Sex-Specific Differences in Running Injuries: A Systematic Review with Meta-Analysis and Meta-Regression

Karsten Hollander1,2 · Anna Lina Rahlf3 · Jan Wilke4 · Christopher Edler5 · Simon Steib6 · Astrid Junge1,7 · Astrid Zech3

Accepted: 10 December 2020 / Published online: 12 January 2021 © The Author(s) 2021

Abstract

Background Running is a popular sport with high injury rates. Although risk factors have intensively been investigated, synthesized knowledge about the differences in injury rates of female and male runners is scarce.

Objective To systematically investigate the differences in injury rates and characteristics between female and male runners.

Methods Database searches (PubMed, Web of Science, PEDro, SPORTDiscus) were conducted according to PRISMA guidelines using the keywords “running AND injur*”. Prospective studies reporting running related injury rates for both sexes were included. A random-effects meta-analysis was used to pool the risk ratios (RR) for the occurrence of injuries in female vs. male runners. Potential moderators (effect modifiers) were analysed using meta-regression.

Results After removal of duplicates, 12,215 articles were screened. Thirty-eight studies were included and the OR of 31 could be pooled in the quantitative analysis. The overall injury rate was 20.8 (95% CI 19.9–21.7) injuries per 100 female runners and 20.4 (95% CI 19.7–21.1) injuries per 100 male runners. Meta-analysis revealed no differences between sexes for overall injuries reported per 100 runners (RR 0.99, 95% CI 0.90–1.10, n = 24) and per hours or athlete exposure (RR 0.94, 95% CI 0.69–1.27, n = 6). Female sex was associated with a more frequent occurrence of bone stress injury (RR (for males) 0.52, 95% CI 0.36–0.76, n = 5) while male runners had higher risk for Achilles tendinopathies (RR 1.86, 95% CI 1.25–2.79, n = 2). Meta-regression showed an association between a higher injury risk and competition distances of 10 km and shorter in female runners (RR 1.08, 95% CI 1.00–1.69).

Conclusion Differences between female and male runners in specific injury diagnoses should be considered in the development of individualised and sex-specific prevention and rehabilitation strategies to manage running-related injuries.

1 Introduction

Running is a very popular sport practiced all over the world. While regular physical activity and sports such as running are beneficial for prevention and rehabilitation of many health complaints (“exercise is medicine”) [1, 2], running is frequently associated with high injury prevalence and incidence rates [3–5].

For injury prevention, risk factors need to be well understood [6]. Risk factors for running are manifold and consist of training load, biomechanical, anatomical and anthropometrical variables [7–12]. While some previous studies exclusively investigated either male [9, 13] or female [14–16] runners, sex has been suggested to be a risk factor for specific injury patterns in running, as well as for overall injury risk [7, 17, 18]. This is supported by a study investigating injury rates for female and male elite

Key Points

- There were no differences between female and male runners in overall injury rates.
- Female runners had more bone stress injuries.
- Male runners had more Achilles tendon injuries.
- Shorter competition distances increase the risk of injury for female runners.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40279-020-01412-7.
running athletes [19]. Analysing data collected during 14 international athletics championships, Edouard et al. [19] showed that male elite athletes had lower injury incidence rates for bone stress injuries (BSI) than female counterparts. However, injury risks differed between sexes for running disciplines (from middle distances upwards) although only with a small to trivial relative risk (1.5 for middle distances, 0.9 for long distances and 1.3 for marathon running) [19].

Including and investigating both sexes in running injury research is in line with evidence for the different risks between female and male athletes for specific types of injuries such as anterior cruciate ligament ruptures or concussions in different team sports as well as ankle sprains in all sports [20–22]. However, considering the current literature, it is difficult to derive conclusive summaries about differences in overall or specific injury epidemiology for both sexes in specific sports [18]. To develop and optimize individualized prevention and treatment options for running injuries, it is crucial to understand if and to what extent injury epidemiology differs between the sexes. Therefore, the aim of this systematic review was to evaluate the differences in injury rates and characteristics between male and female runners using meta-analytical techniques. First, differences in overall injury rates were compared between both sexes. Secondly, depending on the availability of sufficient data, specific injury diagnoses were analysed regarding their occurrence in female and male runners.

2 Methods

This study was conducted and presented according to the PRISMA guidelines for reporting systematic reviews and meta-analysis [23]. Prior to the start of the study, the review protocol was registered in the PROSPERO database (CRD4201911883).

2.1 Search Strategy and Inclusion Criteria

Two independent investigators (K.H. and C.E.) conducted a systematic literature search including articles from inception till April 2020. Prospective cohort studies and randomized controlled trials investigating healthy runners from different age groups were included. The search was restricted to articles from peer-reviewed journals published in English, German, or Spanish languages. Furthermore, studies had to report rates of running-related injuries for both sexes. Overall injury rates and injury rates for specific locations, diagnoses or injury mechanisms were considered. Included running disciplines were middle distance and long-distance track as well as cross-country, trail and road running. There was no restriction to a specific injury definition. Reviews, systematic reviews, commentaries, case studies, case series, cross-sectional studies, retrospective studies and interventional arms of randomised controlled trials (RCT) were excluded. For RCTs, only untreated control groups were considered.

The search strategy using specific keywords (running AND injur*) was applied to four different databases (PubMed, Web of Science, PEDro, SPORTDiscus). All databases were searched to identify relevant studies based on keywords, title and abstract. Two independent investigators (C.E. and K.H.) extracted relevant studies based on the inclusion criteria first by reading the title, the abstract and the full text, if available. A third reviewer (A.Z.) was available for consensus decisions. The bibliographical information of included articles was examined for further relevant references (backward search). A forward search was done via citation tracking using Web of Science® (Thomson Reuters).

2.2 Data Extraction

Study characteristics (design, running discipline, population, age and number of participants) as well as prevalence and incidence rates for both sexes were extracted. For prevalence rates, number of injuries or number of injured runners were related to the number of runners investigated. For incidence rates, number of injuries and specific exposures (in hours, kilometres or athlete exposure) were used. An athlete exposure (AE) is defined as one athlete participating in one practice or competition [24]. When it was not possible to extract the data from an article for specific running distances (e.g., pooling of overall injuries for track disciplines), corresponding authors were contacted by email to obtain the data. If specific data were not able to be obtained, the respective study was included in the systematic review but not in subsequent analyses.

2.3 Study Quality Assessment

Due to insufficient study quality assessment tools in sports injury epidemiology, a new tool was developed by consensus of K.H., A.J., A.L.R., A.Z. and S.S. on the basis of previously used tools [20, 22, 25, 26]. The modification ensured that all relevant points regarding the quality of the study design and important content-related information would be considered—e.g., differences in methodological approaches such as competition or season, or the type of data collection. This tool consisted of 15 items on recruitment, reporting, injury and exposure collection, injury definition and dropout (Table 1).

The identified quality score was used to determine a high (above the median) or low (below the median) study quality of the studies investigated (median score was 18). Two independent reviewers (K.H., A.J.) with a third reviewer (A.L.R.) for consensus assessed the study quality of the included studies.

...
Publication bias was checked by visual inspection of funnel plots (log risk ratio against standard errors) and regression test for funnel plot asymmetry.

### 2.4 Data Synthesis and Statistics

To compare injury risk between male and female runners, risk ratios (RR) with 95% confidence intervals (CI) were computed for each study. Meta-analytic pooling was done using a random-effects model (DerSimonian and Laird method [27]). Between-study heterogeneity was estimated using Cochran’s $Q$ and $I^2$ statistics. To reveal potential publication biases, funnel plots were constructed if more than ten studies were available [28]. Besides visually checking their symmetry, Egger’s regression test was applied.

Following the calculation of pooled RRs, we used a mixed-effects meta-regression model to identify variables potentially affecting the outcome of the meta-analysis [27]. The choice of tested moderators (effect modifiers) was based on three criteria: (1) a plausible impact on the tested variables, (2) reporting in the included studies, (3) sufficient variation of the moderators’ values [29]. The following moderators were submitted into the meta-regression model: performance/expertise level (recreational: no competitions, competitive: participating in local competitions, elite: qualifying for national or international competitions); age (youth: < 18, adult: ≥ 18) competition distance (≤ 10 km, > 10 km); study quality (low: study quality score < 18, high: study quality score ≥ 18), training duration (low: < 7.5 h or high: ≥ 7.5 h/week), training mileage (low: < 64 km/week, high: ≥ 64/week). Moderator analyses were performed if ten or more studies were available [28]. If a significant moderator was detected, a subgroup analysis comparing the respective values of the moderator was performed using the meta-analytic procedures described above.

All calculations were performed using algorithms of the metaphor package embedded in R (R Foundations for Statistical Computing, Vienna, Austria) as well as the software JAMOVI [30] and OpenMeta [Analyst] software (OS X version 10.12 obtained from http://www.cebm.brown.edu/openmeta/).

### 3 Results

#### 3.1 Search Results

The search returned 15,914 studies and 29 additional studies were identified through other sources. After removing 3699 duplicates and applying inclusion criteria, a total of 38 studies were considered eligible [7, 19, 24, 31–65]. Thirty-one of them could be included in the quantitative analysis. Seven studies reported on the same data sets as other included studies and were excluded from the quantitative analysis [19, 31–33, 39, 40, 65]. The full literature search process is displayed in Fig. 1.
3.2 Characteristics of Included Studies

Of the included studies, 36 reported injury data from 35,689 participants (40.8% female). Two studies reporting on injuries from the National Collegiate Athletic Association (NCAA) database did not state the number of athletes but did report the athlete exposure (242,244 athlete exposures with 46.7% females [24] and 276,207 athlete exposures with 50.7% females [59]). Most studies were prospective cohort studies (n = 37), while the control group (not receiving any intervention) from one randomised controlled study met the inclusion criteria [42]. Twenty-three studies investigated road runners, 11 track runners (middle and long distance), 10 cross-country runners and 3 studies reported on trail running/orienteering (Table 2). Studies from major competitions (European or World Championships) reported concurrently on track and road running (half or full marathon) [19, 31–33, 41]. Regarding competition level, 18 studies reported on novice and recreational runners, 11 on competitive and 9 on elite runners. Study characteristics of all included studies are summarized in Table 2.

3.3 Study Quality

The two independent reviewers evaluating study quality agreed on 441 of 570 evaluated items (agreement = 77.4%). The scores for study quality ranged between 9 and 23 out of 24 points with a median of 18 and a mean ± SD of 16.8 ± 4.1.
| Study                  | Sport                  | Cohort/populations, (Country) | Level              | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                      | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|-----------------------|------------------------|------------------------------|--------------------|--------------------------------------|-------------|-----------------------------|--------------------------------------------------------|----------------------|------------------------|--------------------------|---------------------|
| Nicholl et al. [54]   | Marathon               | Sheffield Marathon (1982 participants) | Recreational       | 53/2236                              | over 18     | 1 day                       | Contact with medical staff at first-aid posts          | One full marathon   | 18 injured runners per 100 marathon runners; Female: 32 injured runners per 100 marathon runners; Male: 17.5 injured runners per 100 marathon runners | Female: 32 injured runners per 100 marathon runners; Male: 17.5 injured runners per 100 marathon runners | 14                  |
| Hughes et al. [47]    | Road racing            | Chicago Distance Classic (20 km) | Recreational       | 188/1071                             | 32.3 (range 9—75) | 1 day                       | Self-reported specific orthopaedic problems            | 20 km race          | 28.4 injured runners per 100 runners | Female: 54.3 injured runners per 100 runners; Male: 31.6 injured runners per 100 marathon runners | 11                  |
| Johansson [49]        | Orienteers             | College students              | Elite              | 33/56                                | 17.5 ± 1.5  | 1 year                      | Time loss training or competition injuries            | Daily training logs, monthly reports of training      | 3 injuries per 1000 h; 74 injuries per 100 runners | Female: 72.7 injuries per 100 runners; Male: 75.0 injuries per 100 runners | 20                  |
| de Loes and Goldie [38]| Road/Trail Population based (Sweden) | Recreational                | 2505/3530           | 15—59                                | 1 year      | medically diagnosed: injury registry from hospitals and sports medicine physician, validated by telephone interview | Data were collected from representative sample via questionnaire, then extrapolation to whole population | 0.7 injuries per 1000 h | 10.7 injuries per 100 runners | Female: 0.7 injuries per 1000 h; Male: 0.7 injuries per 1000 h | 14                  |
| McLain and Reynolds [52]| Cross-country High school students (high school) | Competitive              | 40/54               | NA                                   | 1 year      | Athletic trainer: Any time loss incident resulting from athletic participation | NA                      | 10.7 injuries per 100 runners | Female: 7 injured runners per 100 runners; Male: 13 injured runners per 100 runners | 11                  |
| Study            | Sport                  | Cohort/ populations, (Country) | Level                  | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                      | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|------------------|------------------------|-------------------|-----------------------|---------------------------------------|-------------|-----------------------------|--------------------------------------------------------|----------------------|----------------------|------------------------|----------------------|
| Walter et al.    | Road runners           | Community running events (4–22.4 km) in Ontario | Recreational          | 301/980                               | over 14     | 52 weeks                    | Injuries severe enough to reduce the number of miles run, take medicine, or see a health professional | NA                  | 48.4 injured runners per 100 runners | Female: 45.5 injured runners per 100 runners; Male: 49.3 injured runners per 100 runners | 13                  |
| Bennell et al.   | Track                  | Victoria athletics | Competitive (college) | 26/28                                 | 17–26       | 48 weeks                    | Stress fracture; medical imaging after clinical evaluation | Structured interview: hours per week, weeks without running, | 0.7 stress fractures per 1000 h | 25.9 runners with stress fractures per 100 runners | Female: 30.8 runners with stress fractures per 100 runners; Male: 21.4 runners with stress fractures per 100 runners | 21                  |
| Beachy et al.    | Cross-country          | High school students (Punahou, Hawaii) | Competitive (high school) | 787/501                               | NA          | 8 years                     | Any athlete complaint that required the attention of the athletic trainer, regardless of the time lost from activity | NA                  | 65 injuries per 100 runners | Female: 65 injuries per 100 girls; Male: 66 injuries per 100 boys | 14                  |
| Colbert et al.   | Road running           | Patients from Cooper Clinic | Recreational          | 220/1771                               | NA          | 8 years                     | Clinical visit                                        | NA                  | 26.3 injured runners per 100 runners | Female: 25.0 injured runners per 100 runners; Male: 26.4 injured runners per 100 runners | 9                   |
| Study                  | Sport       | Cohort/populations, (Country)       | Level                | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                      | Injury rates (overall) | Injury rates (female/male) | Injury rates (female/male) | Risk of bias score |
|-----------------------|-------------|-------------------------------------|----------------------|--------------------------------------|-------------|----------------------------|----------------------------------------------------------------------------------|--------------------------------------------|----------------------|--------------------------|--------------------------|-----------------------|
| Rauh et al. [58]      | Cross country | High school students (Washington state) | Competitive (high school) | 1202/2031 NA | 15 years | An injury was defined as a medical problem resulting from athletic participation that required an athlete to be removed from a practice or competitive event or to miss a subsequent practice or competitive event | An AE was defined as any practice or meet (competition) in which there was the possibility of sustaining an athletic injury | 13.1 injuries per 1000 AEs | Female: 16.7 injuries per 1000 AEs; Male: 10.9 injuries per 1000 AEs | 18                      |
| Steinacker et al. [61]| Marathon    | Berlin Marathon participants        | Recreational         | 22/36 44.5 24 weeks | Self-reported orthopaedic problems (Survey) | NA          | 46.6 injured runners per 100 runner | Female: 41.6 injured runners per 100 runners; Male: 54.5 injured runners per 100 runners | 11                          |
| Taunton et al. [62]   | Road race (10 km) | Vancouver Sun Run (10 km)    | Recreational         | 635/205 NA 13 weeks | Self-reported pain (Survey) with medical confirmation | NA          | 29.5 injured runners per 100 runner | Female: 30.2 injured runners per 100 runners; Male: 28.3 injured runners per 100 runners | 14                          |
| Study          | Sport       | Cohort/ populations, (Country) | Level           | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|---------------|-------------|-------------------------------|-----------------|--------------------------------------|-------------|----------------------------|------------------------------------------------------------------------------------|----------------------|--------------------------|--------------------------|----------------------|
| Dane et al.   | Road running | College students              | Competitive (college) | 47/45                                | 17–28       | One season (12 weeks)      | Medically diagnosed: contusions, bleeding, wounds, and fractures, except small bruises, were classified as injuries | NA                   | 57.1 injured runners per 100 runners | Female: 52 injured runners per 100 runners; Male: 60 injured runners per 100 runners | 10                    |
| Rauh et al.   | Cross country | College students (Seattle)    | Competitive (college) | 186/235                              | NA          | One season                 | An AE was any practice or competitive event where a runner was at risk of sustaining an injury | 17.0 injuries per 1000 AEs | Female: 19.6 injuries per 1000 AEs; Male: 15.0 injuries per 1000 AEs | 20                      |
| Study          | Sport               | Cohort/populations, (Country) | Level                        | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                 | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|---------------|---------------------|------------------------------|------------------------------|-------------------------------------|-------------|-----------------------------|-----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|-----------------------|--------------------------|-------------------|
| Plisky et al. [56] | Cross country       | High school students (Wisconsin) | Competitive (college)        | 46/59                               | NA          | 13 weeks                    | Medial tibial stress fracture: pain in the tibial region, exacerbated with repetitive weight-bearing activity, and localized pain with palpation along the distal two thirds of the posterior-medial tibia | AE: any practice or competitive event                                                | 2.8 stress fractures per 1000 AEs | Female: 4.3 stress fractures per 1000 AEs; Male: 1.7 stress fractures per 1000 AEs | 21                |
| Alonso et al. [32] | Track + Marathon    | 2007 IAAF World championships (Osaka) participants | Elite                        | 249/267                             | 17–37       | 9 days                      | All musculoskeletal injuries regardless of the consequences with respect to the athlete’s absence from competition or training | Number of competing athletes | 150 competition injuries per 1000 athletes | Time-loss injuries per 1000 registered athletes |
|               |                     |                              |                              |                                     |             |                             | - Female: 800 m: 22, 1500 m: 26, 3000 m SC: 48, 5000 m: 38, 10000 m: 158, marathon 61; |
|               |                     |                              |                              |                                     |             |                             | - Male: 800 m: 43, 1500 m: 24, 3000 m SC: 79, 10000 m: 91, marathon: 118 |                                                                                       |                       |                          | 22               |
| Study                | Sport        | Cohort/populations, (Country) | Level | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                 | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|---------------------|--------------|-------------------------------|-------|--------------------------------------|-------------|-----------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------|----------------------|-----------------------------|-------------------|
| Alonso et al. [33]  | Track + Marathon | 2009 IAAF World championships (Berlin) participants | Elite | 244/312 NA | 9 days | All time-loss musculoskeletal injuries (traumatic and overuse) regardless of the consequences with respect to the athlete’s absence from competition or training | The number of competing athletes was defined as all athletes who started at least once in a discipline | MD: 173.3 injuries per 1000 registered athletes - Female: 800 m 46.5; 1500 m 71.4; 3000 m SC: 48.8; 5000 m 43.5; 10000 m 90.9 Marathon 0 - Male: 800 m 0; 1500 m 37.0; 3000 m SC: 26.5; 5000 m 102.6; 10000 m 32.3 Marathon 30.6 | 22 |
| Buist et al. [7]    | Road racing (4 Miles) | Groningen 4 mile | Recreational | 422/207 43.7 ± 9.5 | 8 weeks | Any time loss running-related musculoskeletal pain at the lower extremity or back | Exposure as given by training programme | 25.9 injured runner per 100 runners; 30.1 injuries per 1000 h | Injury incidence rate per 1000 h - Female: 27.5; Male: 35.0 | Mean Prevalence - Female: 23.4 injured runners per 100 runners Male: 31.4 injured runners per 100 runners | 18 |
| Study        | Sport               | Cohort/populations, (Country) | Level | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                 | Injury rates (overall)                                                                 | Injury rates (female/male)                                                                 | Risk of bias score |
|--------------|---------------------|-------------------------------|-------|-------------------------------------|-------------|-----------------------------|-----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|---------------------------------------------------------------|-------------------|
| Alonso et al. [31] | Track + Marathon | 2011 IAAF World championship (Daegue) participants | Elite | 208/268                             | 17-42       | 9 days                      | All musculoskeletal injuries regardless of the consequences with respect to the athlete's absence from competition or training | Number of competing athletes                                                        | MD: 176.1 injuries per 1000 registered athletes | LD: 187.8 injuries per 1000 registered athletes                                                                 | - Female: 800 m: 55.6, 1500 m: 57.1, 3000 m SC: 0, 5000 m: 125 injuries, 10000 m: 52.6, marathon 53.6;  
- Male: 800 m: 22.7, 1500 m: 76.9, 3000 m SC: 0, 5000 m: 122 injuries, 10000 m: 47.6 injuries marathon: 220.6 | 22                                                                                                                                 |
Table 2 (continued)

| Study                        | Sport         | Cohort/populations, (Country) | Level | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                      | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|------------------------------|---------------|-------------------------------|-------|--------------------------------------|-------------|-----------------------------|-----------------------------------------------------------------------------------|---------------------------------------------|------------------------|--------------------------|-----------------------|
| Jacobsson et al. [48]        | Track (MD + LD) | Swedish national team          | Elite | 54/55                                | 17–37       | 52 weeks                    | Self-reported musculoskeletal pain, soreness or injury with time loss or changes in normal training/competition | Self-reported athletic training participation | 83 injured runners per 100 runners | Adults: Female: 74 injured runners per 100 runners; Male: 81 injured runners per 100 runners Youth: Female: 57 injured runners per 100 runners; Male: 58 injured runners per 100 runners | 19                     |
| edouard et al. [40]          | Track (MD)    | European Athletics indoor championships Paris 2011 participants | Elite | 125/75                               | NA          | 3 days                      | Any musculoskeletal complaint and concussion that received medical attention regardless of time loss | Athletes’ exposure in competition          | MD: 53 injuries per 1000 registered athletes | Injuries per 1000 registered athletes – Female: 800 m: 47.6 3000 m 150.0 - Male: 800 m: 107.1 3000 m 34.5 | 21                     |
| Nielsen et al. [55]          | Road racing   | DANO-RUN study                | Novice runners | 441/432                              | 37.2 ± 10.3 | 1 year                      | Any musculoskeletal complaint of the lower extremity or back caused by running that restricted the amount of running for at least 1 week | Online diary: GPS or manually kilometers | 23.1 injured runner per 100 runners | Female: 21.8 injured runners per 100 runners; Male: 24.5 injured runners per 100 runners | 23                     |
| Study                  | Sport                | Cohort/ populations, (Country) | Level   | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                 | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|-----------------------|----------------------|--------------------------------|---------|--------------------------------------|-------------|-----------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------|---------------------------|-----------------|
| Edouard et al. [39]   | Track (MD)           | European Athletics championships Helsinki 2012 participants | Elite   | 66/164                               | NA          | 3 days                      | Any musculoskeletal complaint and concussion that received medical attention regardless of time loss | Athletes’ exposure in competition                                                | MD: 53 injuries per 1000 registered athletes | -Female: 800 m: 41.7, 1500 m: 30.3, 3000 m: 142.9, 5000 m: 347.8, 10000 m: 176.5 - Male: 800 m: 69.8, 1500 m: 171.4, 3000 m: 275.9, 5000 m: 71.4, 10000 m: 103.4 | 21               |
| Changstrom  et al. [24]| Cross-country        | National High School Sports-Related Injury Surveillance System (2011–2012), (USA) | Competitive (high school) | NA | 13–19                      | 2 years | (Stress) fractures, concussions and dental injuries with or without time loss. All injuries with time loss requiring medical attention | Athlete exposure (AE) | 7.8 stress fractures per 100,000 AEs | Female: 10.6 stress fractures per 100,000 AEs; Male: 5.4 stress fractures per 100,000 AEs | 19               |
| Study | Sport | Cohort/populations, (Country) | Level | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|-------|-------|------------------------------|-------|-------------------------------------|-------------|----------------------------|------------------|----------------------|----------------------|------------------------|--------------------|
| Edouard et al. [19] | Track + Marathon | All athletic world championships (2007–2014) | Elite | 1302/1573 | NA | (3–9 days per championship) | All musculoskeletal injuries (traumatic and overuse) and concussion newly incurred during competition or training regardless of the consequences with respect to the athlete’s absence from competition or training | Total number of registered athletes | N/A | Injuries per 1000 registered athletes - Female: MD 94.6 LD 155.3 Marathon 153.3 - Male: MD 108.5 LD 141.4 Marathon 195.5 | 21 |
| Kluitenberg et al. [50] | Road racing | NLstart2run | Novice runners | 1332/364 | 43.3 | 6 weeks | A musculoskeletal complaint of the lower extremity or back that hampered running ability for three consecutive training sessions | Weekly running frequency and running exposure (in minutes) for each training session | 27.5 injuries per 1000 h | Female: 10.4 injured runners per 100 runners; Male: 12.6 injured runners per 100 runners | 17 |
Table 2 (continued)

| Study                | Sport                    | Cohort/ populations, (Country) | Level         | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|----------------------|--------------------------|--------------------------------|---------------|----------------------------------------|-------------|-----------------------------|---------------------|------------------------|--------------------------|--------------------------|------------------------|
| Hespanhol Junior et al. [45] | Road racing (10 Miles)   | Tilburg Ten Miles              | Recreational  | 31/22                                   | 44.1        | 18 weeks                    | OSTRC: All running-related injuries | Online questionnaires completed every fortnight | Mean prevalence: 30.8 injured runners per 100 runners and cumulative prevalence 60.4 injured runners per 100 runners | Mean prevalence: Female: 11.5% injured runners per 100 runners Male: 19.3 injured runners per 100 runners | 18 |
| Hespanhol Junior et al. [44] | Trailrunning Dutch trail runners | Recreational                  | 57/171        | 43.4                                    | 6 months   | 10.7 injuries per 1000 h; mean prevalence 22.4% | OSTRC: All running-related injuries | Online questionnaires completed every fortnight | Mean prevalence: Female: 20.7%; Male: 23.0% | 17 |
| Study              | Sport       | Cohort/populations, (Country) | Level        | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                 | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|--------------------|-------------|------------------------------|--------------|--------------------------------------|-------------|-----------------------------|----------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|----------------------|--------------------------|-------------------|
| Rizzone et al.     | Cross country | NCAA (2004–2014)             | Competitive  | NA/NA                               | 9 years     | Time loss stress fractures that required medical attention: (1) occurred due to participation in a school-sanctioned practice or competition, (2) required attention from an AT or physician, (3) resulted in at least 24 h of time missed from participation, and (4) had a reported diagnosis of stress fracture | AE: 1 student-athlete participating in 1 NCAA-sanctioned practice or competition | 22.4 stress fractures per 100,000 AEs                                               | Female: 28.6 stress fractures per 100,000 AEs; Male: 16.1 stress fractures per 100,000 AEs | 18                   |
| Study | Sport | Cohort/ populations, (Country) | Level | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition | Exposure measurement | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|-------|-------|------------------------------|-------|-------------------------------------|-------------|-----------------------------|------------------|-----------------------|----------------------|--------------------------|----------------------|
| Messier et al. [53] | Road racing | TRAILS study | Recreational | 128/172 | Range 18—60 | 104 weeks | Overuse running injuries; grade 1, maintained full activity in spite of symptoms; grade 2, reduced weekly mileage; and grade 3, interrupted all training for at least 2 weeks | NA | 66 injured runners per 100 runners | Female: 73 injured runners per 100 runners; Male: 62 injured runners per 100 runners | 15 |
| Winter et al. [64] | Road running | Runners from local running club | Recreational + Competitive | 35/57 | 18—65 | 52 weeks | Pain preventing the runner from performing or completing at least one training session | Training diary with information on running sessions per week, distance and duration of runs | 51.3 injured runners per 100 runners | Female: 54.8 injured runners per 100 runners; Male: 48.9 injured runners per 100 runners | 20 |
| Fokkema et al. [42] | Road racing | INSPIRE trial (NN City Pier City The Hague, NN Marathon Rotterdam, Ladies Run Rotterdam) | Recreational | 553/629 (Control group) | 41.4 ± 12 | 4.5 ± 1.6 months | Injuries of the lower back or lower extremities caused by running with change of training for at least 1 week, a medical visit or medication | NA | 36.7 injured runners per 100 runners | Female: 35.8 injured runners per 100 runners; Male: 38.3 injured runners per 100 runners | 15 |
| Study          | Sport          | Cohort/populations, (Country)                  | Level                              | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                      | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|---------------|----------------|-----------------------------------------------|-----------------------------------|-------------------------------------|-------------|-----------------------------|----------------------------------------------------------------------------------|-----------------------------------------------------------|----------------------|--------------------------|----------------------|
| Hayes et al.  | Cross-country  | NCAA (Ivy League & New England Small College Athletics) | Competitive (college)            | 57/10                               | 17–21       | 1 US-cross-country season  | Injuries that were not present during administration of the pre-season survey | Average and maximum weekly mileage in increments of 10 miles (e.g. 31–40 miles per week) | 53 injured runners per 100 runners | Female: 51 injured runners per 100 runners; Male: 55 injured runners per 100 runners |
| Lagas et al.  | Road racing    | INSPIRE trial (NN City Pier City The Hague, NN Marathon Rotterdam, Ladies Run Rotterdam) | Recreational                      | 909/1020                            | 41.9 ± 12.1 | 20.5 ± 7 weeks              | Self-reported Achilles tendinopathy caused by running with change of training for at least 1 week, a medical visit or medication | NA                                                  | 5.2 injured runners per 100 runners | Female: 3.6 injured runners per 100 runners; Male: 6.6 injured runners per 100 runners |
| Ruffe et al.  | Cross-country  | High school students (California)             | Competitive (high school)         | 80/68                               | 15.6        | 1 US-cross-country season  | Muscle, bone, or joint problem/injury of the low back or lower extremity requiring removal from training/competitions or leading to missed subsequent training/competitions | Runners' daily participation in practices and competitive events | 33.1 injured runners per 100 runners (over one season) | Female: 38.8 injured runners per 100 runners; Male: 26.5 injured runners per 100 runners |
### Table 2 (continued)

| Study          | Sport               | Cohort/populations, (Country) | Level                     | Number of participants (female/male) | Age (years) | Duration of data collection | Injury definition                                                                 | Exposure measurement                                                                                     | Injury rates (overall) | Injury rates (female/male) | Risk of bias score |
|----------------|---------------------|------------------------------|---------------------------|--------------------------------------|-------------|-----------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|------------------------|----------------------------|---------------------|
| Winter et al.  | Road running        | Runners from local running club | Recreational + Competitive | 35/57                                | 18—65       | 52 weeks                    | Pain preventing the runner from performing or completing at least one training session assessed by an experienced health or medical professional | Average kilometers per week; average duration (minutes) per week; average frequency per week | 51.3 injured runners per 100 runners | Female: 54.8 injured runners per 100 runners; Male: 48.9 injured runners per 100 runners | 21                  |
| Edouard et al. | Track + Marathon    | IAAF World and European Championships participants | Elite                      | MD: 742/943; LD: 656/793; Marathon 464/550 | NA          | 78 days (3–9 days per championship) | All musculoskeletal injuries (traumatic and overuse) and concussion newly incurred during competition or training regardless of the consequences with respect to the athlete’s absence from competition or training | Total number of registered athletes | Injuries per 1000 registered athletes— MD: 97 LD: 126 Marathon: 139 | Injuries per 1000 registered athletes— Female: MD 84.9 LD 128 Marathon 118.5 Male: MD 106 LD 123.6 Marathon 156.4 | 19                  |
Most studies (>90%) reported recruitment procedures, injury assessment and documented injury characteristics. Fewer studies achieved maximal points due to not recording individual exposure data (50.0% of maximal points) or exposure data at all (57.9% of maximal points) as well as not using a medical attention definition (56.1% of maximal points). The results of the study quality assessment are presented in Electronic Supplementary Material Table S1.

Except for one outlier [47], visual inspection of the funnel plot (Fig. 2) showed a symmetrical distribution of the log risk ratios and the regression test for funnel plot asymmetry (−0.150; \( p = 0.881 \)) suggested no indication of publication bias.

### 3.4 Overall Injury Rates

The overall injury rate was 20.4 (95% CI 19.7–21.1) injuries per 100 male runners and 20.8 (95% CI 19.9–21.7) injuries per 100 female runners. Meta-analytic pooling did not reveal differences between female and male runners’ injury rates per runner (\( n = 21; \) RR 0.99, 95% CI 0.90–1.10; \( p = 0.84; \) \( I^2 = 72.31 \)) or per specific exposures (\( n = 6; \) RR 0.94, 95% CI 0.69–1.27; \( p = 0.669; \) \( I^2 = 85.93 \)) (Figs. 3 and 4). Due to the small number (\( n = 6 \)) of studies reporting injuries per exposure (athlete exposures (\( n = 2 \)) or hours (\( n = 4 \))), no aggregation of overall injury rates per specific exposures was performed.

### 3.5 Meta-Regression

Moderator analyses of injury RR rates per runner revealed an association of a higher injury risk in men and competition distances exceeding distances of 10 km (\( p = 0.002 \)) (Table 3). Specifically, the subgroup meta-analysis of competition distance showed a significantly higher RR of 1.08 (95% CI: 1.04–1.39) for female runners with competition distance exceeding 10 km.
Sex-Specific Differences in Running Injuries

3.5 Meta-Analysis of Injury Rates

For all injuries, the pooled meta-analysis revealed a lower risk of injury for male runners compared to female runners (RR 0.77, 95% CI: 0.58–1.02) (Fig. 3). No meta-regression was performed for specific injuries and moderators training duration or training mileage due to absence of more than ten studies reporting these variables [28].

3.5.1 Bone Stress Injuries

Four studies reported on bone stress injuries with a pooled decreased probability for male runners (estimated RR 0.52, 95% CI 0.36–0.76, p < 0.001; I² = 0) (Fig. 4).

3.5.2 Achilles Tendinopathy

Furthermore, data pooling for two studies reporting injury rates for Achilles tendinopathy revealed an increased chance for male runners to have an Achilles tendon injury (estimated RR 1.86, 95% CI 1.25–2.79, p = 0.022; I² = 0%) (Fig. 7).

3.6 Specific Injury Rates

Data for two specific running-related injuries were available for synthesis.

### 3.6.1 Bone Stress Injuries

#### Four studies reported on bone stress injuries with a pooled decreased probability for male runners (estimated RR 0.52, 95% CI 0.36–0.76, p < 0.001; I² = 0) (Fig. 4).

### 3.6.2 Achilles Tendinopathy

Furthermore, data pooling for two studies reporting injury rates for Achilles tendinopathy revealed an increased chance for male runners to have an Achilles tendon injury (estimated RR 1.86, 95% CI 1.25–2.79, p = 0.022; I² = 0%) (Fig. 7).
The aim of this analysis was to systematically analyse the literature to reveal sex-related differences in running-related injury rates and characteristics. While no differences between sexes were found for overall running-related injuries, female runners were more likely to sustain bone stress injuries while male runners were more prone to Achilles tendinopathies. Meta-regression showed that for

### Table 3 Results of the moderator analysis for injury risk ratio rates per 100 female or male runners

| Moderator                | No of comparisons (k) | Z       | p         | Risk ratio estimate (95% CI) | Tau²/Q |
|--------------------------|-----------------------|---------|-----------|-----------------------------|--------|
| Risk of bias             | 22                    | −0.88   | 0.378     | −0.051 (−0.167 to 0.063)    | 0.0299/68.1 |
| Moderator                | 1.42                  | 0.156   | 0.151 (−0.058 to 0.359) |
| Level                    | 20                    | 0.68    | 0.495     | 0.044 (−0.083 to 0.171)     | 0.0385/63.1 |
| Moderator                | 1.05                  | 0.293   | 0.110 (−0.095 to 0.316) |
| Age                      | 15                    | 0.87    | 0.387     | 0.116 (−0.146 to 0.378)     | 0.0224/27.3 |
| Moderator                | −0.81                 | 0.419   | −0.119 (−0.407 to 0.170) |
| Competition distance     | 14                    | 1.71    | 0.088     | 0.144 (−0.021 to 0.309)     | 0.0311/44.7 |
| Moderator                | −3.05                 | 0.002   | −0.387 (−0.636 to −0.138) |

95% CI 95% confidence interval

### Fig. 5 Forest plot depicting the meta-analytical results for sub-analysis (competition distance) of risk ratios for male and female runners regarding injuries per 100 runners. Subgroup 1 (a) represents studies investigating runners competing in distances below or equal to 10 km and subgroup 2 (b) in distances above 10 km

### 4 Discussion

The aim of this analysis was to systematically analyse the literature to reveal sex-related differences in running-related injury rates and characteristics. While no differences between sexes were found for overall running-related injuries, female runners were more likely to sustain bone stress injuries while male runner were more prone to Achilles tendinopathies. Meta-regression showed that for
Sex-Specific Differences in Running Injuries

4.1 No Differences in Overall Injury Rates between Female and Male Runners

Despite pooling data from all available epidemiological studies, no differences in overall injury rates between female and male runners were found in this systematic review. This was the case for both studies reporting injuries per runner and injuries per specific exposures. The injury rates of 20.4 (male) and 20.8 (female) per 100 runners are in accordance with summaries of injury rates from the last three decades [4]. Nonetheless, these rates are at the lower spectrum of published injury rates that were reported to be up to 79.3% [66].

4.2 Shorter Competition Distances Increase the Risk of Injury for Female Runners

Injury rates depend on several factors that need to be taken into consideration, such as systematic factors (age, BMI), running-/training-related factors (training frequency, training and racing distance, experience, level of running, footwear, biomechanics), health factors (injury history) and lifestyle factors (drinking, smoking) [66–70].

Not all of these factors were reported in each study and may vary between investigated populations. Therefore, the moderator analysis was incorporated into this study. Only competition distance was a statistically significant moderator for an increased risk of female runners compared to male runners when running competition distances of 10 km and shorter. Furthermore, the subanalysis revealed a tendency of increased injury risk for male runners for longer distances than 10 km. This is in accordance with the finding that male runners had a higher risk of sustaining injuries compared to female runners when running high mileages (> 64 km/week) [18]. While running higher mileages are associated with longer competition distances, this can only be used as an estimate for this discussion. Unfortunately, there was insufficient reporting of training load (time or mileage) in the included studies. For future studies reporting data on injury epidemiology or risk factors, it is strongly recommended to report the training load [71, 72].

4.3 Bone Stress Injuries Occur Twice as Often in Female than in Male Runners

Female runners had twofold higher risk of having a bone stress injury compared to male runners in this review. A bone stress injury is an injury pattern with known sex differences for epidemiology and risk factors [73]. Bone stress injuries are common running-related overuse injuries due to cumulative microtrauma to the bone [74]. Especially in younger ages, females seem to have a higher risk for bone stress injuries compared to male runners. For example, Changstrom et al. [24] reported a twofold risk and Plisky et al. [56] a 2.5-fold risk for female high school runners of sustaining a bone stress injury compared to male high school runners in cross-country. In older collegiate athletes, female cross-country runners were found to have 28.6 injuries per 100,000 athlete exposures (AE) compared to 16.4 injuries per 100,000 AE in males, representing a
and vitamin D intake [14, 15, 73, 80]. In summary, bone
treatment, rearfoot eversion), altered hormonal status or calcium
and male runners, depending on specific risk factors, such as
for both sexes, the further treatment differs between female
Despite using the same initial treatment (activity modifica-
triad is used only for female athletes, the more current and
injuries with the female athlete triad (low energy availabil-
that has been discussed was the association of bone stress
injuries are more prevalent in female runners and
is prone to overuse injuries, such as a tendinopathy [81].
life prevalence has been reported as high as 40–50%.
the Achilles tendon has a poor blood supply and, therefore,
important tendon for propulsion during running. However,
Achilles tendon transmits the generated forces from the
gastrocnemius-soleus muscle complex and, thus, is an
The lifetime prevalence has been reported as high as 40–50%
in runners [13, 82] and a recent 1-year prospective study
determined the incidence rate in a cohort of recreational
while the amount of loading is the
The systematic review by Wright et al. [93] found female
men under 40 years. However, when assessing the evidence
quality and one low-quality studies. In contrast, our review
level the authors called for caution in the interpretation of
their findings since these were based on only five high-
level the authors called for caution in the interpretation of
modifications of tendon function [90, 91]. A review summa-
lower energy availability and low mineral bone density.

4.4 Achilles Tendinopathies Occur Twice as Often in Male Compared to Female Runners

Data from two studies showed that male runners had almost
twice the risk of having an Achilles tendinopathy as female
runners [49, 51]. This is in accordance with a systematic
review on the pathogenesis of Achilles tendinopathy [81].
The Achilles tendon transmits the generated forces from the
gastrocnemius-soleus muscle complex and, thus, is an
important tendon for propulsion during running. However,
the Achilles tendon has a poor blood supply and, therefore,
is prone to overuse injuries, such as a tendinopathy [81].
The lifetime prevalence has been reported as high as 40–50%
in runners [13, 82] and a recent 1-year prospective study
determined the incidence rate in a cohort of recreational
runners to be 5.2% [51]. While the amount of loading is the
key factor in the etiology of Achilles tendinopathy, there
are several intrinsic (age, stress, genes, biomechanics, body
composition) and extrinsic factors (footwear) modulating the
risk for this injury [83]. Recent studies found biomechanical
(footstrike pattern, ankle dorsiflexion moments) and train-
ing-related parameters (changes in training, cold weather,
footwear, use of compression socks, mileage) as possible
risk factors [10, 51, 84–86]. This summary of (possible) risk
factors does not directly explain the increased probability
for male runners to have an Achilles tendinopathy. There-
fore, we can only speculate about the possible mechanisms.

One recently published study discusses the mechanism of
the lifetime cumulated load (together with running years)
which might be higher in male runners than in female run-
ners [87]. Chronic loading needs to be taken into account
when evaluating the risk for Achilles tendinopathies.

Another explanation might be found in the hormonal dif-
fferences between women and men. For example, estrogen
is associated with collagen synthesis and could therefore influ-
ence tendon healing capacity [88, 89]. Furthermore, estrogen
deficiency has been reported to negatively affect tendon
metabolism and healing [90]. Hormonal fluctuations that are
typical for the menstrual cycle have not been associated with
modifications of tendon function [90, 91]. A review summa-
rizes that high or low levels of sexual hormones (estrogen,
progesterone and testosterone) are not directly causing ten-
dinopathies but may play a role in tendon pathologies [92].
Therefore, individual hormonal status should be taken into
account for injury risk of female and male runners as well
as for their therapies and prevention [92].

4.5 Results of the Current Review in Contrast with and in Addition to Other Systematic Reviews

This was the first systematic review on sex-specific differ-
ences in running injuries incorporating a meta-regression
analysis to determine moderating variables and shall be
discussed in light of other systematic reviews on this topic.

This systematic review contrasts the findings of the
systematic review by van der Worp et al. [18], who found
girl runners at a lower overall risk of sustaining an injury
than male runners. This finding was particularly found in
men under 40 years. However, when assessing the evidence
level the authors called for caution in the interpretation of
their findings since these were based on only five high-
quality and one low-quality studies. In contrast, our review
included epidemiological studies reporting injury rates
separately for both sexes. With this approach, 26 studies
were included and meta-analyses showed no sex differences
for overall running injuries when calculated per runner or
per exposure (hours or AE). Furthermore, we were able to
conduct a meta-regression analysis showing a higher injury
risk for female runners in competition distances of 10 km
and shorter as well as a tendency for a higher injury risk for
male runners in competition distances longer than 10 km.
This is a new finding and in line with the increased risk for
male runners with a high weekly mileage (> 64 km), which
is typically needed for longer competition distances [18].

The systematic review by Wright et al. [93] found female
sex to be a primary risk factor for lower extremity bone
stress injuries despite conflicting evidence using an explora-
tory meta-analysis incorporating three etiological studies [6,
94, 95]. The meta-analysis found a similar 2.3-fold increased
probability for female runners. Our meta-analysis supports these findings and underlines the evidence for female runners to be more prone to bone stress injuries based on five included prospective studies [24, 35, 49, 56, 59]. Female sex as a risk factor for medial tibial stress syndrome has also been described by a meta-analysis in active individuals (not exclusively runners [96]).

4.6 Limitations and Methodological Considerations of Current Research

This systematic review summarised data from 38 prospective studies representing more than 35,689 participants (from 36 studies) and 518,000 athlete exposures (from 2 studies). While the distribution between female and male runners (40.8–50.7% females) was similar and no overall differences were found, breakdown of injury data regarding sex and according to location or diagnosis was only possible in six studies. Consequently, the available literature included in this systematic review did not allow conclusions on the sex-dependent epidemiology of pathologies other than bone stress injuries and Achilles tendinopathies.

The meta-regression approach of this study included several potential moderators. However, considering the multifactorial aetiology of running-related injuries, other confounding bias such as biomechanical or psychological variables may have influenced the injury risk. Another limitation was the moderate to high heterogeneity of studies included in the overall injury meta-analyses, emphasizing the need for further studies with a clear injury definition and uniform data collection methods [71, 97].

Regarding quality, future studies would benefit from documenting exposure data and using medical attention injury definitions. Furthermore, moderator analysis was only possible for 1 outcome (overall injuries per 100 runners) due to missing descriptive information on study populations (such as mileage, training duration, competition distances). As seen in Table 2, there are several different data collection methods applied and injury definitions used to determine a running injury. In accordance with recent consensus statements in injury epidemiology [71] and a Delphi consensus on running injuries [98], we encourage future running injury research to follow these guidelines to improve the homogeneity of studies. From this, future meta-analyses would benefit from comparing rates of injuries between studies [97, 99].

5 Conclusion

Sex does not seem to represent a specific risk factor when considering the overall occurrence of injuries in running. However, female runners more frequently sustain bone stress injuries, while male runners have higher risk of developing Achilles tendinopathies. Preventive measures targeting these diagnoses may therefore be more effective when accounting for sex-specific aspects such as hormonal changes or biomechanical characteristics. Regarding moderators, there is a paucity of evidence although meta-regression identified running competition distance (cut-off 10 km) as a factor associated with higher injury rates in male runners.

Declarations

Funding Open Access funding enabled and organised by Projekt DEAL. The research fellowship of Karsten Hollander was funded by the German Research Foundation (Grant Number HO 6214/2-1). No sources of funding were used to assist in the preparation of this article.

Conflict of Interest Karsten Hollander, Anna Rahlf, Jan Wilke, Christopher Edler, Simon Steib, Astrid Junge and Astrid Zech have no conflicts of interest relevant to the content of this review.

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Data Availability Statement The data from the current study are presented in the article/electronic supplementary material and are available from the corresponding author upon request.

Code availability Not applicable.

Author Contributions KH: conceptualization, methodology, literature search, study quality assessment, formal analysis, writing (original draft preparation). ALR: conceptualization, methodology, study quality assessment, writing (review and editing). AJ: conceptualization, methodology, study quality assessment, writing (review and editing). SS: conceptualization, methodology, visualization, writing (review and editing). CE: literature search, writing (review and editing). JW: formal analysis, visualization, writing (review and editing). AF: conceptualization, methodology, study quality assessment, writing (review and editing). AZ: conceptualization, methodology, literature search, writing (review and editing), supervision. All authors read and approved the final manuscript.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Pedersen BK, Saltin B. Exercise as medicine - evidence for prescribing exercise as therapy in 26 different chronic diseases. Scand
4. Nigg BM, Baltich J, Hoerzer S, Enders H. Running shoes and running injuries: mythbusting and a proposal for two new paradigms: “preferred movement path” and “comfort filter.” Br J Sports Med. 2015;49(20):1290–4. https://doi.org/10.1136/bjsports-2015-095054.

5. Hollander K, Baumann A, Zech A, Verhagen E. Prospective investigation. Br J Sports Med. 2016;50(14):887–92. https://doi.org/10.1136/bjsports-2015-094957.

6. Pedisic Z, Shrestha N, Kovalchik S, Stamatakis E, Liangruenrom J, Davis IS. Distinct hip and rearfoot kinematics in female runners with a history of tibial stress fracture. J Orthop Sports Phys Ther. 2010;40(2):59–66. https://doi.org/10.2519/jospt.2010.3024.
32. Alonso JM, Junge A, Renstrom P, Engebretsen L, Mountjoy M, Dvorak J. Sports injuries surveillance during the 2007 IAAF World Athletics Championships. Clin J Sport Med. 2009;19(1):26–32. https://doi.org/10.1097/JSM.0b013e318191ce87.

33. Alonso JM, Tscholl PM, Engebretsen L, Mountjoy M, Dvorak J, Junge A. Occurrence of injuries and illnesses during the 2009 IAAF World Athletics Championships. Br J Sports Med. 2010;44(15):1100–5. https://doi.org/10.1136/bjsports.2010.078030.

34. Beachy G, Akau CK, Martinson M, Olderr TF. High school sports injuries. A longitudinal study at Punahou School; 1988 to 1996. Am J Med Sci. 1997;25(5):675–81. https://doi.org/10.1097/00042752-199707000-00015.

35. Bennell KL, Malcolm SA, Thomas SA, Wark JD, Brukner PD. The incidence and distribution of stress fractures in competitive track and field athletes. A twelve-month prospective study. Am J Sports Med. 1996;24(2):211–7. https://doi.org/10.1177/036354659602400217.

36. Colbert LH, Hootman JM, Macera CA. Physical activity-related injuries in walkers and runners in the atherosclerosis risk in young adults study. Clin J Sport Med. 2000;10(4):259–63. https://doi.org/10.1097/00042752-200010000-00006.

37. Dane S, Can S, Gursoy R, Ezirmik N. Sport injuries: relations to sex, sport, injured body region. Percept Mot Skills. 2004;98(2):519–24. https://doi.org/10.2466/pms.98.2.519-524.

38. de Loeis M, Goldie I. Incidence rate of injuries during sport activity and physical exercise in a rural Swedish municipality: incidence rates in 17 sports. Int J Sports Med. 1988;9(6):461–7. https://doi.org/10.1055/s-1988-103052.

39. Edouard P, Depiesse F, Branco P, Alonso JM. Analyses of Helsinki 2012 European Athletics Championships injury and illness surveillance to discuss elite athletes risk factors. Clin J Sport Med. 2014;24(5):409–15. https://doi.org/10.1097/JSM.0000000000000052.

40. Edouard P, Depiesse F, Herpert P, Branco P, Alonso JM. Injuries and illnesses during the 2011 Paris European Athletics Indoor Championships. Scand J Med Sci Sports. 2013;23(4):e213–8. https://doi.org/10.1111/j.1600-0838.2012.02139.x.

41. Edouard P, Navarro L, Branco P, Gremeaux V, Timpka T, Junge A. Injury frequency and characteristics (location, type, cause and severity) differed significantly among athletics (‘track and field’) disciplines during 14 international championships (2007–2018): implications for medical service planning. Br J Sports Med. 2020;54(3):159–67. https://doi.org/10.1136/bjsports-2019-100717.

42. Fokkema T, de Vos RJ, van Ochten JM, Verhaar JAN, Davis IS, Bindels PJE, et al. Online multifactorial prevention programme has no effect on the number of running-related injuries: a randomised controlled trial. Br J Sports Med. 2019;53(23):1479–85. https://doi.org/10.1136/bjsports-2018-099744.

43. Hayes LE, Boulos A, Cruz AJ Jr. Risk factors for in-season injury in varsity collegiate cross-country athletes: an analysis of one season in 97 athletes. J Med Sci Sports. 2019;51(9):1536–43. https://doi.org/10.1242/ajpam.2019.09221-1.

44. Hespanhol Junior LC, van Mechelen W, Verhagen E. Health and economic burden of running-related injuries in Dutch trailrunners: a prospective cohort study. Sports Med. 2017;47(2):367–77. https://doi.org/10.1007/s12292-016-0551-8.

45. Hespanhol Junior LC, van Mechelen W, Postuma E, Verhagen E. Health and economic burden of running-related injuries in runners training for an event: a prospective cohort study. Scand J Med Sci Sports. 2016;26(9):1091–9. https://doi.org/10.1111/sms.12541.

46. Hofstede H, Franke TPC, van Eijk RPA, Backx FJG, Kemler E, Huisstede BMA. In training for a marathon: runners and running-related injury prevention. Phys Ther Sport. 2020;41:80–6. https://doi.org/10.1016/j.ptsp.2019.11.006.

47. Hughes WA, Noble HB, Porter M. Distance race injuries: an analysis of runners’ perceptions. Phys Sportsmed. 1985;13(11):43–58. https://doi.org/10.1080/00913847.1985.11708924.

48. Jacobsson J, Timpka T, Kowalski J, Nilsson S, Ekberg J, Dahlstrom O, et al. Injury patterns in Swedish elite athletics: annual incidence, injury types and risk factors. Br J Sports Med. 2013;47(15):941–52. https://doi.org/10.1136/bjsports-2012-091651.

49. Johansson C. Injuries in elite orienteers. Am J Sports Med. 1986;14(5):410–5. https://doi.org/10.1177/036354658601400515.

50. Kluitenberg B, van Middelkoop M, Smits DW, Verhagen E, Hargens F, Diercks R, et al. The NLSummer2run study: Incidence and risk factors of running-related injuries in novice runners. Scand J Med Sci Sports. 2015;25(5):e515–23. https://doi.org/10.1111/sms.12346.

51. Lagas IF, Fukkema T, Verhaar JAN, Bierma-Zeinstra SMA, van Middelkoop M, de Vos RJ. Incidence of Achilles tendinopathy and associated risk factors in recreational runners: a large prospective cohort study. J Sci Med Sport. 2020;23(5):448–52. https://doi.org/10.1016/j.jsams.2019.12.013.

52. McLain LG, Reynolds S. Sports injuries in a high school. Pediatrics. 1989;94(3):446–50.

53. Messier SP, Martin DF, Mihalko SL, Ip E, DeVita P, Cannon DW, et al. A 2-year prospective cohort study of overuse running injuries: the runners and injury longitudinal study (TRAILS). Am J Sports Med. 2018;46(9):2211–21. https://doi.org/10.1177/0363543518773755.

54. Nicholl JP, Williams BT. Injuries sustained by runners during a popular marathon. Br J Sports Med. 1983;17(1):10–5. https://doi.org/10.1136/bjsm.17.1.10.

55. Nielsen RO, Parner ET, Nohr EA, Sorensen H, Lind M, Rasmussen S. Excessive progression in weekly running distance and risk of running-related injuries: an association which varies according to type of injury. J Orthop Sports Phys Ther. 2014;44(10):739–47. https://doi.org/10.2519/jospt.2014.5164.

56. Plisky MS, Rauh MJ, Heiderscheit B, Underwood FB, Tank RT. Medial tibial stress syndrome in high school cross-country runners: incidence and risk factors. J Orthop Sports Phys Ther. 2007;37(2):40–7. https://doi.org/10.2519/jospt.2007.2343.

57. Rauh MJ, Koepsell TD, Rivara FP, Margherita AJ, Rice SG. Epidemiology of musculoskeletal injuries among high school cross-country runners. Am J Epidemiol. 2006;163(2):151–9. https://doi.org/10.1093/aje/kwj022.

58. Rauh MJ, Margherita AJ, Rice SG, Koepsell TD, Rivara FP. High school cross country running injuries: a longitudinal study. Clin J Sport Med. 2000;10(2):110–6. https://doi.org/10.1207/s15327752J PA730108.

59. Rizzone KH, Ackerman KE, Roos KG, Dompier TP, Kerr ZY. The epidemiology of stress fractures in collegiate student-athletes, 2004–2005 through 2013–2014 academic years. J Athl Train. 2017;52(10):966–75. https://doi.org/10.4085/1062-6050-52.8.01.

60. Ruffe NJ, Sorce SR, Rosenhall MD, Rauh MJ. Lower quarter- and upper quarter Y balance tests as predictors of running-related injuries in high school cross-country runners. Int J Sports Phys Ther. 2019;14(5):695–706.

61. Steinacker T, Steuer M, Holtke V. Orthopedic problems in older marathon runners. Sportverletz Sportschaden. 2001;15(1):12–5. https://doi.org/10.1055/s-2000-11962.

62. Lynam DR, Whiteside S, Jones S. Self-reported psychopathy: a validation study. J Pers Assess. 1999;73(1):110–32. https://doi.org/10.1080/0022357X.1997.12537752JPA730108.
63. Walter SD, Hart LE, McIntosh JM, Sutton JR. The Ontario cohort study of running-related injuries. Arch Intern Med. 1989;149(11):2561–4.

64. Winter SC, Gordon S, Brice SM, Lindsay D, Barrs S. Overuse injuries in runners of different abilities-a one-year prospective study. Res Sports Med. 2019. https://doi.org/10.1080/15436272.2019.1616548.

65. Winter SC, Gordon S, Brice SM, Lindsay D, Barrs S. A multifactorial approach to overuse running injuries: a 1-year prospective study. Sports Health. 2020;12(3):296–303. https://doi.org/10.1177/194173811988504.

66. van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SM, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br J Sports Med. 2007;41(8):469–80. https://doi.org/10.1136/bjsm.2006.033548.

67. van Poppel D, de Koning J, Verhagen AP, Scholten-Peeters GG. Risk factors for lower extremity injuries among half marathon and marathon runners of the Lage Landen Marathon Eindhoven 2012: a prospective cohort study in the Netherlands. Scand J Med Sci Sports. 2016;26(2):226–34. https://doi.org/10.1111/sms.12424.

68. Malisoux L, Delattre N, Urhausen A, Theisen D. Shoe cushioning influences the running injury risk according to body mass: a randomized controlled trial involving 848 recreational runners. Am J Sports Med. 2020;48(2):473–80. https://doi.org/10.1177/0363543319859278.

69. Hollander K, Heidt C, Babette CVDZ, Braumann KM, Zech A. The effects of habitual foot strike patterns on Achilles tendon loading in female runners. Gait Posture. 2018;66:283–7. https://doi.org/10.1016/j.gaitpost.2018.09.016.

70. Krabak BJ, Roberts WO, Tenforde AS, Ackerman KE, Adami PE, Baggish AL, et al. Youth running consensus statement: minimising risk of injury and illness in youth runners. Br J Sports Med. 2020. https://doi.org/10.1136/bjsports-2020-102518.

71. Bahr R, Clarsen B, Derman W, Dvorak J, Emery CA, Finch CF, et al. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sport 2020 (including STROBE Extension for Sport Injury and Illness Surveillance (STROBE-SIIS)). Br J Sports Med. 2020;54(7):372–89. https://doi.org/10.1136/bjsports-2019-101969.

72. Soligard T, Schwellnus M, Alonso JM, Bahr R, Clarsen B, Dijkstra HP, et al. How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. Br J Sports Med. 2016;50(17):1030–41. https://doi.org/10.1136/bjsports-2016-096581.

73. Lin CY, Casey E, Herman DC, Katz N, Tenforde AS. Sex differences in common sports injuries. PM R. 2018;10(10):1073–82. https://doi.org/10.1016/j.pmrj.2018.03.008.

74. Hoenig T, Tenforde A, Strahl A, Rolvien T, Hollander K. Does MRI grading correlate with return to sports following bone stress injuries? A systematic review and meta-analysis. Am J Sports Med. 2021. (accepted for publication).

75. Rauh MJ, Barrack R, Nichols JF. Associations between the female athlete triad and injury among high school runners. Int J Sports Phys Ther. 2014;9(7):948–58.

76. Tenforde AS, Carlson JL, Chang A, Sainani KL, Shultz R, Kim JH, et al. Association of the female athlete triad risk assessment stratification to the development of bone stress injuries in collegiate athletes. Am J Sports Med. 2017;45(2):302–10. https://doi.org/10.1177/0363546516676262.

77. Mountjoy M, Sundgot-Borgen J, Burke L, Ackerman KE, Blauwet C, Constantini N, et al. International Olympic Committee (IOC) consensus statement on Relative Energy Deficiency in Sport (RED-S): 2018 update. Int J Sport Nutr Exerc Metab. 2018;28(4):316–31. https://doi.org/10.1123/ijsnem.2018-0136.

78. Tenforde AS, Parziale AL, Popp KL, Ackerman KE. Low bone mineral density in male athletes is associated with bone stress injuries at anatomic sites with greater trabecular composition. Am J Sports Med. 2018;46(1):30–6. https://doi.org/10.1177/0363546517730584.

79. Tenforde AS, Beaucesne AR, Borg-Stein J, Hollander K, McNinnis K, Kotler D, et al. Awareness and comfort treating the female athlete triad and relative energy deficiency in sport among healthcare providers. Dtsch Z Sportmed. 2020;71(3):76–80. https://doi.org/10.5960/dzsm.2020.422.

80. Brederweg SW, Kluitenberg B, Bessem B, Buist I. Differences in kinetic variables between injured and noninjured novice runners: a prospective cohort study. J Sci Med Sport. 2013;16(3):205–10. https://doi.org/10.1016/j.jsams.2012.08.002.

81. Magnan B, Bondi M, Pierantoni S, Samaia E. The pathogenesis of Achilles tendinopathy: a systematic review. Foot Ankle Surg. 2014;20(3):154–9. https://doi.org/10.1016/j.fas.2014.02.010.

82. Lopes AD, Hespanhol Junior LC, Yeung SS, Costa LO. What are the main running-related musculoskeletal injuries? A systematic review. Sports Med. 2012;42(10):891–905. https://doi.org/10.1007/s12255-012-1989-z.

83. Asplund CA, Best TM. Achilles tendon disorders. BMJ. 2013;465:2162. https://doi.org/10.1136/bmj.f1262.

84. Uweing S, Davis JS, Brauner T, Hooper SL, Horstmann T. Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait? J Sports Sci. 2019;37(23):2735–43. https://doi.org/10.1080/02640414.2019.1663656.

85. Lieberthal K, Paterson KL, Cook J, Kiss Z, Girdwood M, Bradshaw EJ. Prevalence and factors associated with asymptomatic Achilles tendon pathology in male distance runners. Phys Ther Sport. 2019;39:64–8. https://doi.org/10.1016/j.ptsp.2019.06.006.

86. Bryant AL, Clark RA, Bartold S, Murphy A, Bennell KL, Homann E, et al. Effects of estrogen on the mechanical behavior of the human Achilles tendon in vivo. J Appl Physiol (1985). 2008;105(4):1035–43. https://doi.org/10.1152/japplphysiol.01281.2007.

87. Leblanc DR, Schneider M, Angele P, Vollmer G, Docheva D. The effect of estrogen on tendon and ligament metabolism and function. J Steroid Biochem Mol Biol. 2017;172:106–16. https://doi.org/10.1016/j.jsbmb.2017.06.008.

88. Oliva F, Piccirilli E, Berardi AC, Frizziero A, Tarantino U, Maffulli N. Hormones and tendinopathies: the current evidence. Br Med Bull. 2016;117(1):39–58. https://doi.org/10.1093/bmbldv054.

89. Kubo K, Miyamoto M, Tanaka S, Maki A, Tsunoda N, Kanehisa H. Muscle and tendon properties during menstrual cycle. Int J Sports Med. 2009;30(2):139–43. https://doi.org/10.1055/s-0028-1104573.

90. Abate M, Gueli M, Pantalone A, Vanni D, Schiavone C, Andia I, et al. Therapeutic use of hormones on tendinopathies: a narrative review. Muscles Ligaments Tendons J. 2016;6(4):445–52. https://doi.org/10.11138/mltj.2016.6.4.445.

91. Wright AA, Taylor JB, Ford KR, Siska L, Smoliga JM. Risk factors associated with lower extremity stress fractures in runners: a systematic review with meta-analysis. Br J Sports Med.
Sex-Specific Differences in Running Injuries

2015;49(23):1517–23. https://doi.org/10.1136/bjsports-2015-094828.

94. Tenforde AS, Sayres LC, McCurdy ML, Sainani KL, Fredericson M. Identifying sex-specific risk factors for stress fractures in adolescent runners. Med Sci Sports Exerc. 2013;45(10):1843–51. https://doi.org/10.1249/MSS.0b013e3182963d75.

95. Yagi S, Muneta T, Sekiya I. Incidence and risk factors for medial tibial stress syndrome and tibial stress fracture in high school runners. Knee Surg Sports Traumatol Arthrosc. 2013;21(3):556–63. https://doi.org/10.1007/s00167-012-2160-x.

96. Reinking MF, Austin TM, Richter RR, Krieger MM. Medial Tibial stress syndrome in active individuals: a systematic review and meta-analysis of risk factors. Sports Health. 2017;9(3):252–61. https://doi.org/10.1177/1941738116673299.

97. Timpka T, Alonso JM, Jacobsson J, Junge A, Branco P, Clarsen B, et al. Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field):

Affiliations

Karsten Hollander1,2, Anna Lina Rahlf3, Jan Wilke4, Christopher Edler5, Simon Steib6, Astrid Junge1,7, Astrid Zech3

1 Medical School Hamburg, Hamburg, Germany
2 Department of Physical Medicine and Rehabilitation, Spaulding National Running Center, Harvard Medical School, Cambridge, MA, USA
3 Department of Human Movement Science and Exercise Physiology, Institute of Sport Science, Friedrich Schiller University Jena, Jena, Germany
4 Department of Sports Medicine and Exercise Physiology, Goethe University Frankfurt, Frankfurt, Germany
5 Prevention, Rehabilitation and Interdisciplinary Sports Medicine, BG Trauma Hospital of Hamburg, Hamburg, Germany
6 Department of Human Movement, Training and Active Aging, Institute of Sports and Sports Science, Heidelberg University, Heidelberg, Germany
7 Swiss Concussion Center, Schulthess Klinik, Zürich, Switzerland