical
Brumitt et al. ^[61]	110	19.1 (1.1)	S,BB,VB,L,+	College	1 season	Any (17), ankle (12)	TL	Medical
Brumitt et al. ^[64]	360	19.3 (1.4)	S,BB,VB	College	1 season	Any (73), ACL (7)	NC	Medical
Brumitt et al. ^[44]	119	19.2 (1.2)	S	College	1 season	Any (36)	TL, NC	Medical
Brumitt et al. ^[43]	82	18.9 (1.0)	VB	College	1 season	Any (15), ankle (6)	TL, NC	Medical
Brumitt et al. ^[45]	104	19.2 (1.2)	S,VB,+	College	1 season	Any (19)	TL	Medical
Brumitt et al. ^[63]	210	19.2 (1.1)	S,VB,BB,L,+	College	1 season	Any (40), ankle (15)	TL NC	Medical
Cheng et al. ^[46]	177	14.8 (1.8)	S	Competitive	5-9 years	Any (42)	TL	Self
Chorba et al. ^[90]	38	19.2 (1.2)	S,BB,VB	College	1 season	Any (19)	ALL	Medical
Clausen et al. ^[66]	326	15.6 (0.9) ^a	S	Recreational	1 season	Knee (34)	TL	Self
Devan et al. ^[32]	53	19.4 (1.3)	S,BB,FH	College	1 season	Knee (9)	OU	Medical
Dingenen et al. ^[68]	50	20.2 (2.9)	S,VB,HB	National	1 year	Knee (7)	TL, NC	Medical
Dingenen et al. ^[47]	43	20.8 (3.5)	S,VB,HB	National	1 year	Any (6)	TL	Medical
Dragoo et al. ^[33]	128	19.5 (1.6)	S,BB,VB,FH,L,+	College	4 years	ACL (28)	ALL	Medical
Emery et al. ^[91]	164	14.8 (—)	S	Competitive	1 season	Any (26)	TL	Medical
Faude et al. ^[48]	143	22.4 (5.0)	S	National	1 season	Any (99), ankle (33), knee (23), ACL (11)	TL	Medical
Goetschius et al. ^[69]	65	18.1 (1.7)	S,BB,VB,FH,L	College/H-school	3 years	ACL (20)	NC	Medical
Hartley et al. ^[85]	167	19.8 (1.5)	S,BB,VB	College	2 years	Ankle (21)	TL, LIG	Medical
Herbst et al. ^[34]	255	12.7 (0.9)	BB	Middle school	1 season	Anterior knee pain (38)	PFP	Medical
Hewett et al. ^[77]	205	16.1 (1.7)	S,BB,VB	High school	3 seasons	ACL (9)	NC	Medical
Holden et al. ^[80]	76	12.9 (0.3)	BB,FH,GF,+	High school	2 years	Anterior knee pain (8)	PFP	Self
Hopper et al. ^[49]	72	20.6 (3.6)	NB	Competitive	1 season	Any (22)	ALL	Medical
Kofotolis and Kellis ^[87]	204	24.8 (4.6)	BB	National	2 years	Ankle (32)	TL, LIG	Medical

Kosaka et al. ^[70]	303	15.0 (0.0)	BB,HB	High school	2 years	ACL (25)	ALL	Coach
Krosshaug et al. ^[71]	710	21.0 (3.9)	S,HB	National	< 7 years	ACL (42)	NC	Staff
Landis et al. ^[65]	187	18 - 25	S,BB,VB	College	1 season	Any (17), ACL (4)	TL, NC	Medical
Leetun et al. ^[92]	80	19.1 (1.37)	BB,+	College	1 season	Any (34)	TL, NC	Medical
Leppanen et al. ^[78]	171	15.4 (1.9)	BB,FB	Competitive	< 3 years	ACL (15)	NC	Staff
Leppanen et al. ^[79]	171	15.4 (1.9)	BB,FB	Competitive	< 3 years	ACL (15)	NC	Staff
Leppanen et al. ^[35]	258	16.0 (1.9)	BB,FB	Competitive	1 year	ACL (8)	NC	Staff
Maestro et al. ^[93]	23	22.5 (5.7)	S	National	1 season	Any (12)	OU	Medical
Maulder ^[36]	24	21.6 (3.2)	NB	National	1 season	Any (9)	TL	Self
McCann et al. ^[88]	43	19.7 (1.1)	S	College	1 season	Ankle (8)	TL, LIG	Medical
Myer et al. ^[81]	145	13.4 (1.6)	BB	Middle/H-school	1 season	Anterior knee pain (14)	AKP	Medical
Myer et al. ^[94]	1558	16.3 (1.7)	S,BB	College/H-school	4 years	ACL (19)	ALL	—
Naicker et al. ^[95]	30	23.8 (3.2)	FH	National team	1 season	Ankle (14)	ALL	Self
Nilstad et al. ^[50]	173	21.5 (4.1)	S	National	1 season	Any (171), thigh (35), knee (53), ankle (40)	TL	Self
Numata et al. ^[72]	291	15.0 (0.0)	BB,HB	High school	3 years	ACL (28)	NC	—
O'Kane et al. ^[96]	351	12 - 15	S	Adolescent	< 2 seasons	Any (83), knee (38)	OU	Self
O'Kane et al. ^[97]	351	12.8 (0.9)	S	Competitive	< 2 years	Any (134), knee (41)	TL	Self
Oshima et al. ^[73]	273	15.0 (—)	BB,HB	High school	3 years	ACL (24)	NC	Coach
Ostenberg and Roos ^[51]	123	20.7 (4.6)	S	National/competitive	1 year	Any (47)	ALL	Medical
Pickering Rod et al. ^[52]	29	24.1 (3.2)	NB	National/competitive	1 season	Any (10)	TL, NC	Medical, self
Plisky et al. ^[98]	105	15.4 (1.0) ^a	BB	High school	1 season	Any (29)	TL	Coach
Ryman Aug and Ageberg ^[37]	89	17.0 (1.0)	S,BB,HB,FB,+	High school	< 4 years	ACL (14), knee (26)	AC	Self
Shimozaki et al. ^[74]	168	15.5 (0.3)	BB	High school	3 years	ACL (12)	NC	Self
Siupsinskas et al. ^[53]	169	23.1 (5.7)	BB	National	1 season	Any (92)	TL	Medical
Smeets et al. ^[75]	46	20.7 (3.2)	S,VB,HB	National	1 year	ACL (4)	NC	Medical
Smith et al. ^[38]	63	18.0 (1.7)	S,BB,VB,FH,L,+	College/H-school	3 years	ACL (19)	NC	Medical
Smith et al. ^[54]	57	14.4 (1.7)	S,BB,VB	High school	1 season	Any (15)	NC, AC	Medical
Soderman et al. ^[55]	146	20.6 (4.7)	S	National	1 season	Any (61)	TL, AC	Self, coach
Steffen et al. ^[99]	1430	15.4 (0.8)	S	Competitive	1 season	Ankle (113), knee (58), thigh (48), hip/groin (17)	TL	Medical
Steffen et al. ^[76]	867	20.9 (4.0)	S,HB	National	< 8 years	ACL (57)	NC	Self
Steffen et al. ^[39]	838	21.0 (4.0)	S,HB	National	< 8 years	ACL (55)	NC	Self

Vauhnik et al. ^[67]	585	18.0 (3.0)	BB,VB,HB	National	1 season	Knee (20), ACL (11)	TL	Self, coach
Verrelst et al. ^[56]	90	19.3 (0.9)	S,HB,VB,BB,+	Recreational	2 years	Any (35)	ALL	Self
Visnes et al. ^[82]	82	16.7 (0.8)	VB	National	5 years	Anterior knee pain (6)	AKP	Medical
Visnes et al. ^[83]	78	16.7 (0.7)	VB	High school	3 years	Anterior knee pain (4)	AKP	Self
Walbright et al. ^[57]	35	–	BB,VB,HB	College	1 season	Any (11)	TL	Medical
Warren et al. ^[58]	75	19.1 (1.1)	S,BB,VB	College	1 year	Any (52)	NC	Medical
Watson et al. ^[59]	54	15.7 (1.5)	S	High school	1 season	Any (23)	TL	Self
Zazulak et al. ^[40]	140	19.4 (1.0)	–	College	3 years	ACL (4), knee (11)	ALL	–
Zazulak et al. ^[41]	140	19.4 (1.0)	–	College	3 years	Knee (11)	ALL	Medical
Zebis et al. ^[42]	55	24.0 (5.0)	S,HB	National	2 seasons	ACL (5)	NC	–

Sports: basketball (BB), field-hockey (FH), Gaelic Football (GB), floorball (FB), handball (HB), lacrosse (LC), netball (NB), soccer (SC),volleyball (VB), additional individual or non-field/court sport (+).

Injury definition: acute (AC), anterior knee pain (AKP), no restrictions (ALL), ligament injury (LIG), patellofemoral pain (PFP), non-contact (NC), overuse (OU), time-loss (TL).

Report method: team coach (coach), team physiotherapist, athletic trainer, doctor or surgeon (medical), player self -report (self), other team staff (staff).

^a age calculated from available data. – data unavailable. Standard deviation (SD).

3.2 Risk of bias assessment

Independent assessment of individual QUIPS criteria resulted in 84% agreement between reviewers ($\kappa = 0.53$, 95% CI = 0.43 – 0.63), with 100% agreement achieved after discussion. A low risk of bias was found for 42 studies and a high risk of bias for 27 studies (Table 2). The most common source of bias was not measuring or accounting for confounding variables (62% of studies), predominately due to grouping all lower limb injuries together. Other common sources of bias were using invalid or unreliable outcome measure (22% of studies), and low numbers of observed injuries (20% of studies). Risk of publication bias was not assessed due to low study numbers for the majority of individual risk factors. However, overall, 83% of risk factors were found to be non-significant, indicating that non-significant findings are frequently published.

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16 **Table 2.** Quality of Prognosis Studies (QUIPS) risk of bias assessment for included studies.

Reference number	Participation	Attrition	Prognostic factor	Outcome measure	Confounders	Statistical Analysis	Overall
35, 38, 39, 41, 47, 68, 69, 71, 74, 76, 78, 79, 85, 86, 87, 99	✓	✓	✓	✓	✓	✓	Low risk
33, 34, 43, 44, 48, 51, 57, 58, 60, 62, 63, 64, 70, 80, 90, 91, 92, 96, 98	✓	✓	✓	✓	X	✓	Low risk
37	✓	✓	✓	X	✓	✓	Low risk
82, 83	✓	X	✓	✓	✓	✓	Low risk
40, 77, 81, 94	X	✓	✓	✓	✓	✓	Low risk
31, 32, 54, 56	✓	✓	✓	✓	X	X	High risk
73	✓	✓	✓	X	✓	X	High risk
52, 72, 84, 97	✓	✓	✓	X	X	✓	High risk
50, 53	✓	X	✓	✓	X	✓	High risk
67	✓	X	✓	X	✓	✓	High risk
75	X	✓	✓	✓	✓	X	High risk
45, 49, 61, 65, 88, 89	X	✓	✓	✓	X	✓	High risk
36, 42	✓	✓	✓	X	X	X	High risk
55, 66	✓	X	✓	X	X	✓	High risk
59	X	✓	✓	X	X	✓	High risk
46	✓	X	✓	X	X	X	High risk
93, 95	X	✓	✓	X	X	X	High risk

✓ indicates low risk in >75% of questions. X indicates high risk in > 25% of questions.

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18 **3.3 Risk factor synthesis**

19 A total of 754 injury risk estimates for 80 distinct risk factors were extracted. This database
 20 can be interactively explored online at: <https://tcollings.shinyapps.io/risk-factor-app/>. Figure
 21 2 summarises the decision making pathway from data extraction to synthesis (e.g. meta-
 22 analysis, best evidence synthesis). Risk factors reported by a single study are presented in
 23 Electronic Supplementary Material Appendix S3 [31-42].

3.4 Meta-analysis

A total of 69 risk factors for different lower limb injury groups had more than one study with identical data analysis and reporting methods and were included in a meta-analysis. Meta-analyses are summarised by injury group, including risk factors for any lower limb injury (Figure 3), knee injury, ACL injury, and anterior knee pain (Figure 4), and ankle injury (Figure 5). There were no risk factors for thigh injuries or hip/groin pain eligible for inclusion in a meta-analysis. Forest plots for individual risk factors are presented in Electronic Supplementary Material Appendix S4.

3.4.1 Any lower limb injury

Five significant risk factors [43-59] and 21 non-significant factors were identified for lower limb injury (Figure 3) [43-54, 57, 58, 60-65]. Significant risk factors included greater body mass (SMD = 0.24, 95% CI = 0.18 – 0.29) [43, 44, 47-54, 58], greater body mass index (BMI) (SMD = 0.22, 95% CI = 0.05 – 0.40) [43, 44, 46-48, 50, 51, 54, 56, 59], advancing age (SMD = 0.20, 95% CI = 0.09 – 0.31) [43, 44, 46-48, 50-56, 58, 59], greater star excursion balance test anterior reach for the right leg (SMD = 0.18, 95% CI = 0.12 – 0.24) [45, 57], and

smaller single-leg hop distance for the left leg (SMD = -0.09, 95% CI = -0.12 – -0.06) (Figure 3) [43, 44].

42

3.4.2 Knee injury

The meta-analyses for knee injury indicated one significant risk factor [48, 66, 67] and six non-significant factors (Figure 4a) [50, 60, 67, 68]. Athletes with previous knee injuries were at greater risk of a recurrent knee injury (OR = 2.41, 95% CI = 1.24 – 4.68) [48, 66, 67]. The

47 meta-analyses for ACL injury indicated three significant risk factors [48, 64, 67, 69-76] and
48 16 non-significant factors (Figure 4b) [65, 67, 69-79]. Significant risk factors for ACL injury
49 included previous ACL injury (OR = 3.94, 95% CI = 2.07 – 7.50) [48, 64, 76], greater
50 postural sway (centre of gravity movement per second) during 30s double-leg balance with
51 eyes open (SMD = 0.58, 95% CI = 0.02 – 1.15) [73, 74], and greater body mass (SMD =
52 0.25, 95% CI = 0.12 – 0.39) [67, 69-76]. There were no significant risk factors for anterior
53 knee pain (Figure 4c) [80-83].

54

55 **3.4.3 Ankle injury**

56 The meta-analyses for ankle injury indicated three significant risk factors [43, 61, 63, 84, 85]

57 and 10 non-significant factors [43, 48, 50, 60, 61, 63, 84-88]. Significant risk factors for

ankle injury included less anterior reach on a star excursion balance test (SMD = -0.13, 95% CI = -0.14 – -0.13) [84, 85], and single-leg hop distance between-leg asymmetry greater than 10% (OR= 3.67, 95% CI = 1.42 – 9.45) [43, 61]. Time to complete an agility course greater than 121s was associated with reduced risk of ankle injury (OR= 0.20, 95% CI = 0.05 – 0.88) (Figure 5) [61, 63].

3.5 Best evidence synthesis

A total of 84 factors for different lower limb injury groups were investigated by more than one study and were included in the best evidence synthesis (Figure 6). Seventy of these factors contained additional data that were not included in a meta-analysis [89-98]. The best evidence synthesis found that prior ACL injury had strong evidence for an association with recurrent ACL injury [64, 48, 94, 76], and lower knee injury and osteoarthritis outcome score (KOOS) (e.g. worse knee related symptoms) had moderate evidence for an association with any future knee injury [99, 66]. Remaining risk factors had moderate (26 factors) to strong (21 factors) evidence for no association with any of the lower limb injury categories and 35

73 risk factors had conflicting evidence. No risk factors for hip/groin pain and one risk factor for
 74 thigh injuries was investigated by more than one study. Risk factors with limited evidence
 75 (e.g. one study) are presented in Electronic Supplementary Material Appendix S3.

4 Discussion

This study systematically reviewed 69 prospective studies to provide a summary of the evidence for intrinsic risk factors in female athletes for a wide range of sports and injury types. Risk factors for any lower limb injury included greater body mass, greater BMI, older age, greater star excursion balance test anterior reach distance, and smaller single-leg hop distance. Lower KOOS was a risk factor for knee injury. ACL injury risk factors included prior ACL injury, greater double-leg postural sway, and greater body mass. Risk factors for ankle injury included smaller star excursion balance test anterior reach distance, greater single-leg hop distance asymmetry, and slower agility course time. Significant risk factors indicate a statistical association with injury risk, while predictive ability was not assessed. Evidence was often conflicting between prospective studies and the majority of factors investigated to date were not associated with lower limb injury risk in female athletes. Further, significant differences between subsequently injured and uninjured players were generally small to trivial. Risk factors and tests identified in this review may warrant consideration when evaluating an athlete's risk of injury, determining training requirements, or monitoring player development over time. It should

4.1 Age and anthropometric measures

Greater body mass and BMI were risk factors for lower limb injury, though only greater body mass was associated with ACL injury. Players with greater body mass may experience greater knee joint loads during physical activity that contributes to injury [100]. Age was a risk factor for lower limb injury [43, 46, 48, 50-52, 54-56, 58, 59], with included studies investigating participants ranging from 12 to 25 years. Players who sustained a future lower limb injury were, on average, approximately 0.4 years older than uninjured players. While we are unable to explain why older players are at greater risk of injury with this data, there are

likely a number of speculative causes. For example, greater injury risk may arise from age-related physical changes in body size, composition, and/or hormones that coincide with emergence of lower limb biomechanics associated with increased knee joint loads [101, 102]. Additionally, older players typically compete at higher competition levels, and are more likely to have prior injuries due to cumulative sport exposure [21]. It is important to note that although age, body mass, and BMI were statistically significant due to the increased estimate precision of a meta-analysis, the differences between injured and uninjured players at a group level are very small.

4.2 Prior injury

Athletes with prior ACL and knee injury had 3.5 and 2.4 greater odds of experiencing a subsequent ACL or knee injury, respectively. Previous reviews have highlighted ACL injury history as a risk factor for subsequent ACL injury in female athletes [103]. In male athletes, prior injury is the strongest independent risk factor for several prevalent lower limb injuries, including injuries to the same limb, the contralateral limb, and injury at adjacent locations (e.g. previous ACL injury increases risk of hamstring and calf strains) [18, 21, 104, 105]. Those who have sustained a previous injury may be at greater risk due to the persistence of risk factors that contributed to the original insult. However, injury may also cause maladaptation in tissue structure and function that in turn increases risk of subsequent injury. For example, following ACL reconstruction athletes display chronic deficits in hamstring muscle activation [106], medial hamstring muscle volumes [106, 107], and knee flexor/internal rotator strength [108, 107]. Lower KOOS was also associated with an increased risk of future knee injury, which may be, in part, related to an individual's injury history [109], as well as quality of healing and restoration of function. Therefore, KOOS may be a useful tool for monitoring players after injury, and a modifiable target for training.

4.3 Performance tests

Overall, evidence for risk factors relating to performance on physical tests was limited. Star excursion balance test anterior reach, and single-leg hop distance and asymmetry were associated with future lower limb injury and ankle injury respectively. However, caution should be taken in interpreting these results, as each meta-analysis included two studies and had high effect homogeneity, resulting in significant, albeit trivial effect sizes ($SMD < 0.2$). Despite the small effect sizes, these risk factors warrant further investigation, and may prove to be clinically meaningful when combined in a multivariable injury risk model. Double-leg postural sway was associated with ACL injury. The association of other tests of strength, biomechanics, balance, mobility and joint characteristics with future lower limb injury risk were not supported by current evidence. For the star excursion balance test, greater anterior reach distance was associated with lower limb injury [45, 57], and less reach distance associated with ankle injury [84, 85]. As such, the anterior reach direction may provide useful insight into ankle dorsi-flexion range of motion, which may be important for ankle function, as well as controlling knee position in the frontal plane [110]. Single-leg hop distance is commonly used as a surrogate measure of lower limb power, and asymmetries may indicate deficits in strength or coordination [111]. It should be noted that the meta-analyses for single-leg hop distance, and agility time trial [61, 44, 43, 63], as well as double-leg static balance [73, 74] were based on results from studies undertaken by the same research groups, and may be influenced by unintentional systematic bias. Further, there are a number of performance tests associated with lower limb injury risk that have been reported by single-studies, including the triple hop jump [56], side-step muscle activation [42], and single-leg drop vertical jump [68].

4.4 Study limitations

Synthesis of evidence was predominantly limited by each study's chosen testing protocol, statistical analysis method, grouping of injury types, and reporting of results. Although a wide range of risk factors have been explored, there were limited studies that investigated the same risk factors. Meta-analysis was used as the preferred approach to synthesise study results, however given the broad scope of this review, meta-analyses often included a low number of studies. As a result, meta-analyses with a low number of studies should be interpreted with caution, as effects may be overestimated [112] and heterogeneity statistics (I^2) can become inaccurate [113]. To compensate for inconsistencies in methods between empirical studies, a best evidence synthesis was used to supplement the meta-analyses. Only data that were presented in the original paper or supplementary material were extracted for analysis. This review included prospective study designs only, however, for some non-modifiable risk factors, evidence from other study designs such as case-control could warrant consideration. Due to the low number of consistent studies investigating female risk factors, this review included participants across a relatively wide range of ages and sports. Potential participant heterogeneity was accounted for by limiting studies to team field and court sports with similar physical demands, and performing random effect model meta-analyses. Further, this review focussed on synthesising evidence across studies, however, there were a number of risk factors found by single studies that require further examination [68, 40, 42, 70, 56, 35, 32].

When interpreting the findings of this review, it is important to consider how study design may prevent accurate identification of injury risk factors and hinder replication of findings. First, injury risk is multifactorial [11], however the majority of prospective studies consider single variables in isolation. As such, a limitation of this study is the analysis of risk factors as independent factors. Second, many modifiable risk factors are dynamic [114, 115], fluctuating in response to training and competition throughout a season, and consequently

may be vastly different from the time of measurement [116]. However, all studies included in this review obtained data at a single time point, months to years before the injury occurred. Third, grouping a wide range of injury types together may confound results, given that injuries to different structures can greatly vary in injury mechanism. Finally, a number of prospective studies include a low number of observed injuries, either creating a bias sample due to chance, or preventing detection of small differences between groups [117].

4.5 Future direction

This review highlights the absence of evidence for many factors and tests thought to be associated with injury risk in female athletes. Tests such as the drop vertical jump [77], landing error score system (LESS) [38], functional movement screen [90], the majority of single- and double-leg balance tasks [39], and isometric/isokinetic strength testing [50] were not found to be associated with subsequent injury in female athletes. Conflicting evidence between studies is a major contributor to this outcome, and it is possible that non-significant findings reflect limitations of study design more so than the test itself. Further high-quality prospective studies are required to identify injury risk factors and establish valid tests, and to develop a greater understanding of any interaction between risk factors. Specifically, studies are required to investigate the most common lower limb injuries in female team field and court sports, such as quadriceps strains, hamstring strains, and hip/groin pain [1], while attempting to minimise the limitations of current prospective study design.

Given the limitations of the prospective studies included in this review, injury risk reduction strategies may be better informed by a combination of injury risk factors and injury mechanisms. Although risk factors derived from prospective studies are associated with greater risk of injury at a cohort level, this may not necessarily indicate a causative relationship, and therefore modifying risk factors may not always generate the intended risk

reduction. Randomised controlled trials are required to determine whether modifying risk factors via targeted interventions lead to a meaningful reduction in lower limb injuries.

4.6 Conclusion

Risk factors for lower limb injury in female team sport athletes include greater body mass, greater BMI, older age, prior injury, lower KOOS, greater star excursion balance test anterior reach distance, smaller single-leg hop distance and asymmetry, greater postural sway during double-leg balance and slower agility time trial. Overall, many tests/risk factors assessed in female athletes had no association with injury risk and conflicting evidence between studies was common. Readers should be cognisant of the limitations of existing prospective studies when interpreting findings from this review. Further high-quality prospective studies are required to establish risk factors for lower limb injury in female team and court sport athletes.

209 **5 Declarations**

210 **Funding**

211 No funding was received to conduct this review.

212 **Conflicts of interest/Competing interests**

213 Tyler Collings, Matthew Bourne, Rod Barrett, William du Moulin, Jack Hickey and Laura

214 Diamond declare that they have no conflicts of interest relevant to the content of this review.

215 **Availability of data and material**

216 Data extracted from articles is available to view online at: [https://tcollings.shinyapps.io/risk-](https://tcollings.shinyapps.io/risk-factor-app/)
217 [factor-app/](https://tcollings.shinyapps.io/risk-factor-app/).

218 **Author contributions**

219 TC, MB, LD, RB contributed to the review design. TC, WD, MB performed the literature
220 screening. TC, JH performed the risk of bias assessment. All authors contributed to the
221 writing of the manuscript.

6 References

1. DiStefano LJ, Dann CL, Chang CJ, et al. The first decade of web-based sports injury surveillance: descriptive epidemiology of injuries in US high school girls' soccer (2005–2006 through 2013–2014) and national collegiate athletic association women's soccer (2004–2005 through 2013–2014). *J Athl Train*. 2018;53:880-92.
2. Finch CF, Kemp JL, Clapperton AJ. The incidence and burden of hospital-treated sports-related injury in people aged 15+ years in Victoria, Australia, 2004-2010: A future epidemic of osteoarthritis? *Osteoarthritis Cartilage*. 2015;23:1138-43.
3. Waldén M, Häggglund M, Ekstrand J. Football injuries during European Championships 2004–2005. *Knee Surg Sports Traumatol Arthrosc*. 2007;15:1155-62.
4. Lohmander LS, Östenberg A, Englund M, et al. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis Rheum*. 2004;50:3145-52.
5. Larruskain J, Lekue JA, Diaz N, et al. A comparison of injuries in elite male and female football players: A five-season prospective study. *Scand J Med Sci Sports*. 2018;28:237-45.
6. Chandrashekar N, Slauterbeck J, Hashemi J. Sex-based differences in the anthropometric characteristics of the anterior cruciate ligament and its relation to intercondylar notch geometry: a cadaveric study. *Am J Sports Med*. 2005;33:1492-8.
7. Quatman CE, Ford KR, Myer GD, et al. The effects of gender and pubertal status on generalized joint laxity in young athletes. *J Sci Med Sport*. 2008;11:257-63.
8. Mendiguchia J, Ford KR, Quatman CE, et al. Sex differences in proximal control of the knee joint. *Sports Med*. 2011;41:541-57.
9. Trost SG, Pate RR, Sallis JF, et al. Age and gender differences in objectively measured physical activity in youth. *Med Sci Sports Exerc*. 2002;34:350-5.
10. van Mechelen W, Hlobil H, Kemper HCG. Incidence, Severity, Aetiology and Prevention of Sports Injuries: A Review of Concepts. *Sports Med*. 1992;14:82-99.
11. Meeuwisse WH, Tyreman H, Hagel B, et al. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17:215-9.
12. Fulton J, Wright K, Kelly M, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther*. 2014;9:583.

13. Verhagen E, van Dyk N, Clark N, et al. Do not throw the baby out with the bathwater; screening can identify meaningful risk factors for sports injuries. *Br J Sports Med*. 2018;52:1223-4.
14. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann Intern Med*. 2009;151:264-9.
15. Santos CMdC, Pimenta CAdM, Nobre MRC. The PICO strategy for the research question construction and evidence search. *Rev Lat Am Enfermagem*. 2007;15:508-11.
16. McHugh ML. Interrater reliability: the kappa statistic. *Biochem Med*. 2012;22:276-82.
17. Hayden JA, van der Windt DA, Cartwright JL, et al. Assessing bias in studies of prognostic factors. *Ann Intern Med*. 2013;158:280-6.
18. Green BD, Bourne MN, Van Dyk N, et al. Recalibrating the risk of hamstring strain injury (HSI): a 2020 systematic review and meta-analysis of risk factors for index and recurrent HSI in sport. *Br J Sports Med*. 2020;54:1081-8.
19. Schut L, Wangenstein A, Maaskant J, et al. Can clinical evaluation predict return to sport after acute hamstring injuries? A systematic review. *Sports Med*. 2017;47:1123-44.
20. Balduzzi S, Rücker G, Schwarzer G. How to perform a meta-analysis with R: a practical tutorial. *Evid Based Ment Health*. 2019;22:153-60.
21. Toohey LA, Drew MK, Cook JL, et al. Is subsequent lower limb injury associated with previous injury? A systematic review and meta-analysis. *Br J Sports Med*. 2017;51:1670-8.
22. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: A systematic review and meta-analysis. *Br J Sports Med*. 2013;47:351-8.
23. Hedges LV. Distribution theory for Glass's estimator of effect size and related estimators. *J Educ Behav Stat*. 1981;6:107-28.
24. Higgins JP, Green S. *Cochrane handbook for systematic reviews of interventions*. John Wiley & Sons; 2011.
25. Ruddy JD, Cormack SJ, Whiteley R, et al. Modeling the risk of team sport injuries: a narrative review of different statistical approaches. *Front Physiol*. 2019;10.
26. Cohen J. *Statistical power analysis for the behavioural sciences*. 2 ed. Hillsdale (NJ): Lawrence Erlbaum Associates; 1988.
27. Sidik K, Jonkman JN. A simple confidence interval for meta-analysis. *Statist Med*. 2002;21:3153-9.
28. Borenstein M, Hedges LV, Higgins JP, et al. *Introduction to meta-analysis*. John Wiley & Sons; 2011.

- 288 29. Slavin RE. Best evidence synthesis: an intelligent alternative to meta-analysis. *J Clin*
289 *Epidemiol.* 1995;48:9-18.
- 290 30. Green B, Bourne MN, Pizzari T. Isokinetic strength assessment offers limited predictive
291 validity for detecting risk of future hamstring strain in sport: a systematic review and
292 meta-analysis. *Br J Sports Med.* 2018;52:329-36.
- 293 31. Barber Foss KD, Hornsby M, Edwards NM, et al. Is body composition associated with an
294 increased risk of developing anterior knee pain in adolescent female athletes? *Phys*
295 *Sportsmed.* 2012;40:13-9.
- 296 32. Devan MR, Pescatello LS, Faghri P, et al. A prospective study of overuse knee injuries
297 among female athletes with muscle imbalances and structural abnormalities. *J Athl*
298 *Train.* 2004;39:263-7.
- 299 33. Dragoo JL, Castillo TN, Braun HJ, et al. Prospective correlation between serum relaxin
300 concentration and anterior cruciate ligament tears among elite collegiate female
301 athletes. *Am J Sports Med.* 2011;39:2175-80.
- 302 34. Herbst KA, Barber Foss KD, Fader L, et al. Hip strength is greater in athletes who
303 subsequently develop patellofemoral pain. *Am J Sports Med.* 2015;43:2747-52.
- 304 35. Leppänen M, Rossi MT, Parkkari J, et al. Altered hip control during a standing knee lift
305 test is associated with increased risk of knee injuries. *Scand J Med Sci Sports.*
306 2020;30:922-31.
- 307 36. Maulder PS. Dominant limb asymmetry associated with prospective injury occurrence. *S*
308 *Afr J Res Sport PH.* 2013;35:121-31.
- 309 37. Ryman Augustsson S, Ageberg E. Weaker lower extremity muscle strength predicts
310 traumatic knee injury in youth female but not male athletes. *BMJ Open Sport Exerc*
311 *Med.* 2017;3:e000222.
- 312 38. Smith HC, Johnson RJ, Shultz SJ, et al. A prospective evaluation of the landing error
313 scoring system (LESS) as a screening tool for anterior cruciate ligament injury risk.
314 *Am J Sports Med.* 2012;40:521-6.
- 315 39. Steffen K, Nilstad A, Krosshaug T, et al. No association between static and dynamic
316 postural control and ACL injury risk among female elite handball and football
317 players: a prospective study of 838 players. *Br J Sports Med.* 2017;51:253-9.
- 318 40. Zazulak BT, Hewett TE, Reeves NP, et al. Deficits in neuromuscular control of the trunk
319 predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J*
320 *Sports Med.* 2007;35:1123-30.

41. Zazulak BT, Hewett TE, Reeves NP, et al. The effects of core proprioception on knee injury: a prospective biomechanical-epidemiological study. *Am J Sports Med.* 2007;35:368-73.
42. Zebis MK, Andersen LL, Bencke J, et al. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med.* 2009;37:1967-73.
43. Brumitt J, Mattocks A, Loew J, et al. Preseason functional performance test measures are associated with injury in female college volleyball players. *J Sport Rehabil.* 2019;29:320-5.
44. Brumitt J, Mattocks A, Engilis A, et al. Off-season training habits and BMI, not preseason jump measures, are associated with time-loss injury in female collegiate soccer players. *Sports (Basel).* 2020;8:36.
45. Brumitt J, Sikkema J, Mair S, et al. Preseason Y balance test scores are not associated with a lower quadrant sports injury in a heterogeneous population of division III collegiate athletes. *Int J Athl Ther Train.* 2020;25:68-75.
46. Cheng AL, Merlo JA, Hunt D, et al. Are hip physical examination findings predictive of future lower body injury rates in elite adolescent female soccer athletes at minimum 5-year follow-up? *J Sport Rehabil.* 2019;29:476-82.
47. Dingenen B, Malfait B, Nijs S, et al. Postural stability during single-leg stance: a preliminary evaluation of noncontact lower extremity injury risk. *J Orthop Sports Phys Ther.* 2016;46:650-7.
48. Faude O, Junge A, Kindermann W, et al. Risk factors for injuries in elite female soccer players. *Br J Sports Med.* 2006;40:785-90.
49. Hopper DM, Hopper JL, Elliott BC. Do selected kinanthropometric and performance variables predict injuries in female netball players? *J Sports Sci.* 1995;13:213-22.
50. Nilstad A, Andersen TE, Bahr R, et al. Risk factors for lower extremity injuries in elite female soccer players. *Am J Sports Med.* 2014;42:940-8.
51. Ostenberg A, Roos H. Injury risk factors in female European football. A prospective study of 123 players during one season. *Scand J Med Sci Sports.* 2000;10:279-85.
52. Pickering Rodriguez EC, Watsford ML, Bower RG, et al. The relationship between lower body stiffness and injury incidence in female netballers. *Sports Biomech.* 2017;16:361-73.

53. Siupsinskas L, Garbenyte-Apolinskiene T, Salatkaite S, et al. Association of pre-season musculoskeletal screening and functional testing with sports injuries in elite female basketball players. *Sci Rep*. 2019;9:9286.
54. Smith J, DePhillipo N, Kimura I, et al. Prospective functional performance testing and relationship to lower extremity injury incidence in adolescent sports participants. *Int J Sports Phys Ther*. 2017;12:206-18.
55. Soderman K, Alfredson H, Pietila T, et al. Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season. *Knee Surg Sports Traumatol Arthrosc*. 2001;9:313-21.
56. Verrelst R, Van Tiggelen D, De Ridder R, et al. Kinematic chain-related risk factors in the development of lower extremity injuries in women: A prospective study. *Scand J Med Sci Sports*. 2018;28:696-703.
57. Walbright PD, Walbright N, Ojha H, et al. Validity of functional screening tests to predict lost-time lower quarter injury in a cohort of female collegiate athletes. *Int J Sports Phys Ther*. 2017;12:948-59.
58. Warren M, Lininger MR, Smith CA, et al. Association of functional screening tests and noncontact injuries in division I women student-athletes. *J Strength Cond Res*. 2019;34:2302-11.
59. Watson A, Brickson S, Brooks MA, et al. Preseason aerobic fitness predicts in-season injury and illness in female youth athletes. *Orthop J Sports Med*. 2017;5:1-7.
60. Blokland D, Thijs KM, Backx FJ, et al. No effect of generalized joint hypermobility on injury risk in elite female soccer players: a prospective cohort study. *Am J Sports Med*. 2017;45:286-93.
61. Brumitt J, Heiderscheit BC, Manske RC, et al. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *Int J Sports Phys Ther*. 2013;8:216-27.
62. Brumitt J, Heiderscheit BC, Manske RC, et al. Preseason functional test scores are associated with future sports injury in female collegiate athletes. *J Strength Cond Res*. 2018;32:1692-701.
63. Brumitt J, Wilson V, Ellis N, et al. Preseason lower extremity functional test scores are not associated with lower quadrant injury - a validation study with normative data on 395 division III athletes. *Int J Sports Phys Ther*. 2018;13:410-21.
64. Brumitt J, Mattocks A, Engilis A, et al. Prior history of anterior cruciate ligament (ACL) reconstruction is associated with a greater risk of subsequent ACL injury in female collegiate athletes. *J Sci Med Sport*. 2019;22:1309-13.

65. Landis SE, Baker RT, Seegmiller JG. Non-contact anterior cruciate ligament and lower extremity injury risk prediction using functional movement screen and knee abduction moment: an epidemiological observation of female intercollegiate athletes. *Int J Sports Phys Ther.* 2018;13:973-84.
66. Clausen MB, Tang L, Zebis MK, et al. Self-reported previous knee injury and low knee function increase knee injury risk in adolescent female football. *Scand J Med Sci Sports.* 2016;26:919-26.
67. Vauhnik R, Morrissey MC, Rutherford OM, et al. Knee anterior laxity: a risk factor for traumatic knee injury among sportswomen? *Knee Surg Sports Traumatol Arthrosc.* 2008;16:823-33.
68. Dingenen B, Malfait B, Nijs S, et al. 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.* 2015;30:781-7.
69. Goetschius J, Smith HC, Vacek PM, et al. 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.* 2012;40:1978-84.
70. Kosaka M, Nakase J, Numata H, et al. Psychological traits regarding competitiveness are related to the incidence of anterior cruciate ligament injury in high school female athletes. *Knee.* 2016;23:681-5.
71. Krosshaug T, Steffen K, Kristianslund E, et al. The vertical drop jump is a poor screening test for acl injuries in female elite soccer and handball players. *Am J Sports Med.* 2016;44:874-83.
72. Numata H, Nakase J, Kitaoka K, et al. Two-dimensional motion analysis of dynamic knee valgus identifies female high school athletes at risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc.* 2018;26:442-7.
73. Oshima T, Nakase J, Kitaoka K, et al. Poor static balance is a risk factor for non-contact anterior cruciate ligament injury. *Arch Orthop Trauma Surg.* 2018;138:1713-8.
74. Shimozaki K, Nakase J, Takata Y, et al. Greater body mass index and hip abduction muscle strength predict noncontact anterior cruciate ligament injury in female Japanese high school basketball players. *Knee Surg Sports Traumatol Arthrosc.* 2018;26:3004-11.
75. Smeets A, Malfait B, Dingenen B, et al. Is knee neuromuscular activity related to anterior cruciate ligament injury risk? A pilot study. *Knee.* 2019;26:40-51.

- 421 76. Steffen K, Nilstad A, Kristianslund EK, et al. Association between Lower Extremity
422 Muscle Strength and Noncontact ACL Injuries. *Med Sci Sports Exerc.* 2016;48:2082-
423 9.
- 424 77. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control
425 and valgus loading of the knee predict anterior cruciate ligament injury risk in female
426 athletes: a prospective study. *Am J Sports Med.* 2005;33:492-501.
- 427 78. Leppanen M, Pasanen K, Krosshaug T, et al. Sagittal plane hip, knee, and ankle
428 biomechanics and the risk of anterior cruciate ligament injury: a prospective study.
429 *Orthop J Sports Med.* 2017;5:2325967117745487.
- 430 79. Leppänen M, Pasanen K, Parkkari J, et al. Stiff landings are associated with increased
431 ACL injury risk in young female basketball and floorball players. *Am J Sports Med.*
432 2017;45:386-93.
- 433 80. Holden S, Boreham C, Doherty C, et al. Two-dimensional knee valgus displacement as a
434 predictor of patellofemoral pain in adolescent females. *Scand J Med Sci Sports.*
435 2017;27:188-94.
- 436 81. Myer GD, Ford KR, Barber Foss KD, et al. The incidence and potential pathomechanics
437 of patellofemoral pain in female athletes. *Clin Biomech.* 2010;25:700-7.
- 438 82. Visnes H, Aandahl HÅ, Bahr R. Jumper's knee paradox - Jumping ability is a risk factor
439 for developing jumper's knee: A 5-year prospective study. *Br J Sports Med.*
440 2013;47:503-7.
- 441 83. Visnes H, Tegnander A, Bahr R. Ultrasound characteristics of the patellar and quadriceps
442 tendons among young elite athletes. *Scand J Med Sci Sports.* 2015;25:205-15.
- 443 84. Attenborough AS, Sinclair PJ, Sharp T, et al. The identification of risk factors for ankle
444 sprains sustained during netball participation. *Phys Ther Sport.* 2017;23:31-6.
- 445 85. Hartley EM, Hoch MC, Boling MC. Y-balance test performance and BMI are associated
446 with ankle sprain injury in collegiate male athletes. *J Sci Med Sport.* 2018;21:676-80.
- 447 86. Beynnon BD, Renstrom PA, Alosa DM, et al. Ankle ligament injury risk factors: a
448 prospective study of college athletes. *J Orthop Res.* 2001;19:213-20.
- 449 87. Kofotolis N, Kellis E. Ankle sprain injuries: a 2-year prospective cohort study in female
450 Greek professional basketball players. *J Athl Train.* 2007;42:388-94.
- 451 88. McCann RS, Kosik KB, Masafumi T, et al. Acute lateral ankle sprain prediction in
452 collegiate women's soccer players. *Int J Sports Phys Ther.* 2018;13:12-8.

89. Brumitt J, Heiderscheit BC, Manske RC, et al. The lower-extremity functional test and lower-quadrant injury in NCAA division III athletes: a descriptive and epidemiologic report. *J Sport Rehabil.* 2016;25:219-26.
90. Chorba RS, Chorba DJ, Bouillon LE, et al. Use of a functional movement screening tool to determine injury risk in female collegiate athletes. *N Am J Sports Phys Ther.* 2010;5:47-54.
91. Emery CA, Meeuwisse WH, Hartmann SE. Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system. *Am J Sports Med.* 2005;33:1882-91.
92. Leetun DT, Ireland ML, Willson JD, et al. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc.* 2004;36:926-34.
93. Maestro A, Lago J, Revuelta G, et al. Analysis of hip strength and mobility as injury risk factors in amateur women's soccer: A pilot study. *Arch Med Deporte.* 2017;34:25-9.
94. Myer GD, Ford KR, Paterno MV, et al. The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med.* 2008;36:1073-80.
95. Naicker M, Coetzee D, Schall R. Morphological and skill-related fitness components as potential predictors of injuries in elite female field hockey players. *S Afr J Res Sport PH.* 2016;38:127-41.
96. O'Kane JW, Neradilek M, Polissar N, et al. Risk factors for lower extremity overuse injuries in female youth soccer players. *Orthop J Sports Med.* 2017;5:2325967117733963.
97. O'Kane JW, Tencer A, Neradilek M, et al. Is knee separation during a drop jump associated with lower extremity injury in adolescent female soccer players? *Am J Sports Med.* 2016;44:318-23.
98. Plisky PJ, Rauh MJ, Kaminski TW, et al. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther.* 2006;36:911-9.
99. Steffen K, Myklebust G, Andersen TE, et al. Self-reported injury history and lower limb function as risk factors for injuries in female youth soccer. *Am J Sports Med.* 2008;36:700-8.
100. Markolf K, Yamaguchi K, Matthew J, et al. Effects of tibiofemoral compression on ACL forces and knee kinematics under combined knee loads. *J Orthop Res.* 2019;37:631-9.

- 487 101. Ford KR, Shapiro R, Myer GD, et al. Longitudinal sex differences during landing in
488 knee abduction in young athletes. *Med Sci Sports Exerc.* 2010;42:1923-31.
- 489 102. Holden S, Boreham C, Delahunt E. Sex differences in landing biomechanics and
490 postural stability during adolescence: a systematic review with meta-analyses. *Sports*
491 *Med.* 2016;46:241-53.
- 492 103. Smith HC, Vacek P, Johnson RJ, et al. Risk factors for anterior cruciate ligament injury:
493 a review of the literature—part 2: hormonal, genetic, cognitive function, previous
494 injury, and extrinsic risk factors. *Sports Health.* 2012;4:155-61.
- 495 104. Whittaker JL, Small C, Maffey L, et al. Risk factors for groin injury in sport: an updated
496 systematic review. *Br J Sports Med.* 2015;49:803-9.
- 497 105. Orchard JW, Chaker Jomaa M, Orchard JJ, et al. Fifteen-week window for recurrent
498 muscle strains in football: a prospective cohort of 3600 muscle strains over 23 years
499 in professional Australian rules football. *Br J Sports Med.* 2020:bjsports-2019-
500 100755.
- 501 106. Messer DJ, Shield AJ, Williams MD, et al. Hamstring muscle activation and
502 morphology are significantly altered 1–6 years after anterior cruciate ligament
503 reconstruction with semitendinosus graft. *Knee Surg Sports Traumatol Arthrosc.*
504 2020;28:733-41.
- 505 107. Konrath JM, Vertullo CJ, Kennedy BA, et al. Morphologic characteristics and strength
506 of the hamstring muscles remain altered at 2 years after use of a hamstring tendon
507 graft in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2016;44:2589-98.
- 508 108. Bourne MN, Bruder AM, Mentiplay BF, et al. Eccentric knee flexor weakness in elite
509 female footballers 1–10 years following anterior cruciate ligament reconstruction.
510 *Phys Ther Sport.* 2019;37:144-9.
- 511 109. Antosh IJ, Svoboda SJ, Peck KY, et al. Change in KOOS and WOMAC scores in a
512 young athletic population with and without anterior cruciate ligament injury. *Am J*
513 *Sports Med.* 2018;46:1606-16.
- 514 110. Lima YL, Ferreira VMLM, de Paula Lima PO, et al. The association of ankle
515 dorsiflexion and dynamic knee valgus: A systematic review and meta-analysis. *Phys*
516 *Ther Sport.* 2018;29:61-9.
- 517 111. van der Harst JJ, Gokeler A, Hof AL. Leg kinematics and kinetics in landing from a
518 single-leg hop for distance. A comparison between dominant and non-dominant leg.
519 *Clin Biomech.* 2007;22:674-80.

112. Thorlund K, Imberger G, Walsh M, et al. The number of patients and events required to limit the risk of overestimation of intervention effects in meta-analysis--a simulation study. *PLoS One*. 2011;6:e25491.
113. von Hippel PT. The heterogeneity statistic I² can be biased in small meta-analyses. *BMC Med Res Methodol*. 2015;15:35.
114. Bittencourt N, Meeuwisse W, Mendonça L, et al. Complex systems approach for sports injuries: moving from risk factor identification to injury pattern recognition—narrative review and new concept. *Br J Sports Med*. 2016;50:1309-14.
115. Stern BD, Hegedus EJ, Lai Y-C. Injury prediction as a non-linear system. *Phys Ther Sport*. 2019;41:43-8.
116. Lonie TA, Brade CJ, Finucane ME, et al. Hip adduction and abduction strength and adduction-to-abduction ratio changes across an Australian Football League season. *J Sci Med Sport*. 2020;23:2-6.
117. Bahr R, Holme I. Risk factors for sports injuries — a methodological approach. *Br J Sports Med*. 2003;37:384-92.

7 Figure captions

Fig 1 PRISMA flow chart outlining the article identification, screening and selection process, with reasons for exclusion of articles, and article counts at each stage.

Fig 2 Flow diagram of data from extraction to inclusion in results, highlighting the conditions required for data to be assigned to either the meta-analysis, best evidence synthesis, or included in supplementary files. Band thickness indicates the number of data in each condition and colour indicates where data were presented.

Fig 3 Summary of results from individual random effect model meta-analyses of risk factors for any lower limb injury. Top figure shows SMD and mean difference (mean diff) with 95% CI in original units. Bottom figure shows the odds ratio. FMS: functional movement screen; SEBT: star excursion balance test; leg: leg length; yrs: years; ht: height.

Fig 4 Summary of results from individual random effect model meta-analyses of risk factors for knee injury (a), ACL injury (b), and anterior knee pain (c). Top figure shows SMD and mean difference (mean diff) with 95% CI in original units. Bottom figure shows the odds ratio COG: center of gravity; DVJ: drop vertical jump; H/Q: hamstring to quadriceps ratio; VGRF: vertical ground reaction force; yrs: years.

Fig 5 Summary of results from individual random effect model meta-analyses of risk factors for ankle injury. Top figure shows SMD and mean difference (mean diff) with 95% CI in original units. Bottom figure shows the odds ratio SEBT: star excursion balance test; leg: leg length; yrs: years.

Fig 6 Best evidence synthesis, indicating the association and strength of evidence between risk factors and lower limb injury by group. Figure includes all risk factors investigated by a minimum of two studies. ^a indicates risk factors that were also analysed using a meta-analysis. 1RM: one repetition maximum; ACL: anterior cruciate ligament; AKP: anterior

560 knee pain; DVJ: drop vertical jump; KOOS: knee injury and osteoarthritis outcome score;
561 pKAM: probability of high knee abduction moment; ROM: range of motion; VGRF: vertical
562 ground reaction force; VO₂: maximal oxygen uptake.