

## **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 (GRADE)

**Data Sources:** Systematic search of 8 data sources.

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

**Results:** Across 82 studies – including 48 randomized controlled trials (59%), 16 quasi-experimental 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-based training programs [(NMT) n=60, 73%] were the most frequently studied intervention, followed by personal protective equipment (PPE) (n=9, 11%), policy/rules 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 9 studies revealed that NMT programs, which include LE balance, strength, agility, and change of direction exercises, with a minimum dose of 10 minutes twice weekly, reduced female/woman/girl athletes' LE injuries by 19% (0.81; 95% CI: 0.61, 1.08; low certainty evidence). Point estimate of pooled results from 6 studies uncovered that NMT reduced ankle sprains by 39% (0.61; 95% CI: 0.36, 1.03; moderate certainty evidence). NMT significantly reduced anterior cruciate ligament (ACL) injuries 61% (0.39; 95% CI: 0.25, 0.60, high certainty evidence).

**Conclusion:** NMT programs 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 programs. Evidence informing PPE, policy/rule changes, and education to prevent female/woman/girl athletes' LE injuries is needed.

**Registration:** PROSPERO: CRD42024486715

**Key Words:** Neuromuscular training, exercise, policy, protective equipment, education

## Summary Box

### *What is already known.*

- 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 are the new findings?*

- Neuromuscular training and other exercise-based injury prevention programs are inconclusive to reduce female/woman/girl athletes' lower-extremity injuries (low certainty evidence from 9 studies including 6,074 females/women/girls).
- Neuromuscular training-based injury prevention programs, with a minimum dose of 10 minutes, twice weekly, and progression from bilateral to single leg training including balance, lower-extremity strength, agility, and change of direction should be implemented.
- Neuromuscular training programs reduce female/woman/girl athletes' ankle sprains and anterior cruciate ligament tears (moderate certainty evidence from 6 studies including 4,799 female/women/girls; high certainty of evidence including 6,492 female/women/girls).
- Given the relatively low burden of neuromuscular training prevention programs, there is an opportunity for international and national policies to support widespread implementation across female/woman/girl sport.
- 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.

## **Box 1: Equity, Diversity and Inclusion Statement**

***Female Women Girls:*** Participants are referred 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 from 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, 7 senior, 9 mid-career, 7 early-career, and one PhD candidate.

***Authors:*** The 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 organizations (33%, n=11), government (15%, n=5), and healthcare committees (21%, n=7), with expertise spanning pediatric (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 (n=10), mid (n=9), and late career (n=11).

## **Box 2: Patient and Public Involvement and Engagement**

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 Consensus and dissemination.

## Introduction

Female, woman, and/or girl (hereafter female/woman/girl) sport participation are at high risk of injury.<sup>1,2</sup> Lower-extremity injuries account for over 60% of all female/woman/girl sport injuries.<sup>1</sup>

<sup>2</sup> In any given season, up to 50% of female/woman/girl athletes playing a variety of sports experience a lower-extremity injury,<sup>2,3</sup> with reported injury rates of 0.43 to 1.96 injuries per 1,000 athlete exposures across high school, university, and professional levels.<sup>2,4,5</sup> This is compared to the upper extremity, which accounts for 19% to 28% of all female/woman/girl sports-related injuries in a single season,<sup>1,6-8</sup> less than the lower extremity.<sup>2,4,5</sup> Thus, focusing on lower extremity injury prevention programs have 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 (United States),<sup>9</sup> costing between \$14,339,203 to \$21,797,582 (New Zealand),<sup>10</sup> \$1,944,267 within football (soccer) (New South Wales, Australia),<sup>11</sup> and \$13,403 median total healthcare costs from Anterior Cruciate Ligament injuries in the United States alone annually.<sup>12</sup> Long-term health consequences of lower-extremity injuries include post-traumatic osteoarthritis<sup>13</sup> and reduced function,<sup>14</sup> physical activity,<sup>15</sup> and quality of life.<sup>16,17</sup>

Given the burden,<sup>2-5</sup> and consequences<sup>13,14,16</sup> of female/woman/girl athletes' lower-extremity injuries, substantial research has evaluated the impact of lower-extremity injury prevention interventions on lower-extremity injury risk and/or severity, including neuromuscular training programs, personal protective equipment (PPE), and policy/rule changes.<sup>18</sup> Additional research identified that neuromuscular training-based injury prevention programs (NMT) 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.<sup>19-21</sup> Less is known about female/woman/girl athlete PPE (e.g. knee and ankle braces) with unknown or inconsistent benefit across injury locations (e.g., ankle, knee, hip).<sup>22 23</sup>

The effectiveness of lower-extremity NMT programs varies by sex and/or gender. A systematic review and meta-analysis in female/woman/girl football (soccer) reported low-certainty evidence that NMT programs reduce lower-extremity injuries by 27% [IRR: 0.73 (95% CI: 0.59, 0.91)] and ACL injuries by 45% [IRR: 0.55 (95% CI 0.32, 0.92)].<sup>24</sup> A cluster-randomised controlled trial (RCT) (1,067 students aged 11-16 /12 schools) revealed that a NMT program 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).<sup>25</sup> In contrast, a cluster-RCT (n=3,611 athletes, n=14 schools) reported that a NMT program did not reduce lower-extremity injuries in females/girls [OR: 1.27 (95% CI: 0.79, 2.06)].<sup>26</sup> These discrepancies in findings may be due to differences in population (general middle school students versus high school athletic teams) or specific intervention performed.

The effects of female/woman/girl-specific lower-extremity injury prevention strategies varies across intervention type (e.g., NMT, PPE, and policy/rules), and methodologies that assessed these interventions (e.g., cross-sectional, cohort, quasi-experimental, RCTs).<sup>18</sup> 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 (e.g., athletes, coaches, clinicians, parents, community sport partners) to take action (e.g., 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.<sup>27</sup> The purpose of this systematic review was to examine the effectiveness of female/woman/girl athletes' lower-extremity injury prevention strategies (e.g., NMT, PPE, policy/rules, and management) and their unintended consequences.

## **Methods**

*Registration:* This review was prospectively registered on PROSPERO (CRD42024486715) January 1, 2024.

### *Framework*

The Cochrane Handbook,<sup>28</sup> Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines<sup>29</sup> and PRISMA-Search extension<sup>30</sup> 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

(e.g., muscle strength, balance, performance) and/or extrinsic (e.g., training load, rules and regulations, equipment) factors. Athletes were defined as individuals who participate in sports competition and/or performance (e.g., dance) at all levels (e.g., amateur, adult, parasport, and professional).<sup>31</sup> 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, quasi-experimental, prospective cohort, historical cohort, case-control, and cross-sectional studies, 4) sport-related lower-extremity primary injury, recurrent injury, injury severity, and/or unintended consequences 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) no female/women/girl-specific results; and 3) studies that included recreational activity (e.g., hiking, walking, running, skiing) without competition, including active transportation (e.g., cycling, walking, scooter to school or work).

### *Data Sources and Search Strategy*

Studies were identified from the following databases: 1) OVID MEDLINE (R) ALL; 2) CINAHL Plus with Full Text (EBSCO); 3) APA PsycINFO (OVID); 4) Cochrane Databases for Systematic Review (OVID); 5) Cochrane Central Register of Controlled Trials Registry (OVID); 6) SPORTDiscus with full text (EBSCO); 7) EMBASE (OVID); 8) ERIC (EBSCO).

With inputs from the research team, a professional medical librarian (KAH) developed and conducted systematic searches on October 30, 2023, with Cochrane Systematic review Database and CENTRAL on November 23, 2023, focusing on two domains (i.e., 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.<sup>32</sup> The search strategy was also peer-reviewed by an external expert health sciences librarian. Searches were limited to studies published between 2001 to 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 Supplement Search Strategy). 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  $\geq 80\%$  was established among all screeners on a sample set (50 Medline records). Retracted studies were identified ([www.retractionwatch.com](http://www.retractionwatch.com)) and removed prior to screening. A three-step screening process was performed for study

selection. Four reviewers (JML, AMR, ER, 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, MBo, HPD, CAE, MH, JML, SM, ABM, MCM, GM, OO, DP, KP, AMR, ER, KT, EV, MvM, SJW, MW, JLW) for inclusion and discussed resolution of discrepancies. If there was any doubt of a specific abstract to be included in the review, the abstract was progressed to full-text review. Full texts were independently reviewed by AR or CAE and one other reviewer (MB, MBo, MH, JML, CM, GM, MCM, MMø, NSM, SM, OBAO, DP, KP, AR, ER, 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 (GB, AMR, CAE).

### *Data Extraction*

Eligible articles were divided among the same pairs of authors and data extracted into customised excel spreadsheets. Data extraction for all articles included 1) study design; 2) authors, year, location of the study; 3) participant demographics (i.e., number of participants, age, sex/gender, sport, sport level [i.e., pediatric  $\leq 18$  years, professional, or amateur]); 4) definition of lower-extremity injury; 5) definition of lower-extremity injury severity (e.g., time to medical clearance, time-loss from sport); 6) injury type (i.e. 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 training-based program (defined as exercise programs 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)<sup>33</sup>; 8) intervention/comparison group demographics (i.e., number of participants, age, sex/gender, sport, sport level); 9) unintended consequences; 10) point estimates for outcome rates/prevalence by group, and adjusted/unadjusted effect estimates (i.e., incidence ratio, odds ratio, incidence rate ratio, hazard ratio) and measures of variability (e.g., standard errors or confidence intervals). 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.<sup>34</sup> A study risk of bias score was assigned for intervention studies using 22 items (removing items 1, 4, 6, and 8 due to these items 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*

Semi-quantitative or meta-analyses were performed when at least 3 studies assessed a unique injury prevention intervention. A total of three studies was used based on best practice<sup>35</sup> and allowing for a tie break.<sup>28</sup> Semi-quantitative analyses were performed for studies that reported

injury outcome for female/woman/girl athletes with similar estimate type (e.g., group mean, mean group difference, OR, RR or IRR).

### *Meta-Analyses*

Following consensus on adequate homogeneity between studies, determined by lead authors (GB, CM, MM, CE), methods author (AMR), and biostatistician (JMG), 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 (e.g., 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, and RCT's were reported as a risk ratio (RR) or incidence rate ratios (IRR). Sub-group analyses by body part (ankle, knee, thigh), specific injuries (ACL injuries and ankle sprains), and warm up or other training-based injury prevention program were performed. Sensitivity analyses included only studies that performed an NMT-based warm up. All analyses were performed in Stata (Stata v18, StataCorp, USA). Based on contemporary interpretations for 95% CI's, meta-analyses findings were interpreted through a plausible range of effect estimates that are compatible with our data and may be observed in future applications.<sup>36</sup>

### *Certainty of Evidence*

Certainty of evidence was assessed through the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach for each prevention strategy analyzed through semi-quantitative analyses or meta-analyses.<sup>37</sup> 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 a consensus. If needed, we engaged a third rater to resolve disagreements.

## **Results**

### *Study Characteristics*

From 7,295 articles eligible for screening (Figure 1), 82 studies<sup>22 26 34 38-113</sup> were included [RCT n=48, 59%; quasi-experimental 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, United States 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%). Fifty-seven studies (70%) included adult and pediatric participants (≤18 years of age), 25 studies were unclear about including pediatric participants,

and 22 (27%) studies included only participants >18 years of age. No studies included female/woman/girl Para sport athletes (Supplementary Table 2).

<**Figure 1.** Preferred Reporting Items for Systematic Review and Meta-Analyses Flow Diagram>

Included studies spanned a total of 154,561 athletes (intervention n=104,049; control n=50,512), representing 84,915 female/women/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 31 studies (total: 24,915; intervention: 14,344; control: 10,571) reporting on female/woman/girl only samples. A total of 39 studies (total: 28,937; intervention: 18,366; control: 10,571) reported both female/women/girl and male/men/boy. Of note, 10,942 athletes (7%) were from studies that did not report participant numbers by sex or gender (intervention group: n = 7,187; control group: n = 3,305), and four studies did not report their total sample size. Ten 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, Sepak Takraw.

Injuries were most frequently reported by all lower-extremity “specific” (i.e. 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

### *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 quasi-experimental (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/rules 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 (Supplement 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)]. Thirteen percent 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 Supplementary Table 4.

Neuromuscular Training-Based Injury Prevention Programs: Sixty (73%) studies assessed NMT-based programs (general lower-extremity n=32, ankle n=10, knee n=16, hamstring n =3).

Personal Protective Equipment: A total of 9 (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,<sup>65 114</sup> one study for ankle stirrup,<sup>66</sup> and one study for any PPE.<sup>101</sup> Three studies<sup>22 81</sup> investigated ankle braces for ankle injury prevention, one study investigated the use of a smaller ball on knee injuries,<sup>64</sup> and one study evaluated the functional knee brace for secondary knee injury prevention.<sup>112</sup>

Policy/Rules: Four (5%) assessed policy/rules 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.<sup>91</sup> One study assessed the changes in policy of ski length and radius on all lower extremity injuries.<sup>110</sup> One study assessed the change in centerline rule in volleyball and its association with ankle injuries.<sup>59</sup> One study assessed the change in policy of the mandatory use of alpine ski equipment on knee injuries.<sup>96</sup>

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

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 semi-quantitative analyses (ankle braces for ankle injuries).

*Meta-Analyses of Neuromuscular Training-Based Injury Prevention Programs*

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

General Lower-Extremity Injury: Based on pooled results of 9 studies (6,074 female/women/girl athletes),<sup>26 41 82 85 92 100 102 103 114</sup> There is low-certainty evidence that NMT-based programs were inconclusive in reducing overall lower-extremity injury rates (IRR: 0.81; 95% CI: 0.61, 1.08; Figure 2). There was high heterogeneity in these pooled results (tau<sup>2</sup>: 0.13; 95% CI: 0.04, 0.54; I<sup>2</sup>: 94.5%).

<**Figure 2.** Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programs on general lower-extremity injuries for female/woman/girl athletes. REML = Restricted maximum likelihood.>

Ankle, Knee and Thigh Injuries: Pooled results from 6 studies (4,799 female/women/girl athletes),<sup>55 85 92 100 102 114</sup> provided low certainty evidence that it is inconclusive if NMT program reduce ankle injury rates (IRR: 0.78; 95% CI: 0.52, 1.17), with moderate heterogeneity ( $\tau^2$ : 0.00; 95% CI: 0.00, 1.11);  $I^2$ : 56.4%). There was moderate certainty evidence that NMT programs may reduce knee injury rates by 23% (n=10 studies (8,931 female/women/girl athletes)<sup>41 43 55 71 92 100 102 111 114 115</sup>; IRR: 0.76; 95% CI: 0.56, 1.03), with high heterogeneity ( $\tau^2$ : 0.14; 95% CI: 0.03, 0.64);  $I^2$ : 91.4%). In contrast, there was low certainty evidence that NMT programs did not reduce thigh injury rate (n=3 studies (one study contributed twice) (3,982 female/women/girl athletes)<sup>100 114</sup>; IRR: 0.87; 95% CI: 0.51, 1.47), with high heterogeneity ( $\tau^2$ : 0.19; 95% CI: 0.02, 4.23);  $I^2$ : 99.4%; Figure 3).

<**Figure 3.** Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programs on ankle, knee, and thigh injuries for female/woman/girl athletes. Soligard et al. reported both anterior and posterior thigh. REML = Restricted maximum likelihood.>

ACL Injuries and Ankle Sprain Injuries: There is high certainty evidence that NMT programs reduce ACL tear rates by 61% (n=4 studies (6,492 female/women/girl athletes)<sup>74 92 102 111</sup>; IRR: 0.39; 95% CI: 0.25, 0.60), with little heterogeneity ( $\tau^2$ : 0.05; 95% CI: 0.00, 4.76);  $I^2$ : 0.00%), and moderate certainty evidence that NMT programs may reduce ankle sprain injury rates (n=4 studies (2,032 female/women/girl athletes)<sup>34 74 82 92</sup>; IRR: 0.61; 95% CI: 0.36, 1.03), with little heterogeneity ( $\tau^2$ : 0.05; 95% CI: 0.00, 2.28);  $I^2$ : 22.7%; Figure 4).

<**Figure 4.** Random effects meta-analysis forest plot of studies evaluating neuromuscular training-based injury prevention programs for Anterior Cruciate Ligament (ACL) injuries and ankle sprains in female/woman/girl athletes. REML = Restricted maximum likelihood.>

### *Sensitivity Analyses*

Sensitivity analyses focused on differentiating estimates from 13 studies<sup>26 34 41 43 55 71 74 85 92 100 102 103 111 114 115</sup> that evaluated NMT-based warm up programs, with three studies<sup>55 82 114</sup> excluded that evaluated other NMT training 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 already only included NMT-based warm up studies.

Sensitivity analyses suggest that NMT-based warm up programs do not reduce general lower-extremity injury rates (n=7 studies<sup>26 41 82 92 100 102 103</sup>; IRR: 0.85; 95% CI: 0.63, 1.13; Supplement Figure 2) or ankle sprain injury rates (n=3 studies<sup>74 82 114</sup>; IRR: 0.64; 95% CI: 0.37, 1.10; Supplement Figure 4), but may be effective for reducing ankle injury rates by 10% (n=5 studies<sup>55 92 100 102</sup>; IRR: 0.90; 95% CI: 0.82, 0.98; Supplement Figure 3). and knee injury rates by 34% (n=8 studies<sup>41 43 55 71 92 100 102 111 114 115</sup>; IRR: 0.66; 95% CI: 0.52, 0.85; Supplement Figure 3).

### *Semi-Quantitative Results for Injury Prevention*

Equipment interventions to prevent ankle injury met the requisite three study inclusion criterion for semi-quantitative analysis.<sup>22 81 114</sup> Three studies<sup>22 64 81</sup> investigated ankle braces for injury prevention. Two studies investigated pediatric<sup>64 81</sup> and one studied pediatrics and adults.<sup>22</sup> Ankle brace use reduced ankle injuries rates in 2 studies (IRR 95% CI Range: 0.19, 0.95),<sup>64 81</sup> but increased injury rates in the third (Rate Ratio: 1.74 (95% CI: 1.11, 2,.72)).<sup>64</sup> The certainty of

evidence was rated very-low. No policy/rules interventions met the semi-quantitative 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/women/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/women/girl-specific estimates, we included all studies with data from at least one female/women/girl athlete in each study group, regardless of whether sex/gender-specific results were reported. Importantly, all meta-analyses and semi-quantitative analyses were still based exclusively on female/women/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/women/girl athletes. There is low certainty evidence that the point estimate for NMT-based injury prevention programs could reduce lower-extremity injuries, but these confidence intervals were wide. There was moderate certainty evidence that injury prevention programs 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 programs reduce ACL injuries by 61%. Sensitivity analyses only considering NMT-based warm up interventions demonstrated similar results except wider confidence intervals 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 programs; however, these confidence intervals were wide. These findings (direction and magnitude) are similar to other systematic reviews for aggregate data (combined female/woman/girl and male/man/boy) pediatric athletes,<sup>19 64 116</sup> and combined female/woman and male/man recreational adult athletes.<sup>117</sup> 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 pediatric athletes.<sup>118</sup> The inclusion of NMT warm up only interventions resulted in even wider confidence intervals, which may be due to smaller sample size. The results from the

present study are inconclusive concerning NMT-based injury prevention programs in reducing general lower-extremity injuries across all sports in female/woman/girl athletes.

Specific ACL injuries demonstrated a 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 programs.<sup>19</sup> The consistency and precision (i.e., narrow 95% confidence interval 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 programs with interventions ranging from 10 to 30 minutes and two to four times a week.<sup>74 92 119</sup> Thus a dose of at least 10 minutes, twice per week, with a combination of progression bilateral to single leg NMT-based programs, with the inclusion of balance, lower-extremity and core strength, agility, and change of direction as part of an ACL injury prevention strategy is effective in female/women/girl athletes.<sup>34 74 92 111</sup> Smaller effects for NMT-based interventions are reported in studies examining ankle sprain injury outcomes compared to ACL injury outcomes. The 39% reduction in ankle sprain injury rates is similar to the previously reported for female/woman/girl and male/man/boy soccer players<sup>111</sup> and basketball and soccer players.<sup>120</sup> Finally, injury prevention programs 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 (e.g., athlete, parent, coach,

referee, sport governing body).<sup>121-123</sup> Policy, including rules and regulations, are systematically disseminated across all these knowledge users, without the need for athletes and coaches to implement and adhere to specific exercises of training programs, possibly improving the reach and scope of injury prevention.<sup>124</sup> Ankle braces can reduce ankle injuries by 68% based on a RCT including pediatric athletes<sup>125</sup> and mandatory shin guard wear can reduce lower leg injuries by 20% for football (soccer) female/woman/girl athletes.<sup>81</sup> However adherence and equipment fidelity is imperative for proper injury reduction effectiveness.<sup>110</sup>

### *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 Downs and Black, instead of the National Institutes of Health suite of Study Quality Assessment tools.<sup>126</sup> 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 (generalizability), and overall reporting.<sup>127</sup> The Downs and Black inherently assigns lower scores to studies that provide lower levels of evidence, such as cross-sectional, case-control, and quasi-experimental studies.<sup>35</sup> While the tool is versatile, we acknowledge that it was not specifically designed as a standalone 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 confidence intervals were near or at 1, decreasing the strength of these results. The search strategy was greater than one year old, 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 training program effectiveness in reducing ACL and ankle injuries can inform widespread implementation. The low burden<sup>35 128</sup> for sport partners (e.g., sport federations, coaches, athletes) to implement such programs 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 co-designed with knowledge users<sup>129</sup> 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 necessitate more precise investigations on the effectiveness of lower-extremity injury prevention programs. Specifically, research is needed to evaluate the effectiveness of injury

prevention programs (warm up or general training program) and their unintended consequences for different female/women/girl sub-populations across age, sport, and country. There is sparse data on adults and Para sport athlete populations. As different lower-extremity injury types potentially have dissimilar mechanisms of injury,<sup>124 130-134</sup> investigations are needed to evaluate tailored injury prevention programs for different body regions beyond ACL injuries (e.g., hip, thigh, ankle). Large research initiatives are needed to evaluate the effectiveness of protective equipment (e.g., ankle braces, knee braces, shin guard) in conjunction with precise implementation assessments, to evaluate the real world effectiveness of specific protective equipment as a viable injury prevention strategy.<sup>135</sup> Policy/rules 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 participants data (IPD) meta-analysis is also recommended to precisely parse out further clinical questions from the already published data.<sup>126</sup> 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 could be performed to provide more precise results.<sup>136</sup>

### *Conclusion*

There is low certainty evidence that NMT-based injury prevention programs 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 programs reduce knee, more specifically the ACL, and ankle injury rates in female/woman/girl athletes by an estimated 61%. NMT-based injury prevention programs reduce ankle sprain injury rates by an estimated

39%. NMT-based warm up injury prevention programs, with a minimum dose of 10 minutes two times per week, a progression of bilateral to single leg training including balance, lower-extremity strength, agility, and change of direction components is recommended. There is no other current precise evidence for injury prevention programs for other specific lower-extremity body parts. The current evidence is sparse for female/woman/girl specific personal protective equipment, policy/rules, and education injury prevention strategies. The relative low burden of NMT-based interventions opens the door for prioritization of nationwide and international recommendation and policies to support implementation across female/woman/girl athletes.

## **Declarations**

### ***Availability of data and materials***

Deidentified data can be made available upon reasonable request to the corresponding author. Please email the corresponding author with a written proposal outlining the specific research aims and analysis plan and why these specific data are needed. A formal data-sharing agreement between institutions will be required.

### ***Patient and Public Involvement and Engagement***

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 Consensus and dissemination.

### ***Competing Interests***

JLW, MB, HPD, MH, ABM, MCM, NSM, MM, OO, KP, ER, MS, MvM, CAE, KC all have editorial roles with the BJSM. JLW is supported by a Michael Smith Health Research British Columbia Scholar Award (SCH-2020-and holds peer-reviewed funding from the Canadian Institutes of Health Research (CIHR) and Arthritis Society. MOD is supported by a Quebec Health Research Fund Fellowship Award (327156). MCM is supported by a Raine Medical Research Foundation Priming Grant (RPG035-2023) and holds peer-reviewed research funding from the Australian National Health and Medical Research Council (APP2035789), Western Australian Department of Health, Australian Physiotherapy Association, Defence Science Centre of Western Australia, Exercise and Sport Science Australia, Orthopaedic Research Foundation of Western Australia, Perth Wildcats, Sports Medicine Australia, West Coast Eagles Football Club and Athlete Alliance. JO is funded by the Brazilian National Council for Scientific and Technological Development (CNPq-467 305285/2021-1). OO hold research funding from the IOC (RBU/rfr2024-2027). DP holds peer-reviewed funding from World Rugby and the International Olympic Committee. ER is developer of Rehabilendon app©, a Board of Director for Sports Medicine Australia and holds peer reviewed funding from the Victorian Institute of Sport. KMC is project leader of the GLA:D, Australia, and holds research funding from Levin Health, the Australian National Health and Medical Research Council, and Medical Research Future Fund. CAE is supported by a Tier 1 Canada Research Chair and holds peer-reviewed research funding from the CIHR, Canada Foundation for Innovation, and National Football League Scientific Advisory Board Play Smart Play Safe Program. The remaining authors declare that they have no competing interests.

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### ***Authors Contributions***

Authors contributions are reported following the Contributor Role Taxonomy (CRediT). Conceptualisation (GSB, JLW, KMC, CAE), methodology (all authors), software (GSB, AR, JMG, AH), validation (GSB), formal analysis (JMG, GSB), investigation (all authors), resources (GSB, KMC, CAE), data curation (GSB, AR), writing – original draft (GSB, AR, CM, MM), writing – review and editing (all authors), visualisation (GSB, JMG,), supervision (GSB CAE, KMC, AR), project administration (GSB, AR), and funding acquisition (KMC, CAE). The guarantor of this manuscript is GSB.

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### **Patient consent for publication**

Not applicable

### **Ethics approval**

Not applicable

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