Prevention strategies for lower extremity injury: a systematic review and meta-analyses for the Female, Woman and Girl Athlete Injury Prevention (FAIR) Consensus

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ABSTRACT

Objective Examine the effectiveness and unintended consequences of prevention strategies for reducing female/woman/girl athletes' lower extremity (LE) injuries.

Design Systematic review with meta-analyses and Grading of Recommendations, Assessment, Development and Evaluation.

Data sources Systematic search of eight data sources.

Eligibility Primary data studies with a comparison group(s) investigating injury prevention strategies for sport-related LE injuries with ≥1 female/woman/girl in each study group.

Results Across 82 studies—including 48 randomised controlled trials (59%), 16 quasiexperimental studies (20%), 16 cohort studies (20%) and 1 cross-sectional study (1%)—a total of 154 561 participants were included, of whom 84 915 (55%) were females/women/girls. Neuromuscular training (NMT)-based programmes (n=60, 73%) were the most frequently studied intervention, followed by personal protective equipment (PPE) (n=9, 11%), policy/rule change (n=4, 5%) and education (n=6, 7%). The median Downs and Black score for all studies was 17 (range: 5–24). Point estimate from pooled results from nine studies revealed that NMT programmes, which include LE balance, strength, agility and change of direction exercises, with a minimum dose of 10 min two times per week, reduced female/woman/girl athletes' LE injuries by 19% (0.81, 95% CI 0.61% to 1.08%; low certainty evidence). Point estimate of pooled results from six studies uncovered that NMT reduced ankle sprains by 39% (0.61, 95% CI 0.36% to 1.03%; moderate certainty evidence). NMT significantly reduced anterior cruciate ligament (ACL) injuries by 61% (0.39, 95% CI 0.25% to 0.60%; high certainty evidence).

Conclusion NMT programmes can reduce female/woman/girl athletes' ACL injuries by up to 61% and ankle sprains by 39%, highlighting the need for widespread implementation of NMT programmes. Evidence informing PPE, policy/rule changes and education to prevent female/woman/girl athletes' LE injuries is needed.

PROSPERO registration number CRD42024486715.

INTRODUCTION

Female, woman and/or girl (hereafter female/woman/girl) sport participation is at high risk of injury.[1,2] Lower extremity injuries account for over 60% of all female/woman/girl sport injuries.[1,2] In any given season, up to 50% of female/woman/girl athletes playing a variety of sports experience a lower extremity injury,[2,3] with reported injury rates of 0.43–1.96 injuries per 1000 athlete exposures across high school, university and professional levels.[2,4,5] This is compared with the upper extremity, which accounts for 19–28% of all female/woman/girl sports-related injuries in a single season,[1,6–8] less than the lower extremity.[2,4,5] Thus, focusing on lower extremity injury prevention programmes has the highest impact on female/woman/girl sport injury burden. Lower extremity injuries have significant financial and long-term health consequences. Lower extremity injuries are responsible for an estimated 1.32 million emergency department visits annually (USA),[9] costing between $14 339 203 and $21 797 582 (New Zealand),[10] $1 944 267 within football (soccer) (New South Wales, Australia)[11] and $13 403 median total healthcare costs from anterior cruciate ligament (ACL) injuries in the USA alone annually.[12] Long-term health consequences of lower extremity injuries include post-traumatic osteoarthritis[13] and reduced function,[14] physical activity[15] and quality of life.[16,17]

Given the burden[2–5] and consequences[13,14,16] of female/woman/girl athletes' lower extremity injuries, substantial research has evaluated the impact

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Evidence about female/woman/girl sport-related lower extremity injury prevention strategies varies in methodology and across intervention type (neuromuscular training, personal protective equipment, policy/rules).

WHAT THIS STUDY ADDS

⇒ Neuromuscular training and other exercise-based injury prevention programmes are inconclusive to reduce female/woman/girl athletes' lower extremity injuries (low certainty evidence from nine studies including 6074 females/women/girls).

⇒ Neuromuscular training-based injury prevention programmes—with a minimum dose of 10 min, two times per week, and progression from bilateral to single-leg training that includes balance, lower extremity strength, agility and change of direction—should be implemented.

⇒ Neuromuscular training programmes reduce female/woman/girl athletes' ankle sprains and anterior cruciate ligament tears (moderate certainty evidence from six studies including 4799 females/women/girls; high certainty of evidence including 6492 females/women/girls).

⇒ Little is known about preventing female/woman/girl athletes' lower extremity injuries beyond the knee and ankle or through personal protective equipment, policy/rule changes or education.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Given the relatively low burden of neuromuscular training prevention programmes, there is an opportunity for international and national policies to support widespread implementation across female/woman/girl sport.

of lower extremity injury prevention interventions on lower extremity injury risk and/or severity, including neuromuscular training (NMT) programmes, personal protective equipment (PPE) and policy/rule changes.[18] Additional research identified that NMT-based injury prevention programmes that include balance, strength, agility and/or running/movement/cutting drills can reduce lower extremity injuries in female/woman/girl athletes across team sports and competition levels.[19–21] Less is known about female/woman/girl athlete PPE (eg, knee and ankle braces) with unknown or inconsistent benefit across injury locations (eg, ankle, knee, hip).[22 23]

The effectiveness of lower extremity NMT programmes varies by sex and/or gender. A systematic review and meta-analysis in female/woman/girl football (soccer) reported low certainty evidence that NMT programmes reduce lower extremity injuries by 27% (incidence rate ratio (IRR) 0.73, 95% CI 0.59% to 0.91%) and ACL injuries by 45% (IRR 0.55, 95% CI 0.32% to 0.92%).[24] A cluster randomised controlled trial (RCT) (1067 students aged 11–16/12 schools) revealed that an NMT programme reduced lower extremity injury for females/girls (IRR 0.54, 95% CI 0.30 to 1.00), but not for males/boys (IRR 0.87, 95% CI 0.43 to 1.77).[25] In contrast, a cluster RCT (n=3611 athletes, n=14 schools) reported that an NMT programme did not reduce lower extremity injuries in females/girls (OR 1.27, 95% CI 0.79 to 2.06).[26] These discrepancies in findings may be due to differences in population (general middle school students vs high school athletic teams) or specific intervention performed.

The effects of female/woman/girl-specific lower extremity injury prevention strategies vary across intervention type (eg, NMT, PPE and policy/rules) and methodologies that assessed these interventions (eg, cross-sectional studies, cohort studies, quasiexperimental studies, RCTs).[18] This heterogeneity has limited the interpretation and clinical applicability of female/woman/girl sport injury prevention strategies. Disaggregating existing data could provide a better understanding of the effectiveness of lower extremity injury prevention strategies specifically for female/woman/girl athletes and empower knowledge users (eg, athletes, coaches, clinicians, parents, community sport partners) to take action (eg, change practice, implement policy/rules). Evaluating unintended consequences (unexpected poor outcomes that are not the intended effect of an intervention or policy, such as an unintended increase in lower extremity injury rates following concussion prevention mandates) will provide further evaluation of the intervention effectiveness and quality.[27] The purpose of this systematic review was to examine the effectiveness of female/woman/girl athletes' lower extremity injury prevention strategies (eg, NMT, PPE, policy/rules and management) and their unintended consequences.

METHODS

Registration

This review was prospectively registered on PROSPERO (CRD42024486715) on 1 January 2024.

Framework

The Cochrane Handbook,[28] Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines[29] and PRISMA-Search extension[30] informed the conduct and reporting of this review.

Eligibility criteria

The main outcomes of interest for this review were sport-related lower extremity injury resulting in time loss and lower extremity injury severity. The interventions of interest included primary and secondary sport-related lower extremity injury prevention strategies that targeted intrinsic (eg, muscle strength, balance, performance) and/or extrinsic (eg, training load, rules and regulations, equipment) factors. Athletes were defined as individuals who participate in sports competition and/or performance (eg, dance) at all levels (eg, amateur, adult, Para sport and professional).[31] Sport was defined as any physical activity involving physical exertion and skill in which an individual or team competed under a set of rules.

Inclusion criteria included (1) full text in the English language; (2) human participants; (3) original data RCTs, cluster RCTs, quasiexperimental studies, prospective cohort studies, historical cohort studies, case–control studies and cross-sectional studies; (4) sport-related lower extremity primary injury, recurrent injury, injury severity and/or unintended consequence outcomes (unexpected poor outcome that is not the intended effect of an intervention or policy); (5) injury prevention intervention with a comparison group/s; and (6) female/woman/girl-specific data/estimates.

Exclusion criteria included (1) review articles, commentaries, letters to the editor, case series, case studies, conference abstracts, conference proceedings, dissertations and pre-experimental studies; (2) studies without female/woman/girl-specific results; and (3) studies that included recreational activities (eg, hiking, walking, running, skiing) without competition, including active transportation (eg, cycling, walking or using a scooter to commute to school or work).

Data sources and search strategy

Studies were identified from the following databases: (1) Ovid MEDLINE ALL; (2) CINAHL Plus with Full Text (EBSCO); (3) APA PsycInfo (Ovid); (4) Cochrane Database of Systematic Reviews (Ovid); (5) Cochrane Central Register of Controlled Trials (Ovid); (6) SPORTDiscus with Full Text (EBSCO); (7) Embase (Ovid); and (8) ERIC (EBSCO).

With inputs from the research team, a professional medical librarian (AH) developed and conducted systematic searches on 30 October 2023, with Cochrane Database of Systematic Reviews and CENTRAL on 23 November 2023, focusing on two domains (ie, sport-related lower extremity injury, unintended consequences) and terms associated with (1) sport, (2) prevention and risk, and (3) lower extremity constructs. The concepts for 'Sports' and 'Prevention' were adapted from searches conducted for the Consensus Statement on Concussion in Sport.[32] The search strategy was also peer reviewed by an external expert health sciences librarian. Searches were limited to studies published between 2001 and 2023 and were not restricted by language. Reference lists from systematic reviews were searched to identify additional studies that met study criteria. Complete search strategies for all databases are available (see Search Strategy in the online supplemental material). All identified articles were uploaded to Covidence (Veritas Health Innovation, Melbourne, Australia), deduplicated and screened for study inclusion.

Study selection

Before screening, inter-rater agreement of ≥80% was established among all screeners on a sample set (50 MEDLINE records). Retracted studies were identified (www.retractionwatch.com) and removed prior to screening. A three-step screening process was performed for study selection. Four reviewers (JML, AMR, EKR, MW) performed a rapid title-abstract screen to exclude non-sport-related lower extremity injuries, non-human study participants or non-original research such as opinion pieces. Following rapid screening, pairs of two author groups each independently screened title-abstracts (MB, MNB, HPD, CE, MH, JML, SM, ABM, MCM, GM, OBAO, DP, KP, AMR, EKR, KT, EV, MvM, SJW, MW, JLW) for inclusion and discussed resolution of discrepancies. If there was any doubt about a specific abstract to be included in the review, the abstract was progressed to full-text review. Full texts were independently reviewed by AMR or CE and one other reviewer (MB, MNB, MH, JML, CM, GM, MCM, MMø, NSM, SM, OBAO, DP, KP, AMR, EKR, KT, MvM, EV, SJW, MW, JLW) for inclusion. Discrepancies at title-abstract or full-text screening were discussed by raters for consensus and/or resolved by a third reviewer (GSB, AMR, CE).

Data extraction

Eligible articles were divided among the same pairs of authors and data were extracted into customised Excel spreadsheets. Data extraction for all articles included (1) study design; (2) authors, year, location of the study; (3) participant demographics (ie, number of participants, age, sex/gender, sport, sport level (ie, paediatric ≤18 years, professional or amateur)); (4) definition of lower extremity injury; (5) definition of lower extremity injury severity (eg, time to medical clearance, time loss from sport); (6) injury type (ie, general lower extremity injury, knee injury, ankle injury, thigh injury, ACL injury, ankle sprain); (7) intervention strategy or warm-up (defined as an exercise activity at the start of practice and/or games prior to sport-specific skill and tactical training), including NMT-based programme (defined as exercise programmes that primarily target dynamic lower extremity alignment, muscle activation patterns, balance, and landing and/or running techniques, and comprise one or multiple exercise components, such as balance, agility, strength and plyometrics), PPE, policy/rules and education[33]; (8) intervention/comparison group demographics (ie, number of participants, age, sex/gender, sport, sport level); (9) unintended consequences; and (10) point estimates for outcome rates/prevalence by group, adjusted/unadjusted effect estimates (ie, incidence ratio, OR, IRR, HR) and measures of variability (eg, SEs or CIs). Where estimates were not reported and raw data were available, effect estimates and measures of variability were calculated. All paired author groups extracted data from their assigned articles to reach consensus. If disagreement on extraction occurred, a third author resolved the disagreement.

Risk of bias

Methodological quality was independently assessed by paired raters using the Downs and Black checklist.[34] A study risk of bias score was assigned for intervention studies using 22 items (removing items 1, 4, 6 and 8 because these are not pertinent to all study designs included in this systematic review). The two raters discussed any disagreements between raters to reach consensus. If consensus was not reached, a third rater resolved the disagreement.

Data analyses

Semiquantitative analyses or meta-analyses were performed when at least three studies assessed a unique injury prevention intervention. A total of three studies were used based on best practice[35] and allowing for a tie break.[28] Semiquantitative analyses were performed for studies that reported injury outcome for female/woman/girl athletes with similar estimate type (eg, group mean, mean group difference, OR, risk ratio (RR) or IRR).

Meta-analyses

Following consensus on adequate homogeneity between studies, determined by lead authors (GSB, CM, MM, CE), methods author (AMR) and biostatistician (J-MG), data for meta-analyses were pooled to estimate the effect of prevention interventions. Due to methodological heterogeneity of outcome reporting, only studies that reported overall effect estimates for lower extremity, body part or most common injuries (ACL and ankle sprains) with female/woman/girl-specific estimates were included in meta-analyses. Random effects models were performed to account for expected statistical heterogeneity due to clinical and/or methodological heterogeneity by study methodology (eg, age, gender, ethnicity, type of sport, sport exposure) and NMT variation by prevention type, length and injury definition. A standard Q-test was used to assess the heterogeneity between studies, and the I^2 statistic was used to measure the proportion of variance attributable to inconsistency. Results of included cohort studies, quasi-experimental studies and RCTs were reported as an RR or IRR. Subgroup analyses by body part (ankle, knee, thigh), specific injuries (ACL injuries and ankle sprains) and warm-up or other training-based injury prevention programme were performed. Sensitivity analyses included only studies that performed an NMT-based warm-up. All analyses were performed in Stata (Stata V.18, StataCorp, USA). Based on contemporary interpretations for 95% CIs, meta-analysis findings were interpreted through a plausible range of effect estimates that are compatible with our data and may be observed in future applications.[36]

Certainty of evidence

Certainty of evidence was assessed through the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) approach for each prevention strategy analysed through semiquantitative analyses or meta-analyses.[37] GRADE scale assesses five factors concerning risk of bias, imprecision, inconsistency, indirectness and publication bias. These factors lead to a reported score of high, moderate, low or very low certainty of the evidence. Two raters independently generated GRADE ratings for each prevention strategy and discussed any differences to reach a consensus. If needed, we engaged a third rater to resolve disagreements.

Equity, diversity and inclusion statement

Females, women, girls: Participants are referred to as 'female, woman, and/or girl' with the abbreviation of female/woman/girl and 'male, man, and/or boy' athletes with the abbreviation of male/man/boy. We acknowledge that these terms are not interchangeable and may hold different meanings for different individuals. We recognise the ongoing discussion surrounding the definitions of gender and sex and emphasise that the term 'female(s)' is not meant to define individuals solely by their biological sex, just as 'women' and 'girls' are not intended to categorise individuals solely by their gender.

Review, planning and design: Our multidisciplinary study team included mostly women (19/24 (80%)), including academics with broad expertise in epidemiology (18 (75%)), injury prevention (21 (88%)), sports medicine/health professionals (19 (80%)), sport sciences (4 (17%)) and health promotion (2 (85%)). Our expert team included mostly white individuals and from well-resourced countries, currently working across four continents (North America, Europe, Asia and Australasia). Our multidisciplinary team included a range of career stages: seven senior, nine mid-career, seven early career and one PhD candidate

Authors: The Female, Woman and Girl Athlete Injury Prevention (FAIR) Consensus Steering Committee selected authors based on their diverse backgrounds, experiences, expertise and professions. The committee consisted of 53% women (n=17) and 84% white individuals (n=27), with representation from black (African)/African American (6%, n=2), Asian (3%, n=1) and Hispanic/Latino (3%, n=1) communities. Additionally, 16% (n=5) were born in middle to low-income countries, and 3% (n=1) had a disability. The authors had self-reported experience as athletes (48%, n=16), coaches (48%, n=16), referees (9%, n=3) and professionals in health, medical or exercise fields (73%, n=24). They also contributed to sport organisations (33%, n=11), government (15%, n=5) and healthcare committees (21%, n=7), with expertise spanning paediatric (94%, n=30), adult (84%, n=27) and Para sport (53%, n=17) across five continents. Their career stages ranged from trainees (n=2) to early career (n=10), mid-career (n=9) and late career (n=11).

Patient and public involvement and engagement

The FAIR Consensus Steering Committee developed this review. The Steering Committee (n=24) has diverse involvement as athletes, coaches, sport and clinical administrative and service roles and across the research process. Authors (n=32) were determined for inclusion due to varied expertise and experiences in sport, research and clinical work. The FAIR Consensus External Advisory Committee will review recommendations and summary from this systematic review, informing FAIR Consensus and dissemination.

RESULTS

Study characteristics

From 7295 articles eligible for screening (figure 1), 82 studies[22 26 34 38–113] were included (RCT n=48, 59%; quasiexperimental n=16, 20%; cohort n=16, 20%; cross-sectional n=1, 1%; case–control n=1, 1%). Most studies were conducted in Europe (n=46, 56%; Austria n=1, Belgium n=3, Czech Republic n=1, Denmark n=3, Finland n=3, Germany n=4, Greece n=1, Ireland n=1, Italy n=2, Netherlands n=8, Norway n=4, Spain n=1, Sweden n=8, Switzerland n=3, assorted European countries n=3), followed by North America (n=24, 29%; Canada n=5, USA n=19), Asia (n=9, 11%; China n=2, Israel n=2, Japan n=2, Malaysia n=1, Pakistan n=1, Thailand n=1), South America (n=2, 2%; Brazil n=1, Chile n=1) and Oceania (New Zealand, n=1). Studies either described participants as 'females' (n=59, 72%), 'girls' (n=8, 10%), 'girls' and 'females' (n=6, 7%), 'women' (n=4, 5%), 'women' and 'females' (n=3, 4%) or did not mention sex/gender (n=2, 2%). 57 studies (70%) included adult and paediatric participants (≤18 years of age), 25 studies were unclear about including paediatric participants and 22 (27%) studies included only participants >18 years of age. No studies included female/woman/girl Para sport athletes (online supplemental table 2).

Included studies spanned a total of 154 561 athletes (intervention n=104 049; control n=50 512), representing 84 915 female/woman/girl athletes (59%; intervention n=51 155, control n=33 760) and 59 154 male athletes (41%; intervention n=45 707; control n=13 447). A total of 31 studies (total: 24 915; intervention: 14 344; control: 10 571) reported on female/woman/girl only samples. A total of 39 studies (total: 28 937; intervention: 18 366; control: 10 571) reported both female/woman/girl and male/man/boy. Of note, 10 942 athletes (7%) were from studies that did not report participant numbers by sex or gender (intervention group: n=7187; control group: n=3305), and four studies did not report their total sample size. 10 studies (n=10, 12%) included multisport participants (football (soccer)/basketball n=3, 4%; basketball/volleyball n=2, 2%; basketball/soccer/volleyball n=1, 1%; American football/soccer/volleyball n=1, 1%) or non-specific sport contexts. A total of 19 sports were represented across single-sport studies: football (soccer) (n=15, 18%), basketball (n=12, 15%), American football (n=8, 10%), volleyball (n=6, 7%), handball (n=5, 6%), alpine skiing (n=3, 4%), artistic sports (dance n=2, 2%; gymnastics n=1, 1%), flag football (n=2, 2%), floorball (n=2, 2%), running (track and field n=2, 2%) and one study each (n=1, 1%) for field hockey, futsal, Gaelic games, marathon running, orienteering and Sepak Takraw.

Injuries were most frequently reported by all lower extremity 'specific' (ie, stratified by an assortment of lower extremity injuries; n=29, 35%), followed by knee (n=19, 22%; ACL specific n=12, 14%), ankle (n=16, 20%), lower extremity 'non-specific' (n=15, 18%) and hamstring (n=3, 4%). Of note, 11 lower extremity 'specific' studies reported injuries for knee and ankle, resulting in an aggregate total of 47 studies (57%) reporting on either ankle or knee injuries

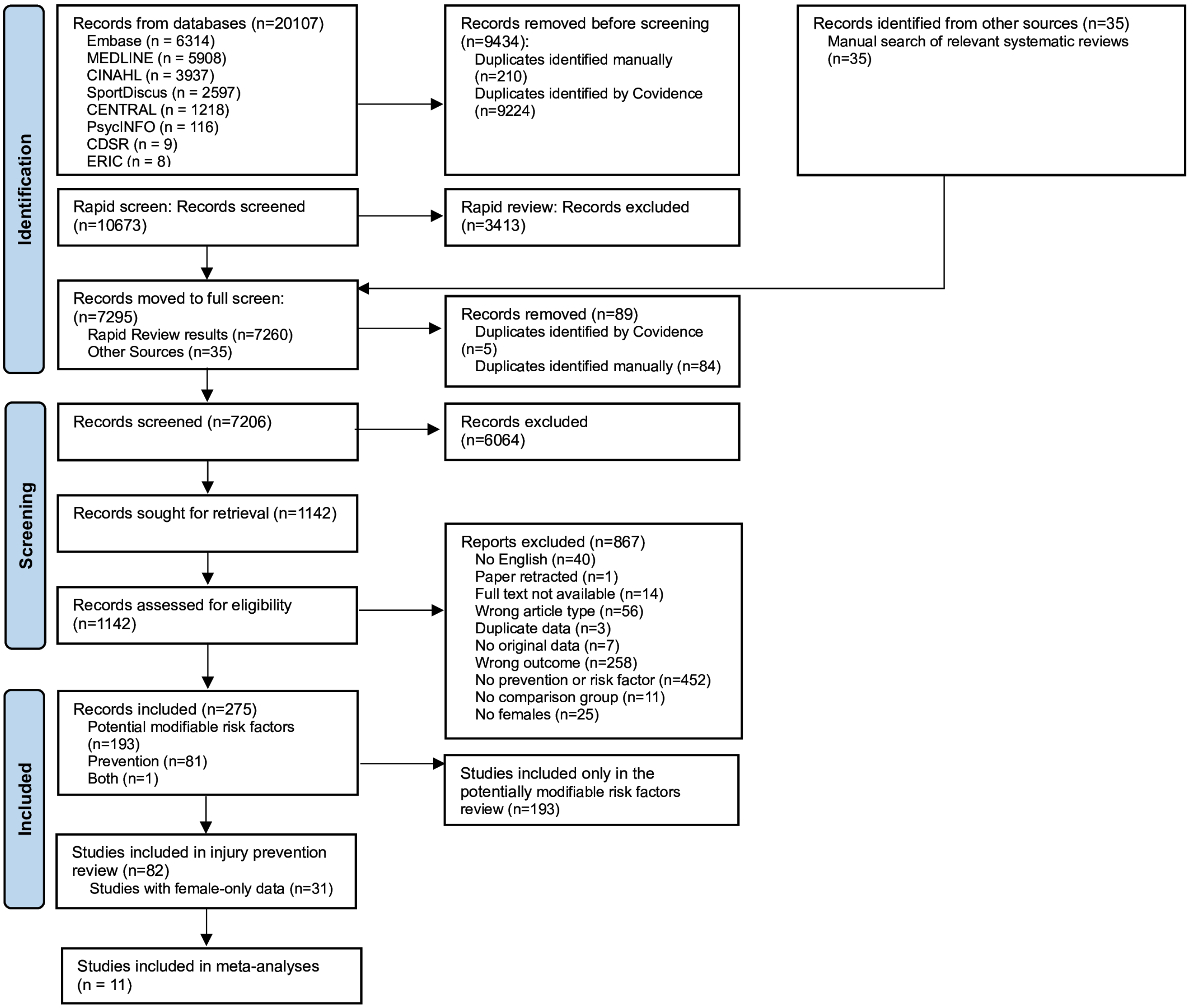

Figure 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flow diagram.

Study risk of bias

The median Downs and Black score for all studies was 17 (range: 5–24). RCTs demonstrated the highest ratings (median: 23, range: 11–24), followed by quasiexperimental (median: 18, range: 11–21) and cohort study designs (median: 14, range: 5–18). Intervention studies that included NMT (median: 19, range: 5–24) and PPE (median: 17, range: 8–22) demonstrated similar risk of bias ratings. Studies investigating policy/rule change (median: 13, range: 11–24) demonstrated the worst risk of bias ratings. A total of 40 (49%) studies were rated as high risk of bias due to confounding, selection bias and statistical analyses. A total of 21 (26%) were rated as moderate risk of bias and 20 (24%) as low risk of bias (online supplemental table 3).

Descriptive results for injury prevention

Interventions were most frequently investigated in football (soccer) (NMT n=20, 24%) and basketball (n=18, 22%; NMT n=15, equipment n=3), followed by multisport (n=10, 12%; NMT n=4, equipment n=3, assorted interventions n=1) and American football (n=9, 11%; NMT n=7, equipment n=1, policy/rules n=1). 13% of intervention studies were conducted in volleyball (n=6; NMT n=3, equipment n=2, policy/rules n=1) and handball (NMT n=5). No studies evaluated injury severity outcomes. No studies evaluated unintended consequences. Full descriptions of intervention type by sport are available in online supplemental table 4.

NMT-based injury prevention programmes

60 (73%) studies assessed NMT-based programmes (general lower extremity n=32, ankle n=10, knee n=16, hamstring n=3).

Personal protective equipment

A total of nine studies (11%) assessed PPE (general lower extremity n=4, ankle n=3, knee n=2). Of the four PPE studies that assessed general lower extremity injury prevention, two studies assessed the use of foot orthotics,[65 114] one study for ankle stirrup[66] and one study for any PPE.[101] Three studies[22 81] investigated ankle braces for ankle injury prevention, one study investigated the use of a smaller ball on knee injuries[64] and one study evaluated the functional knee brace for secondary knee injury prevention.[112]

Policy/rules

Four studies (5%) assessed policy/rule changes (general lower extremity n=2, ankle n=1, knee n=1). One study investigated the change in policy of the mandatory use of shin guards on lower extremity injuries.[91] One study assessed the changes in policy of ski length and radius on all lower extremity injuries.[110] One study assessed the change in centreline rule in volleyball and its association with ankle injuries.[59] One study assessed the change in policy of the mandatory use of alpine ski equipment on knee injuries.[96]

Education

Six studies (7%) assessed education, which was frequently reported in combination with another prevention intervention (NMT general lower extremity n=3, knee n=1; equipment and policy/rule lower extremity n=2). All NMT in combination with NMT focused on training sessions for coaches and/or athletes.[74 92 94 103] Education in combination with equipment and policy rules investigated the association of training sessions on adherence.[49 76]

Considering intervention type, injury location and effect estimates, we were able to conduct six meta-analyses (NMT for general lower extremity, knee, ankle, ACL and ankle sprain injuries) and one semiquantitative analysis (ankle braces for ankle injuries).

Meta-analyses of NMT-based injury prevention programmes

Meta-analyses for lower extremity NMT-based programmes were based on the 16 studies with female/woman/girl estimates (14 829 athletes).[26 34 41 43 55 70 71 74 85 92 100 102 103 111 114 115] A total of 13 studies[26 34 41 43 55 71 82 85 92 100 102 103 111] were NMT warm-ups while three studies[82 114 115] were supplementary NMT programmes.

General lower extremity injury

Based on pooled results of nine studies (6074 female/woman/girl athletes),[26 41 82 85 92 100 102 103 114] there is low certainty evidence that NMT-based programmes were inconclusive in reducing overall lower extremity injury rates (IRR 0.81, 95% CI 0.61 to 1.08; figure 2). There was high heterogeneity in these pooled results (tau^2 0.13, 95% CI 0.04 to 0.54; I^2=94.5%).

Ankle, knee and thigh injuries

Pooled results from six studies (4799 female/woman/girl athletes)[55 85 92 100 102 114] provided low certainty evidence that it is inconclusive if the NMT programme reduces ankle injury rates (IRR 0.78, 95% CI 0.52 to 1.17), with moderate heterogeneity (tau^2 0.00, 95% CI 0.00 to 1.11; I^2=56.4%). There was moderate certainty evidence that NMT programmes may reduce knee injury rates by 23% (n=10 studies (8931 female/woman/girl athletes)[41 43 55 71 92 100 102 111 114 115]; IRR 0.76, 95% CI 0.56% to 1.03%), with high heterogeneity (tau^2 0.14, 95% CI 0.03 to 0.64; I^2=91.4%). In contrast, there was low certainty evidence that NMT programmes did not reduce thigh injury rate (n=3 studies (one study contributed twice) (3982 female/woman/girl athletes)[100 114]; IRR 0.87, 95% CI 0.51 to 1.47), with high heterogeneity (tau^2 0.19, 95% CI 0.02 to 4.23; I^2=99.4%; figure 3).

ACL and ankle sprain injuries

There is high certainty evidence that NMT programmes reduce ACL tear rates by 61% (n=4 studies (6492 female/woman/girl athletes)[74 92 102 111]; IRR 0.39, 95% CI 0.25% to 0.60%), with little heterogeneity (tau^2 0.05, 95% CI 0.00 to 4.76; I^2=0.00%), and moderate certainty evidence that NMT programmes may reduce ankle sprain injury rates (n=4 studies (2032 female/woman/girl athletes)[34 74 82 92]; IRR 0.61, 95% CI 0.36 to 1.03), with little heterogeneity (tau^2 0.05, 95% CI 0.00 to 2.28; I^2=22.7%; figure 4).

Sensitivity analyses

Sensitivity analyses focused on differentiating estimates from 13 studies[26 34 41 43 55 71 74 85 92 100 102 103 111 114 115] that evaluated NMT-based warm-up programmes, with three studies[55 82 114] excluded that evaluated other NMT injury prevention interventions that were not warm-ups. This applied only to general lower extremity injuries, ankle injuries and ankle sprain injuries, as thigh and ACL injuries were already included only in NMT-based warm-up studies.

Sensitivity analyses suggest that NMT-based warm-up programmes do not reduce general lower extremity injury rates (n=7 studies[26 41 82 92 100 102 103]; IRR 0.85, 95% CI 0.63 to 1.13; online supplemental figure 2) or ankle sprain injury rates (n=3 studies[74 82 114]; IRR 0.64, 95% CI 0.37 to 1.10; online supplemental figure 4), but may be effective for reducing ankle injury rates by 10% (n=5 studies[55 92 100 102]; IRR 0.90, 95% CI 0.82% to 0.98%; online supplemental figure 3) and knee injury rates by 34% (n=8

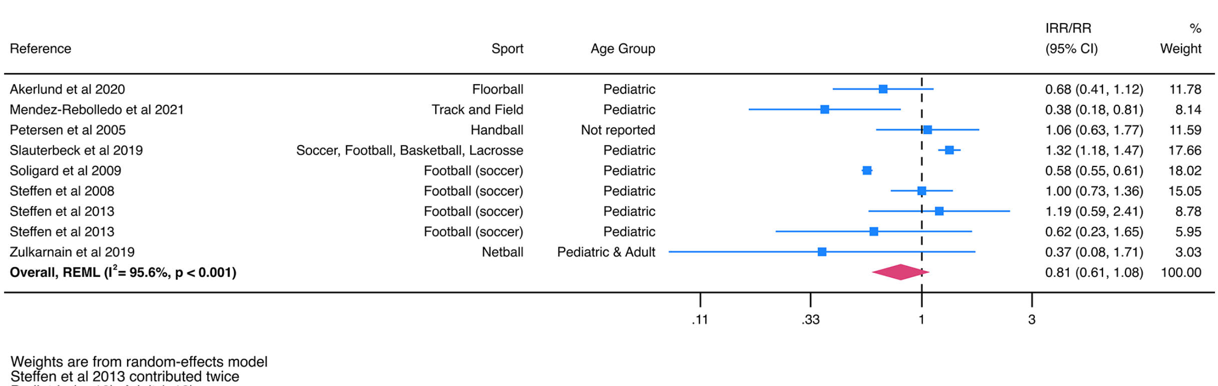

Figure 2 Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programmes on general lower extremity injuries for female/woman/girl athletes. IRR, incidence rate ratio; REML, restricted maximum likelihood; RR, risk ratio.

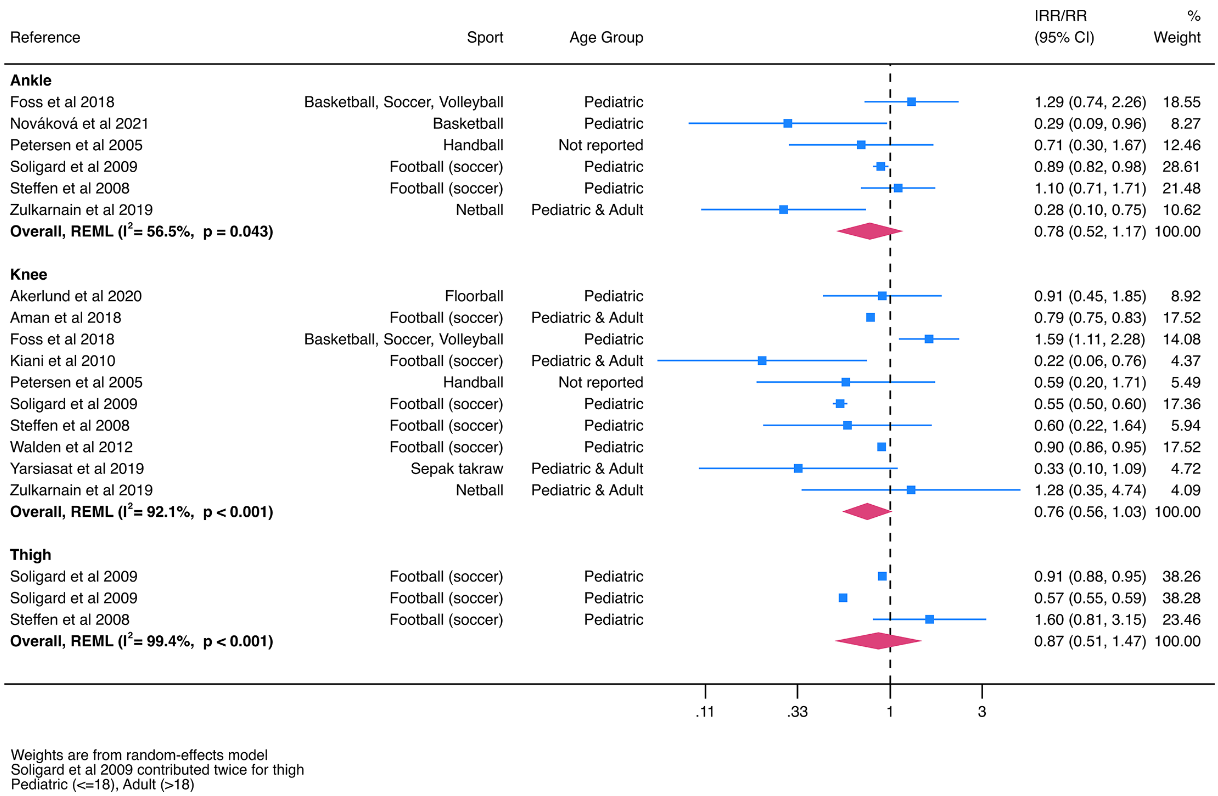

Figure 3 Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programmes on ankle, knee and thigh injuries for female/woman/girl athletes. Soligard *et al*[100] reported both anterior and posterior thighs. IRR, incidence rate ratio; REML, restricted maximum likelihood; RR, risk ratio.

studies[41 43 55 71 92 100 102 111 114 115]; IRR 0.66, 95% CI 0.52% to 0.85%; online supplemental figure 3).

Semiquantitative results for injury prevention

Equipment interventions to prevent ankle injury met the requisite three study inclusion criteria for semiquantitative analysis.[22 81 114] Three studies[22 64 81] investigated ankle braces for injury prevention. Two studies investigated paediatrics[64 81] and one study investigated paediatrics and adults.[22] Ankle brace use reduced ankle injury rates in two studies (IRR, 95% CI 0.19 to 0.95),[64 81] but increased injury rates in the third study (rate ratio 1.74, 95% CI 1.11 to 2.72).[64] The certainty of evidence was rated very low. No policy/rule interventions met the semiquantitative inclusion criteria.

Protocol deviations

There were protocol deviations to study eligibility and risk of bias assessment. The protocol originally specified that studies with no female/woman/girl-specific result(s) or those where such data could not be extracted would be excluded. However, to address concerns about the limited availability of studies with female/woman/

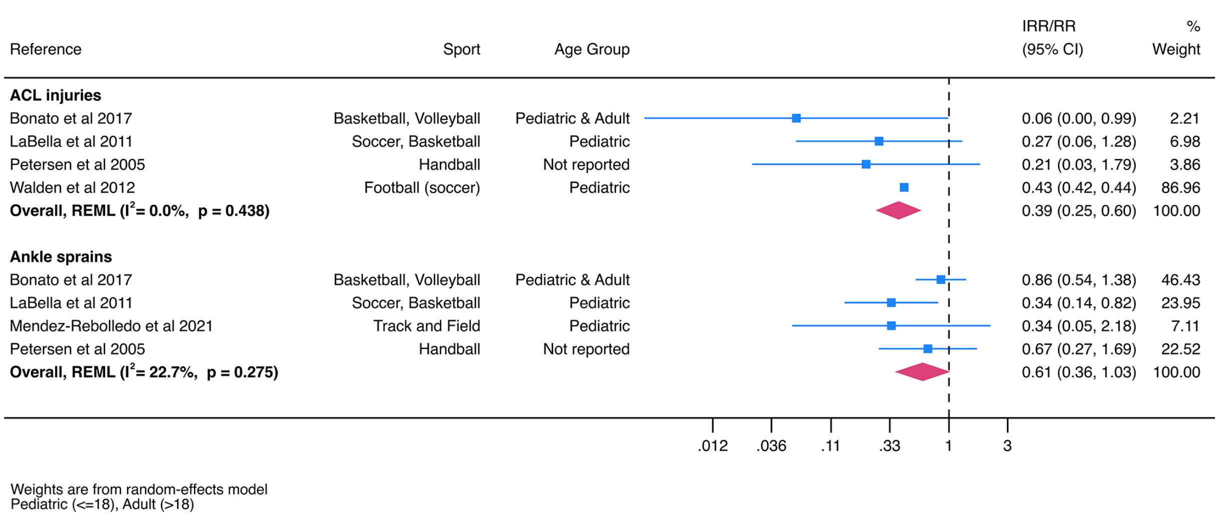

Figure 4 Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programmes for anterior cruciate ligament (ACL) injuries and ankle sprains in female/woman/girl athletes. IRR, incidence rate ratio; REML, restricted maximum likelihood; RR, risk ratio.

girl-specific estimates, we included all studies with data from at least one female/woman/girl athlete in each study group, regardless of whether sex/gender-specific results were reported. Importantly, all meta-analyses and semiquantitative analyses were still based exclusively on female/woman/girl-specific data. This approach allowed for the inclusion of more studies, providing additional data that could generate hypotheses and guide future research.

DISCUSSION

This systematic review including 82 studies (involving 31 studies with female/woman/girl data: 84 915 athletes) found mixed results for the use of current prevention strategies to reduce sport-related lower extremity injuries in female/woman/girl athletes. There is low certainty evidence that the point estimate for NMT-based injury prevention programmes could reduce lower extremity injuries, but these CIs were wide. There was moderate certainty evidence that injury prevention programmes may reduce all knee injuries by 24% and moderate certainty evidence that ankle sprain injury rates may be reduced by up to 39%. Further, there is high certainty evidence that NMT programmes reduce ACL injuries by 61%. Sensitivity analyses, only considering NMT-based warm-up interventions, demonstrated similar results except wider CIs for reducing general lower extremity injuries. Few studies evaluated the effectiveness of PPE and policy/rules to reduce female/woman/girl athletes' lower extremity injuries.

The primary analysis demonstrated a point estimate suggesting a reduction in all lower extremity injury rates for female/woman/girl athletes by performing NMT-based injury prevention programmes; however, these CIs were wide. These findings (direction and magnitude) are similar to other systematic reviews for aggregate data (combined female/woman/girl and male/man/boy) in paediatric athletes[19 64 116] and combined female/woman and male/man recreational adult athletes.[117] When comparing female/girl and male/boy athletes, these results are similar in direction and magnitude to a previous systematic review and meta-analysis in paediatric athletes.[118] The inclusion of NMT warm-up only interventions resulted in even wider CIs, which may be due to smaller sample size. The results from the present study are inconclusive concerning NMT-based injury prevention programmes in reducing general lower extremity injuries across all sports in female/woman/girl athletes.

Specific ACL injuries demonstrated reduced injury rates of up to two-thirds in female/woman/girl athletes with NMT-based interventions, similar to a previous umbrella systematic review of ACL injury prevention programmes.[19] The consistency and precision (ie, narrow 95% CI width) within the ACL injury prevention results led us to the high rating for the certainty of evidence. All studies included in this meta-analysis were NMT-based warm-up programmes, with interventions ranging from 10 min to 30 min, performed two to four times per week.[74 92 119] Thus, a minimum dose of 10 min, two times per week, incorporating progression from bilateral to single-leg NMT-based programmes and including components such as balance, lower extremity and core strength, agility and change of direction, appears effective as part of an ACL injury prevention strategy for female/woman/girl athletes.[34 74 92 111] Smaller effects for NMT-based interventions are reported in studies examining ankle sprain injury outcomes compared with ACL injury outcomes. The 39% reduction in ankle sprain injury rates is similar to the previously reported rates for female/woman/girl and male/man/boy soccer players[111] and basketball and soccer players.[120] Finally, injury prevention programmes that targeted thigh injuries did not lead to thigh injury rate reductions.

There was sparse literature evaluating the effectiveness of PPE and policy/rules on lower extremity injury reduction in female/woman/girl athletes. Injury prevention implementation should consider the socioecological model and all partners involved (eg, athlete, parent, coach, referee, sport governing body).[121–123] Policy, including rules and regulations, is systematically disseminated across all these knowledge users, without the need for athletes and coaches to implement and adhere to specific exercises of training programmes, possibly improving the reach and scope of injury prevention.[124] Ankle braces can reduce ankle injuries by 68% based on an RCT including paediatric athletes,[125] and mandatory shin guard wear can reduce lower leg injuries by 20% for football (soccer) female/woman/girl athletes.[81] However, adherence and equipment fidelity are imperative for proper injury reduction effectiveness.[110]

Potential limitations

As with all studies, there are limitations. Although a calibration exercise was performed to improve consistency in screening and data extraction, using many raters may decrease the homogeneity in literature selection. The high number of data extractors may have led to discrepancies in data extraction. This was mitigated through blinded double extraction. There are multiple tools to assess study methodological quality. This study used the Downs and Black tool, instead of the National Institutes of Health's suite of Study Quality Assessment Tools.[126] The Downs and Black tool is applicable across various study designs and assesses multiple domains, including internal validity (such as study design, reporting quality, selection and misclassification bias, and potential confounding), external validity (generalisability) and overall reporting.[127] The Downs and Black tool inherently assigns lower scores to studies that provide lower levels of evidence, such as cross-sectional, case–control and quasiexperimental studies.[35] While the tool is versatile, we acknowledge that it was not specifically designed as a stand-alone risk-of-bias instrument and does not function as one independently. Most studies were graded as having high risk of bias, decreasing the strength of these results. The meta-analyses reported high heterogeneity, decreasing the weight of these findings. Many of the meta-analysis CIs were near or at 1, decreasing the strength of these results. The search strategy was greater than 1 year, which may decrease the up-to-date literature. However, due to this systematic review informing the larger FAIR Consensus, updating the search would have missed evidence that was not presented for the practical recommendations at the in-person consensus meeting that was held, impacting the consensus.

Practical implications

Moderate to strong certainty of evidence demonstrating NMT-based programme effectiveness in reducing ACL and ankle injuries can inform widespread implementation. The low burden[35 128] for sport partners (eg, sport federations, coaches, athletes) to implement such programmes is low. The low burden creates an opportunity to mandate resource allocation and inform policy to support implementing these interventions across female/woman/girl sports and age groups. Further, educational resources codesigned with knowledge users[129] should be created and made publicly available.

Research implications

The significant heterogeneity of studies informing meta-analyses was associated with differences in aggregated sample populations, outcomes examined, exposure follow-up and mechanisms of injury, necessitating more precise investigations on the effectiveness of lower extremity injury prevention programmes. Specifically, research is needed to evaluate the effectiveness of injury prevention programmes (warm-up or general training programme) and their unintended consequences for different female/woman/girl subpopulations across age, sport and country. There are sparse data on adults and Para sport athlete populations. As different lower extremity injury types potentially have dissimilar mechanisms of injury,[124 130–134] investigations are needed to evaluate tailored injury prevention programmes for different body regions beyond ACL injuries (eg, hip, thigh, ankle). Large research initiatives are needed to evaluate the effectiveness of protective equipment (eg, ankle braces, knee braces, shin guards) in conjunction with precise implementation assessments, to evaluate the real-world effectiveness of specific protective equipment as a viable injury prevention strategy.[135] Policy/rule initiatives, such as mandatory coach accreditation or parent and athlete education, need to be evaluated across age, competition level, sport and cultures for effectiveness in preventing lower extremity injuries. An individual participant data (IPD) meta-analysis is also recommended to precisely parse out further clinical questions from the already published data.[126] An IPD meta-analysis would allow for greater study inclusion and scope, as individual data points could be extracted from raw data. An IPD meta-analysis would also allow for data quality checks, non-linear transformations and effect modifier analyses that could be performed to provide more precise results.[136]

CONCLUSION

There is low certainty evidence that NMT-based injury prevention programmes are inconclusive for reducing general lower extremity injuries across all mechanisms of injury. However, there is moderate to high certainty evidence that NMT-based injury prevention programmes reduce knee, more specifically the ACL, and ankle injury rates in female/woman/girl athletes by an estimated 61%. NMT-based injury prevention programmes reduce ankle sprain injury rates by an estimated 39%. NMT-based warm-up injury prevention programmes—with a minimum dose of 10 min, two times per week, and progression from bilateral to single-leg training that includes components such as balance, lower extremity strength, agility and change of direction—are recommended. There is no other current precise evidence for injury prevention programmes for other specific lower extremity body parts. The current evidence is sparse for female/woman/girl-specific PPE, policy/rules and education injury prevention strategies. The relative low burden of NMT-based interventions opens the door for prioritisation of nationwide and international recommendations and policies to support implementation across female/woman/girl athletes.

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Patient and public involvement statement The Female, woman, and girl Athlete Injury pRevention (FAIR) Consensus Steering Committee developed this review. The Steering Committee (n=24) have diverse involvement as athletes, coaches, sport and clinical administrative and service roles and across the research process. Authors (n=32) were determined for inclusion due to varied expertise and experiences in sport, research, and clinical work. The FAIR Consensus External Advisory Committee (EAC) will review recommendations and summary from this systematic review, informing FAIR Consensusand dissemination.

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