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SYSTEMATIC REVIEW

Biomechanical Risk Factors Associated with Running-Related Injuries: A Systematic Review

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Abstract

Background Running is a popular form of physical activity with many health benefits. However, the incidence and prevalence of running-related injuries (RRIs) is high. Biomechanical factors may be related to the development of RRIs.

Objective This systematic review synthesizes biomechanical risk factors related to the development of RRIs in non-injured runners.

Methods PubMed, Web of Science, CINAHL, Embase, and SPORTDiscus were searched in July 2018 for original peer-reviewed prospective studies evaluating potential biomechanical factors associated with the development of RRIs. Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines were followed. Two reviewers independently assessed articles for inclusion and methodological quality. Due to methodological heterogeneity across studies, a narrative synthesis of findings was conducted, rather than a meta-analysis.

Results Sixteen studies, including 13 of high quality and three of moderate quality, were included. A large number of biomechanical variables were evaluated, producing inconsistent evidence overall. Limited evidence indicated greater peak hip adduction in female runners developing patellofemoral pain and iliotibial band syndrome, but not for a mixed-sex population of cross-country runners sustaining an RRI. The relationship between vertical loading rate and RRIs was inconsistent. Other kinematic, kinetic and spatiotemporal factors were only studied to a limited extent.

Conclusions Current prospective evidence relating biomechanical variables to RRI risk is sparse and inconsistent, with findings largely dependent on the population and injuries being studied. Future research is needed to confirm these biomechanical risk factors and determine whether modification of these variables may assist in running injury prevention and management.

Key Points

Despite the common belief that biomechanical factors greatly influence running-related injury (RRI) risk, only a limited body of high-quality research, with significant heterogeneity in study populations, methodologies and outcome variables, was identified.

Current prospective evidence relating biomechanical variables with the risk to sustain an RRI is inconsistent and largely dependent on the population and injuries being studied.

A number of single-study findings related to kinematics, kinetics and spatiotemporal variables require confirmation via further high-quality prospective studies before clinical recommendations can be made.

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1 Introduction

Physical activity positively influences physical fitness and psychological well-being [1]. The general health benefits of regular physical activity include reduced incidence of obesity, metabolic syndrome, diabetes, cancer, and many other chronic diseases [2–6]. Running is a popular form of physical activity internationally due to its low cost and easy accessibility [7]. From a public health perspective, running may be a cost-effective lifestyle "medicine" by improving health and increasing longevity [8].

One downside to running is the high risk of sustaining a running-related injury (RRI). In novice runners, the main reason to stop running is an RRI [9]. The reported incidence of RRIs ranges from 3 to 85% [10, 11] and from 2.5–33 injuries per 1000 h of running [12]. This large variation in incidence may be explained by differences in running population, follow-up duration and definitions of RRIs across studies [10, 13–15]. Frequently reported RRIs include patellofemoral pain, iliotibial band syndrome, medial tibial stress syndrome, Achilles tendinopathy and plantar fasciitis [16, 17].

Most RRIs can be categorized as "overuse" injuries, thought to occur when there is an imbalance between repetitive loading of a tissue and its adaptive capability [18]. These RRIs develop gradually over time [18, 19] and are thought to be associated with a complex and multifactorial etiology [18]. Within this perspective, biomechanical factors may play an important role, as they are modifiable with targeted interventions [20]. It has been hypothesized that some biomechanical profiles could lead to abnormal stresses on neuromusculoskeletal structures and potentially RRIs [21, 22].

Most biomechanical research in relation to RRIs is cross-sectional or retrospective in nature. This means it is unclear whether differences between groups preceded the onset of injury or were a consequence of the injury. Previous systematic reviews on this topic have identified biomechanical risk factors for specific injuries (e.g., patellofemoral pain [23] or iliotibial band syndrome [24]), focused on biomechanics at one anatomic region (e.g., the foot [25]), had no specific focus on running biomechanics [25] or a running population [25], and/or included a combination of prospective and retrospective studies [23, 24].

The aim of this systematic review was to identify and synthesize biomechanical risk factors related to the development of RRIs in non-injured runners. Identifying potential risk factors that result in RRIs will provide critical information needed to design effective treatment and prevention strategies.

2 Methods

A systematic review of the available literature was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines [26]. This study was registered in the PROSPERO international prospective register of systematic reviews (CRD42018100603).

2.1 Literature Search

The electronic databases PubMed, Web of Science, CINAHL, Embase, and SPORTDiscus were systematically searched up to July 2018 by two independent authors (LC and RV). A combination of keywords was used to obtain relevant articles (Table 1). The search strategy was limited to publications in English. Reference lists from previous systematic reviews on RRIs, complete reference lists and citation lists (Google Scholar) of all included studies were

Table 1 Search results for each database up to 1 July 2018

	Databases				
	Embase	CINAHL	PubMed	Web of Science	SPORTDiscus
Search terms					
1	Running injuries	Running injuries	"Running/injuries" [Mesh]	Running injuries	Running injuries
2	Biomechanics, Biomechanical	Biomechanics	"Biomechanical Phenomena" [Mesh]	Biomechanics, Biomechanical	Biomechanics, Biomechanical
3	Prospective	Prospective	"Prospective Studies" [Mesh]	Prospective	Prospective
4	Spatiotemporal	Spatiotemporal	"Spatio-Temporal Analysis" [Mesh]	Spatiotemporal	Spatiotemporal
5	Kinetics	Kinetics	"Kinetics" [Mesh]	Kinetics	Kinetics
6	Risk factors	Risk factors	"Risk Factors" [Mesh]	Risk factors	Risk factors
7	Kinematics	Kinematics	/	Kinematics	Kinematics
Combined search results					
1 AND 3 AND (2 OR 4 OR 5 OR 6 OR 7)	114	62	64	200	68

hand searched to identify other eligible studies not identified in the search.

2.2 Eligibility Criteria

Data from published prospective cohort studies reporting on biomechanical risk factors associated with RRIs in runners were considered for inclusion. Descriptors used to define an RRI were the presence of a physical complaint (e.g., patellofemoral pain, Achilles tendinopathy), the need to interrupt training or seeking medical assistance [27]. Studies were included if they met the following inclusion criteria: (1) recruited non-injured runners who were prospectively monitored for RRIs in the lower extremity during the follow-up period, (2) involved participants above 16 years of age, (3) investigated kinematic, kinetic, or spatiotemporal factors during running, (4) investigated outcomes based on a combination of kinematic and kinetic measures (joint moments, joint impulses, joint/vertical/leg stiffness). To simplify data reporting, these outcomes were further classified as kinetics. Kinetics were described as the forces that govern movement of the body (e.g., ground reaction forces, center of pressure, joint moments, and bone loads). Kinematics were defined as joint movements in all three cardinal planes of motion, without considering forces that cause the movement (e.g., joint or angular position, velocity, acceleration). Spatiotemporal variables were described as global metrics of the running gait cycle (e.g., running velocity, step rate, stance time, flight time) [28].

We excluded (1) studies that involved individuals who participated in sports other than running (> 6 h/week), (2) studies among sprinters (competitive events under 800 m) or triathletes, (3) studies among military participants or physical education students due to the unknown effect of concurrent training, (4) studies that involved individuals with acute injuries or pain caused by running (e.g., muscle strains), (5) studies where data were collected during a task other than running, (6) studies that assessed muscle activation, muscle strength, range of motion and anthropometric factors (unless they also assessed kinetic, kinematic, and spatiotemporal factors during running), (7) studies focusing on external factors like workload, shoes, surface, or fatigue, and (8) conference abstracts.

First, titles and abstracts of the search results were independently screened by two authors (LC and RV) for potential eligible studies. Second, the full text of the potential eligible studies (based on title and abstract) was retrieved and independently assessed by two authors (LC and RV). Results were discussed in a team meeting and discrepancies were resolved by consulting a third reviewer (BD) when necessary.

2.3 Quality Assessment

Methodological quality of the included prospective studies was evaluated with two separate scales. The first one involved 15 selected components from the "Quality Index" developed by Downs and Black [29], and previously used in other systematic reviews of RRIs [23, 30]. Each item was scored as one point ("yes" = 1, "no" = 0, "not able to determine" = 0), except for item five, which was scored up to two points, meaning each study could score a maximum of 16. Studies scoring 11 or more were considered high quality, 6–10 considered moderate quality, and ≤ 5 considered low quality [23]. The second part of our quality evaluation consisted of a risk of bias assessment, conducted using a 10-point checklist, previously described in a systematic review of RRIs [16]. This checklist addressed specific inclusion and exclusion criteria related to RRIs (e.g., description of the injury definition, diagnosis, running population, data analysis) and was included because of the poor reliability in items relating to external validity in the original Downs and Black "Quality Index" [29]. All criteria were rated as 1 (i.e., low risk of bias) or 0 (i.e., high risk of bias) by two independent reviewers. When insufficient information was presented in the study, rating was categorized as "not able to determine" and counted as 0. Total risk of bias was calculated by counting the scores on each item and expressed as a percentage for each study. If less than half of the quality criteria were fulfilled (scoring $\leq 50\%$), the study was considered as having a high risk of bias. Two independent reviewers (LC and RV) evaluated the methodological quality of all included studies with both scales. Results were discussed in a team meeting and discrepancies were resolved by consulting a third reviewer (BD) when necessary.

2.4 Data Extraction and Analyses

Study characteristics were extracted from all included papers by two authors (LC and RV), and included publication details (author and year), general information regarding injury type, specific running population, duration of the follow-up period, sample size, injury rate, data collection procedure (running surface, shoes, motion capture system), running speed during testing, data analysis, and biomechanical outcome variables. Data relating to participant characteristics (e.g., age, sex, body height, body weight, body mass index) and running exposure were also recorded. A narrative synthesis of data was performed due to the heterogeneity of the studied populations, methodologies and biomechanical variables. Both the significant and consistent non-significant findings are described in Sect. 3. Non-significant findings that were reported only once in the literature are not presented in the results, unless a non-significant finding of a particular variable in one study was not consistent with a significant finding in another study.

2.5 Evidence-Based Recommendations

Qualitative synthesis was performed for similar biomechanical variables and various levels of evidence were defined based on a modified version of the following categories described by van Tulder et al. [31]:

- *Strong evidence* Consistent findings among three or more studies, including a minimum of two high-quality studies.
- *Moderate evidence* Consistent findings among two or more studies, including at least one high-quality study.
- *Limited evidence* Findings from at least one high-quality study or two low- or moderate-quality studies.
- *Very limited evidence* Findings from one low- or moderate-quality study.
- *Inconsistent evidence* Inconsistent findings among multiple studies (e.g., one or multiple studies reported a significant result, while one or multiple studies reported no significant result).
- *Conflicting evidence* We defined conflicting as contradictory results between studies (e.g., one or multiple studies reported a significant result in one direction, while one or multiple studies reported a significant result in the other direction).
- *No evidence* Results were insignificant and derived from multiple studies regardless of quality.

3 Results

3.1 Search Results and Selection

The electronic database search yielded 508 articles (Table 1). After removal of duplicates, 291 articles remained (Fig. 1). 276 articles were excluded based on title and abstract, reducing the number of articles to 15. Primary reasons for exclusion based on title and abstract were not investigating any biomechanical variables, participation in sports other than running, a non-prospective study design, or a study not investigating RRIs. Five additional articles were added through reference screening and citation tracking. After full text screening, four articles were excluded because the

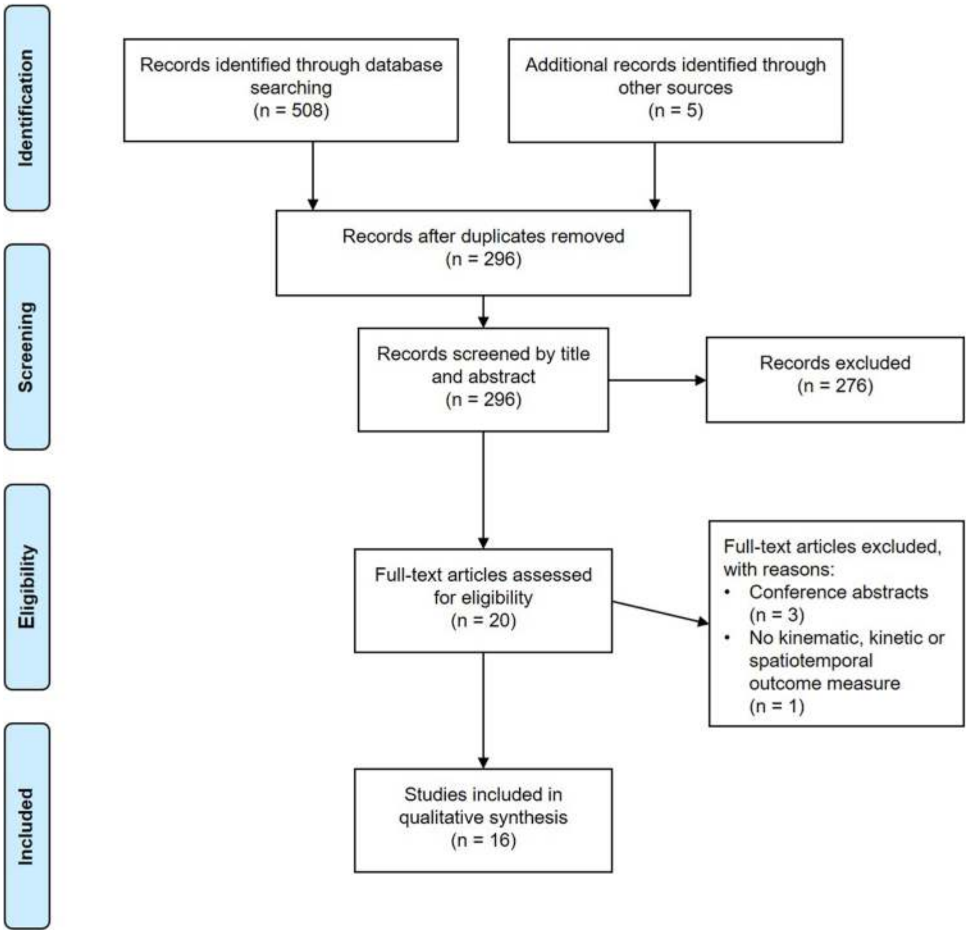


Fig. 1 Flow diagram of literature search

results did not relate to any kinematic, kinetic, or spatiotemporal outcome measures, or because the article was a conference abstract. The remaining 16 articles met all inclusion criteria and were included in the narrative synthesis.

3.2 Methodological Quality

3.2.1 Modified Downs and Black Quality Index

Quality scores of the Downs and Black Index [29] ranged from 9 to 13 out of 16 (56–81%). Of all 16 included articles, 13 were identified as high quality and three as moderate quality. Detailed item scores can be found in Table 2.

3.2.2 Risk of Bias Assessment

Scores on the risk of bias scale ranged from 4 to 9 out of 10. Four of the included articles received a high risk of bias (scores ≤ 50%). Twelve articles had a low risk of bias. Item 4 relating to random inclusion of athletes and item 10 relating to incidence or prevalence on exposure ratio displayed the lowest scores. Items 2, 3, and 6 received the highest scores. Scores of all included articles can be found in Table 3.

3.3 Study and Participant Characteristics

All details of study and participant characteristics are presented in Tables 4 and 5, respectively.

3.4 Biomechanical Outcomes

All significant findings with levels of evidence are presented in Fig. 2. A summary of all outcome measures (both significant and non-significant) with means, standard deviations, and *P* values is presented in Electronic Supplementary Material Table S1. Effect sizes (ES) (Hedges' *g*) were established by calculating the difference between the means of both groups, divided by the pooled standard deviation, multiplied by a correction factor [32]. A modified version of Cohen's classification was used to classify ES: very small ES: < 0.2, small ES: 0.2–0.49; medium ES: 0.5–0.79; large ES: 0.8–1.19, very large ES: 1.20–1.99 and huge ES: ≥ 2.0 [33, 34].

3.4.1 Kinematics

Inconsistent evidence was found in two studies for peak hip adduction in relation to RRIs. Limited evidence indicated greater hip adduction in female recreational runners

Table 2 Modified Downs and Black Quality Index results [29]

Included studies	Criteria															% Total
	(1)	(2)	(3)	(5)	(6)	(7)	(9)	(10)	(11)	(12)	(16)	(18)	(20)	(25)	(26)	Total	
Bredeweg et al. [44]	1	1	1	0	1	1	1	1	1	0	U	1	1	1	1	12	75
Bredeweg et al. [41]	1	1	1	1	1	1	1	0	1	0	U	1	1	1	1	12	75
Brund et al. [48]	1	1	1	2	1	1	1	1	1	0	U	1	1	0	0	12	75
Davis et al. [42]	1	1	1	2	1	1	1	1	1	U	U	1	1	1	0	13	81
Dudley et al. [37]	1	1	0	2	1	1	1	1	U	0	U	1	1	U	1	11	69
Ghani et al. [46]	1	1	0	1	1	1	1	1	0	0	U	1	1	1	1	11	69
Hein et al. [38]	1	1	1	2	1	1	0	0	U	U	U	0	1	1	1	10	63
Kuhman et al. [40]	1	1	0	2	1	1	1	1	U	0	U	1	1	0	1	11	69
Luedke et al. [50]	1	1	0	1	1	1	1	1	0	0	U	1	1	1	1	11	69
Messier et al. [39]	1	1	1	2	1	1	0	1	U	U	U	1	1	1	0	11	69
Napier et al. [43]	1	1	1	2	1	1	1	1	0	0	U	1	1	1	1	13	81
Noehren et al. [36]	1	1	1	2	1	1	1	1	U	U	U	1	1	1	1	13	81
Noehren et al. [35]	1	1	1	1	1	1	1	1	U	U	U	1	1	1	1	12	75
Stefanyshyn et al. [49]	1	1	0	2	1	1	1	1	U	U	U	1	1	1	1	12	75
Thijs et al. [45]	1	1	0	1	1	1	0	1	0	0	U	1	1	0	1	9	56
Van Ginckel et al. [47]	1	1	0	1	1	1	0	1	1	0	U	1	1	U	0	9	56

Scoring: items 1–3, 6–26: "yes" = 1, "no" = 0, "unable to determine" = U (scored as 0). Item 5: "yes" = 2, "partially" = 1, "no" = 0

Criteria: (1) clear aim/hypothesis, (2) main outcome measures clearly described, (3) patient characteristics clearly described, (5) distribution of confounders described, (6) main finding clearly described, (7) random variability of main outcomes provided, (9) characteristics of patients lost to follow-up described, (10) actual probability values reported, (11) subjects asked to participate representative of entire population, (12) subjects prepared to participate representative of entire population, (16) clear mentioning of data dredging (unplanned analysis), (18) appropriate statistical analysis, (20) valid and reliable outcome measures, (25) adequate adjustment for confounding, (26) patients lost to follow-up taken into account

Table 3 Risk of bias assessment of included studies

Included studies	Criteria											% Total
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	Total	
Bredeweg et al. [44]	1	1	1	U	1	1	U	0	0	0	5	50
Bredeweg et al. [41]	1	1	1	U	1	1	1	0	0	0	6	60
Brund et al. [48]	1	1	1	1	0	1	1	1	1	1	9	90
Davis et al. [42]	0	1	1	1	1	1	1	1	1	0	8	80
Dudley et al. [37]	1	1	1	0	1	0	1	0	0	0	5	50
Ghani et al. [46]	1	1	1	0	1	1	1	1	0	0	7	70
Hein et al. [38]	1	1	1	U	0	1	1	1	1	0	7	70
Kuhman et al. [40]	0	1	1	0	0	1	1	0	U	0	4	40
Luedke et al. [50]	1	1	1	0	1	1	1	1	U	1	8	80
Messier et al. [39]	0	1	1	U	1	1	1	1	1	0	7	70
Napier et al. [43]	1	1	1	1	1	1	1	1	0	1	9	90
Noehren et al. [36]	0	1	1	U	0	1	1	1	1	0	6	60
Noehren et al. [35]	1	1	0	U	0	1	U	1	1	0	5	50
Stefanyshyn et al. [49]	1	1	1	U	0	1	1	1	1	0	7	70
Thijs et al. [45]	1	1	1	0	0	1	1	1	0	0	6	60
Van Ginckel et al. [47]	1	1	1	0	0	1	1	1	0	0	6	60

Scoring: 'low risk of bias' = 1, 'high risk of bias' = 0, 'unable to determine' = U (scored as 0)

Criteria: (1) definition of injury clearly described, (2) prospective design that presents incidence or prevalence data, (3) description of level of running (e.g., recreational or professional level), (4) the process of inclusion of athletes in the study was random (i.e., not by convenience) or the data collection was performed with the entire target population; (5) data analysis performed with at least 80% of the athletes included in the study; (6) injury data reported by runners or by a healthcare professional; (7) same mode of injury data collection used; (8) injury diagnosis conducted by a medical professional; (9) follow-up period of at least 6 months; (10) incidence or prevalence rates of injury expressed by a ratio that represents both the number of injuries as well as the exposure to running (i.e., number of injuries/hours of running exposure, or number of injuries/ sessions of running exposure)

developing patellofemoral pain (ES = 1.07) [35] and iliotibial band syndrome (ES = 0.86) [36]. However, limited evidence also indicated no significant difference in hip adduction in a mixed-sex population of cross-country runners developing any RRI [37]. Moderate evidence indicated no significant association between peak hip internal rotation and the development of RRIs in two studies. When divided by population source, limited evidence of no relationship between hip internal rotation for female recreational runners developing patellofemoral pain (ES = 0.26) [35] and a mixed-sex population of cross-country runners developing any RRI was found [37].

Limited evidence indicated greater peak knee internal rotation in female recreational runners developing iliotibial band syndrome in one study (ES = 0.93) [36]. Inconsistent evidence was found for peak knee flexion in relation to RRIs in two studies. Specifically, very limited evidence indicated smaller peak knee flexion in a mixed-sex population of recreational runners developing Achilles tendinopathy (ES = 0.70) [38], while limited evidence indicated no significant association between peak knee flexion and RRI risk in a mixed-sex population of recreational runners (ES = 0.02) [39].

Conflicting evidence was found in two studies for peak ankle eversion velocity in a mixed-sex population of cross-country runners developing any RRI [37, 40]. Specifically, limited evidence was found for greater [37] and smaller (ES = 1.19) [40] peak ankle eversion velocity. Inconsistent evidence was found in two studies for peak ankle eversion angle (ES = 1.02) and ankle eversion range of motion (ES = 0.03) in cross-country runners sustaining any RRI [37, 40]. One study indicated greater peak ankle eversion angle and a smaller ankle eversion range of motion in a mixed-sex population of cross-country runners sustaining any RRI [37], while no significant difference was found in a similar population (ES = 1.02 and 1.18) [40]. Inconsistent evidence was found in four studies for peak rearfoot eversion in relation to RRIs. Specifically, very limited evidence indicated greater peak rearfoot eversion in a mixed-sex population of recreational runners developing Achilles tendinopathy (ES = 0.57) [38]. Limited evidence indicated no significant difference in female recreational runners developing patellofemoral pain (ES = 1.23) [35], female recreational runners developing iliotibial band syndrome (ES = 0.65) [36], and a mixed-sex population developing any RRI (ES = 0.00) [39]. Very limited evidence indicated smaller peak ankle dorsiflexion in

Table 4 Study characteristics and biomechanical measurements for each included study

Included study	Injury type	Injury definition	Population	Duration of follow-up	Injury rate	Data collection procedure	Running speed	Analysis	Outcome variables
Bredeweg et al. [44]	RRI	Any self-reported musculoskeletal complaint of the lower extremity or back causing a restriction of running for at least 1 week	210 novice heel-strike runners	9 weeks	34/210	Instrumented treadmill Usual running shoes	Males: 2.5 and 2.8 m/s Females: 2.2 and 2.5 m/s (fixed)	10 steps analyzed, bilateral	Kinetics: vertical impact-related variables Spatiotemporal variables
Bredeweg et al. [41]	RRI	Any self-reported musculoskeletal complaint of the lower extremity or back causing a restriction of running for at least 1 week	210 novice heel-strike runners	9 weeks	34/210	Instrumented treadmill Usual running shoes	Males: 2.5 and 2.8 m/s Females: 2.2 and 2.5 m/s (fixed)	10 steps analyzed, bilateral	Kinetics: vertical impact-related variables Spatiotemporal variables
Brund et al. [48]	Achilles tendinopathy, plantar fasciopathy and medial tibial stress syndrome	An absence of running for a minimum of one week due to musculoskeletal complaints in the lower extremity or back, caused by running	79 recreational male runners	1500 km of running	25/79	Pressure sensitive treadmill Standard, neutral running shoes	Fastest possible 5000 m-running speed	15 steps analyzed, bilateral	Kinetics: plantar pressure measurements
Davis et al. [42]	RRI	Any pain experienced during running, most interested in those that did not resolve on their own and left the runner to seek medical attention	249 female recreational heelstrike runners	2 years	144/249	25-m runway with force plate Standard, neutral running shoes	3.7 m/s (fixed)	5 steps analyzed, bilateral	Kinetics: vertical impact-related variables

Table 4 (continued)

Included study	Injury type	Injury definition	Population	Duration of follow-up	Injury rate	Data collection procedure	Running speed	Analysis	Outcome variables
Dudley et al. [37]	RRI	Any musculoskeletal complaint of the lower extremities or back causing the restriction of participation in one full practice session	32 collegiate cross-country athletes	14 weeks	12/32	20-m runway with force plate 3D motion capturing Usual running shoes	Average training speed (3.85 m/s)	5 steps analyzed, dominant side	Kinematics: frontal, sagittal and transverse ankle/foot, knee and hip joint angles Kinetics: frontal knee and hip joint moments and vertical impact-related variables
Ghani et al. [46]	RRI	An injury or pain on a localized area that required a change or reduction in training, a visit to a health professional, or the use of medication on a consistent basis	131 novice heel-strike runners	10 weeks	27/131	15-m runway with force plate Barefoot running	Comfortable, self-selected speed	3 steps analyzed, bilateral	Kinetics: plantar pressure measurements
Hein et al. [38]	Achilles tendinopathy	If medical attention was needed, more than 66% of all training sessions in 2 consecutive weeks or more than 50% of all training sessions in 4 consecutive weeks accompanied by running-related pain and diagnosed by the orthopedic surgeon	142 recreational runners	1 year	10/142	13-m runway 3D motion capturing Barefoot running	3.3 m/s (fixed)	10 steps analyzed, bilateral	Kinematics: frontal, sagittal and transverse ankle/foot, knee and hip joint angles

Table 4 (continued)

Included study	Injury type	Injury definition	Population	Duration of follow-up	Injury rate	Data collection procedure	Running speed	Analysis	Outcome variables
Kuhman et al. [40]	RRI	Any injury diagnosed by the team athletic trainer	19 collegiate cross-country runners	3 months	10/19	25-m runway with force plate 3D motion capturing Usual running shoes	Males: 4.5 m/s Females: 4.0 m/s (fixed)	5 steps analyzed, bilateral	Kinematics: frontal, sagittal and transverse ankle/foot joint angles Kinetics: vertical impact-related variables
Luedke et al. [50]	Shin injury and anterior knee pain	A medical problem resulting from athletic participation that required a runner to be removed from a practice or competitive event or to miss a subsequent practice or event, diagnosed by physic al therapist	68 high school cross-country runners	1 interscholastic season	22/68	400-m trial running wearing a Polar RCX5 wristwatch with S3 + Stride Sensor™ Shod running (shoe type not reported)	3.3 m/s (fixed) and self-selected speed	2 trials analyzed at each speed.	Spatiotemporal variables
Messier et al. [39]	RRI	Grade 1: maintained full activity in spite of symptoms Grade 2: reduced weekly mileage Grade 3: interrupted all training for at least 2 weeks	300 recreational runners	2 years	199/300	22.5-m runway with force plate 3D motion capturing Usual running shoes	Average training speed	3 steps analyzed, bilateral	Kinematics: frontal, sagittal and transverse ankle/foot and knee joint angles Kinetics: joint stiffness

Table 4 (continued)

Included study	Injury type	Injury definition	Population	Duration of follow-up	Injury rate	Data collection procedure	Running speed	Analysis	Outcome variables
Napier et al. [43]	RRI	Running-related (due to training), overuse (not related to an acute trauma), musculoskeletal (low back and lower extremities), and reported to be the cause of missing 3 training days within a 2-week moving window	74 female recreational runners	15 weeks	22/74	Instrumented treadmill 3D motion capturing Usual running shoes	Comfortable self-selected speed	30 steps analyzed, bilateral	Kinetics: vertical and horizontal impact-related variables
Noehren et al. [36]	Iliotibial band syndrome	?	400 female recreational runners	2 years	18/400	25-m runway with force plate 3D motion capturing Standard, neutral running shoes	3.7 m/s (fixed)	5 steps analyzed, bilateral	Kinematics: frontal, sagittal and transverse ankle/foot, knee, hip joint angles Kinetics: frontal, sagittal and transverse ankle/foot, knee, hip joint moments
Noehren et al. [35]	Patellofemoral pain	?	400 female recreational runners (rearfoot strikers)	2 years	15/400	25-m runway with force plate 3D motion capturing Standard, neutral running shoes	3.7 m/s (fixed)	5 steps analyzed, bilateral	Kinematics: frontal, sagittal and transverse ankle/foot, hip joint angles
Stefanyshyn et al. [49]	Patellofemoral pain	Meeting 4 historical and 5 physical examination criteria	80 experienced runners	6 months	6/80	30-m runway with footscan pressure plate, 480 Hz (RsScan International) Usual running shoes	4.0 m/s (fixed)	5 steps analyzed, bilateral	Kinetics: frontal knee joint angular impulses

Table 4 (continued)

Included study	Injury type	Injury definition	Population	Duration of follow-up	Injury rate	Data collection procedure	Running speed	Analysis	Outcome variables
Thijs et al. [45]	Patellofemoral pain	Characteristic history and symptoms of patellofemoral pain and seeking medical attention	102 novice recreational heel-strike runners	10 weeks	17/102	15-m runway with footscan pressure plate, 480 Hz (RsScan International) Barefoot running	Comfortable self-selected speed	3 steps analyzed, bilateral	Kinetics: plantar pressure measurements
Van Ginckel et al. [47]	Achilles tendinopathy	A musculoskeletal ailment that causes a restriction of running speed, distance, duration or frequency for at least 1 week	129 novice heel-strike runners	10 weeks	10/129	15-m runway with footscan pressure plate Barefoot running	Comfortable self-selected speed	3 steps analyzed, bilateral	Kinetics: plantar pressure measurements

RRI running-related injury, *3D* three-dimensional, *m* meters, *m/s* meters per second

a mixed-sex population of recreational runners developing Achilles tendinopathy in one study (ES = 1.21) [38]. Limited and very limited evidence from two studies indicated no significant difference in ankle dorsiflexion range of motion in a mixed-sex population of cross-country runners developing any RRI (ES = 0.03) [40], and in a mixed-sex population of recreational runners developing Achilles tendinopathy (ES = 1.00) [38], respectively.

3.4.2 Kinetics

3.4.2.1 Impact-Related Variables Inconsistent evidence was found in three studies for vertical loading rate in relation to RRIs. Limited evidence indicated a greater vertical loading rate in male novice runners developing any RRI (ES = 0.83–0.94) [41]. Moderate evidence indicated no significant difference in vertical average (ES = 0.12) or instantaneous (ES = 0.19) loading rate in female recreational runners developing any RRI [42, 43]. However, using post hoc analysis of their data, Davis et al. [42] reported significantly greater vertical average (ES = 1.43) and instantaneous loading rate (ES = 0.98) in female recreational runners developing any RRI, when comparing runners who required medical attention with runners who had never sustained an injury before (limited evidence). Moderate evidence indicated no significant relationship between vertical (average and/or instantaneous) loading rate and any RRI in a mixed-sex population of cross-country runners (ES = 0.26) [37, 40].

Strong evidence indicated no significant relationship between vertical impact peak and RRIs when comparing a group of injured and non-injured runners in three studies (ES = 0.03–0.35) [39, 41, 42]. However, using post hoc analysis of their data, Davis et al. [42] reported higher vertical impact peak in female runners developing any RRI when comparing runners who required medical attention with runners who had never sustained an injury before (ES = 0.97) (limited evidence). Limited evidence indicated reduced asymmetry between limbs in vertical impact peak in male and female novice runners developing any RRI in one study (ES = 0.36) [44].

Inconsistent evidence was found in two studies for peak braking force. Specifically, greater peak braking force was found for female recreational runners developing any RRI [43], while another study found no significant difference in a mixed-sex population developing any RRI (ES = 0.22) [39].

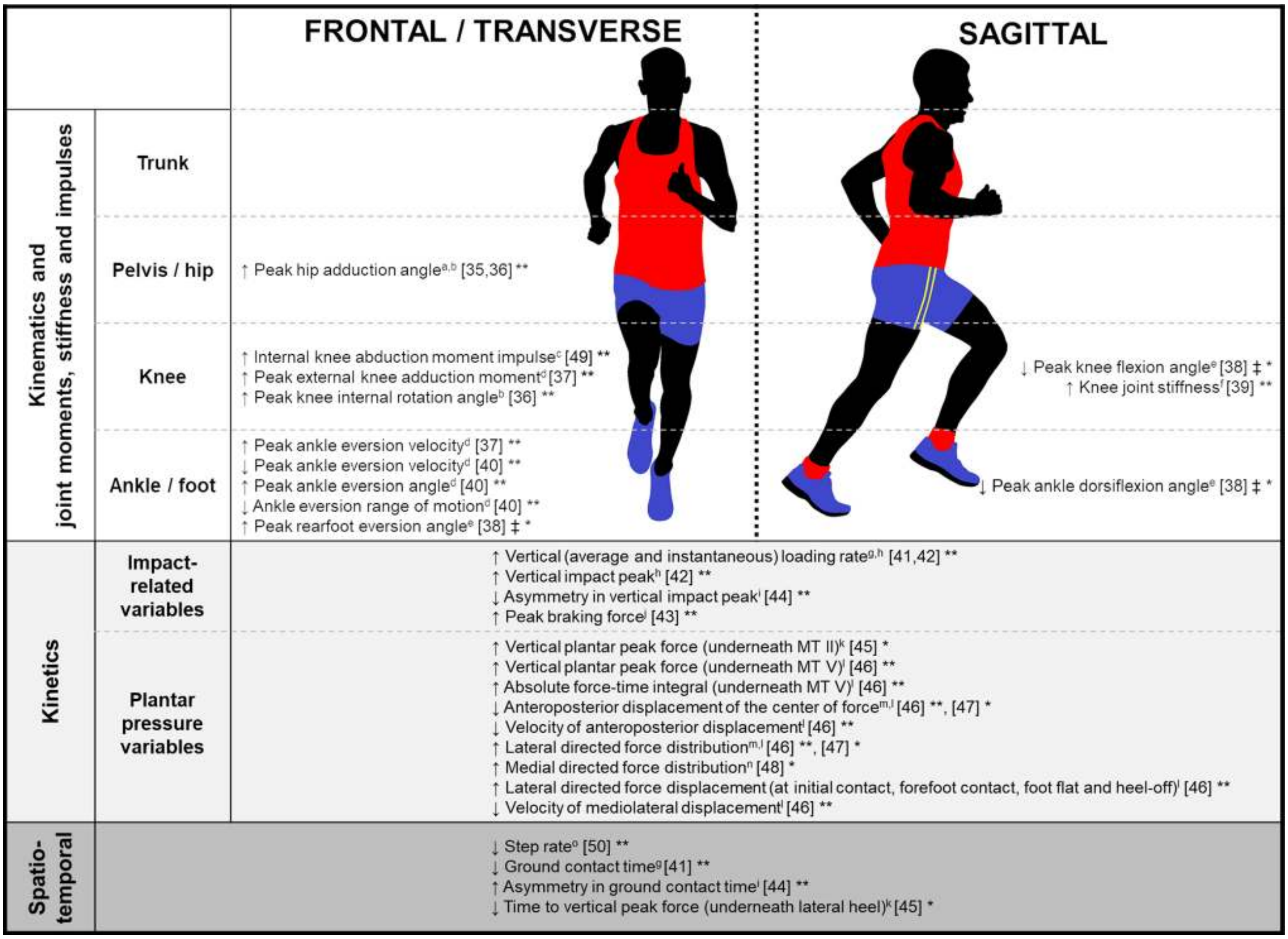
3.4.2.2 Plantar Pressure Variables Inconsistent evidence was found in three studies for vertical plantar peak forces in novice runners developing any RRI. Very limited evidence indicated a significantly greater vertical plantar peak force underneath metatarsal II (ES = 0.65) in a mixed-sex population of novice runners developing patellofemoral pain [45]. Limited evidence indicated a greater vertical plan-

Table 5 Sample sizes and participant characteristics for each included study

Included study	Sample size, *N*		Sex, M/F		Age, y		Height, cm		Weight, kg		BMI, kg/m^2		Running exposure during follow-up, km	
	INJ	CON	INJ	CON	INJ	CON	INJ	CON	INJ	CON	INJ	CON	INJ	CON
Bredeweg et al. [44]	34	176	11 M/23F	66 M/110F	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Bredeweg et al. [41]	34	176	11 M/23F	66 M/110F	40.4 (12.9)	36.6 (10.6)	NR	NR	NR	NR	24.3 (3.2)	23.9 (3.4)	NR	NR
Brund et al. [48]	25	54	25 M	54 M	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Davis et al. [42]	103	21	103F	21F	25.7 (9.2)	25.0 (10.0)	NR	NR	NR	NR	NR	NR	193/mo	151/mo
Dudley et al. [37]	12	19	4 M/8F	11 M/8F	20.0	19.7	173	174	62.4	62.6	NR	NR	88.4/wk	91.3/wk
Ghani et al. [46]	27	104	5 M/22F	15 M/89F	40.6 (8.4)	38.7 (10.7)	168.6 (7.1)	168.4 (8.0)	73.1 (12.2)	69.6 (11.0)	NR	NR	NR	NR
Hein et al. [38]	10	10	8 M/2F	8 M/2F	45 (5)	40 (7)	177 (4.0)	177 (5.0)	72 (8.0)	72 (8.0)	NR	NR	33/wk	32/wk
Kuhman et al. [40]	10	9	4 M/6F	7 M/2F	19.2 (1.3)	20.2 (1.9)	170 (10.0)	180 (10.0)	57.8 (7.5)	66.6 (8.9)	19.9 (1.4)	20.7 (2.1)	NR	NR
Luedke et al. [50]	22	NR	15 M/7F	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Messier et al. [39]	199	101	106 M/93F	66 M/35F	42.3 (9.7)	40.0 (10.3)	173 (9.0)	174 (9.0)	71.6 (13.1)	74.4 (14.6)	23.9 (3.3)	24.5 (3.4)	32.8/wk	32.0/wk
Napier et al. [43]	22	33	22F	33F	34.7 (7.8)	37.4 (8.2)	NR	NR	NR	NR	22.5 (1.9)	22.6 (2.6)	NR	NR
Noehren et al. [36]	18	18	18F	18F	26.8	28.5	NR	NR	NR	NR	21.9	22.1	155/mo	160/mo
Noehren et al. [35]	15	15	15F	15F	27 (10)	27 (10)	NR	NR	NR	NR	NR	NR	165/mo	165/mo
Stefanyshyn et al. [49]	6	6	3 M/3F	3 M/3F	NR	NR	NR	NR	73.2	72.0	NR	NR	32/wk	32.5/wk
Thijs et al. [45]	17	85	1 M/16F	12 M/73F	39.4 (10.3)	37.6 (9.4)	164.5 (26.8)	167.4 (7.5)	69.3 (8.1)	69.3 (15.8)	24.9 (3.5)	25.1 (2.8)	NR	NR
Van Ginckel et al. [47]	10	53	2 M/8F	8 M/45F	38 (11.4)	40 (9.0)	167.1 (6.4)	168.3 (8.2)	69.8 (12.9)	70.0 (8.2)	25.0 (4.1)	24.7 (3.9)	NR	NR

Data are reported as means (SD) for all variables except sample size and sex

INJ injured group, *CON* control group, *N* number of subjects, *M* male, *F* female, *SD* standard deviation, *cm* centimeter, *kg* kilogram, *BMI* body mass index, *km* kilometers, */wk* per week, */mo* per month, *NR* not reported



		FRONTAL / TRANSVERSE	SAGITTAL
Kinematics and joint moments, stiffness and impulses	Trunk		
	Pelvis / hip	↑ Peak hip adduction angle^{a,b} [35,36] **	
	Knee	↑ Internal knee abduction moment impulse^{c} [49] ** ↑ Peak external knee adduction moment^{d} [37] ** ↑ Peak knee internal rotation angle^{b} [36] **	↓ Peak knee flexion angle^{e} [38] ‡ * ↑ Knee joint stiffness^{f} [39] **
	Ankle / foot	↑ Peak ankle eversion velocity^{d} [37] ** ↓ Peak ankle eversion velocity^{d} [40] ** ↑ Peak ankle eversion angle^{d} [40] ** ↓ Ankle eversion range of motion^{d} [40] ** ↑ Peak rearfoot eversion angle^{e} [38] ‡ *	↓ Peak ankle dorsiflexion angle^{e} [38] ‡ *
Kinetics	Impact-related variables	↑ Vertical (average and instantaneous) loading rate^{g,h} [41,42] ** ↑ Vertical impact peak^{h} [42] ** ↓ Asymmetry in vertical impact peak^{i} [44] ** ↑ Peak braking force^{j} [43] **	
	Plantar pressure variables	↑ Vertical plantar peak force (underneath MT II)^{k} [45] * ↑ Vertical plantar peak force (underneath MT V)^{l} [46] ** ↑ Absolute force-time integral (underneath MT V)^{l} [46] ** ↓ Anteroposterior displacement of the center of force^{m,l} [46] **, [47] * ↓ Velocity of anteroposterior displacement^{l} [46] ** ↑ Lateral directed force distribution^{m,l} [46] **, [47] * ↑ Medial directed force distribution^{n} [48] * ↑ Lateral directed force displacement (at initial contact, forefoot contact, foot flat and heel-off)^{l} [46] ** ↓ Velocity of mediolateral displacement^{l} [46] **	
Spatio-temporal		↓ Step rate^{o} [50] ** ↓ Ground contact time^{g} [41] ** ↑ Asymmetry in ground contact time^{i} [44] ** ↓ Time to vertical peak force (underneath lateral heel)^{k} [45] *	

Fig. 2 Visualization of significant results. Levels of evidence are shown with the following symbols: (double asterisks) limited evidence, (asterisk) very limited evidence, (double tagger) no statistical analysis. A detailed description of all significant outcome measures is provided using following superscripts: ^{a} in female runners developing patellofemoral pain, ^{b} in female runners developing iliotibial band syndrome, ^{c} in a mixed-sex population of experienced runners developing patellofemoral pain, ^{d} in a mixed-sex population of cross-country runners developing an RRI, ^{e} in a mixed-sex population of recreational runners developing Achilles tendinopathy, ^{f} in a mixed-sex population of recreational runners developing an RRI, ^{g} in male novice runners developing an RRI, ^{h} in female recreational runners who required medical attention compared with female recreational runners who never sustained an RRI before, ^{i} in male and female novice runners developing an RRI, ^{j} in female recreational runners developing an RRI, ^{k} in a mixed-sex population of novice runners developing patellofemoral pain, ^{l} in a mixed-sex population of novice runners sustaining an RRI, ^{m} in a mixed-sex population of novice runners developing Achilles tendinopathy, ^{n} in male runners developing Achilles tendinopathy, plantar fasciopathy and medial tibial stress syndrome, ^{o} in a mixed-sex population of cross-country runners developing shin injury [35–50]. *MT* metatarsal, *RRI* running-related injury, ↑ greater, ↓ smaller

tar peak force (ES = 0.47) and absolute force-time integral (ES = 0.51) underneath metatarsal V in a mixed-sex population of novice runners developing any RRI [46]. However, very limited evidence indicated no significant difference in vertical plantar peak force in the same study cohort developing Achilles tendinopathy (ES = 0.05–0.84) [47].

Conflicting evidence was found in two studies for anteroposterior displacement of center of force in novice runners developing an RRI. Specifically, limited evidence indicated a greater anteroposterior displacement of the center of force at forefoot flat in a mixed-sex population of novice runners developing any RRI (ES = 0.42) [46], while very limited evidence indicated a significantly smaller anteroposterior displacement of center of force in the same population developing Achilles tendinopathy (ES = 0.95) [47].

Limited evidence indicated a significantly slower velocity of anteroposterior displacement of the center of force at forefoot flat in a mixed-sex population of novice runners developing any RRI in one study (ES = 0.36) [46].

Conflicting evidence was found in three studies for mediolateral plantar pressure distribution. Specifically, limited evidence indicated a significantly more lateral directed force distribution at first metatarsal contact (ES = 0.01–0.50) [46], at forefoot flat (ES = 0.46–0.82) [46] and underneath the forefoot at forefoot flat (ES = 0.88) [47] in a mixed-sex population of novice runners, while limited evidence indicated a greater medial pressure in recreational male runners developing Achilles tendinopathy, plantar fasciopathy and medial tibial stress syndrome [48]. Limited evidence from one study indicated a more laterally directed force displacement in the initial contact phase (ES = 0.48), a more lateral directed center of force during forefoot contact phase (ES = 0.48), foot flat phase (ES = 0.37), and heel-off (ES = 0.43), while a more medial directed center of force was found during forefoot push-off phase (ES = 0.32) in a mixed-sex population of novice runners developing any RRI [46].

Limited evidence indicated a slower velocity of mediolateral displacement of the center of force at forefoot flat in the same study cohort (ES = 0.38) [46].

3.4.2.3 Joint Moments, Impulses, and Stiffness Inconsistent evidence was found in two studies for peak external knee adduction moment. Limited evidence indicated greater peak external knee adduction moment in a mixed-sex population of cross-country runners developing any RRI [37]. However, limited evidence indicated no significant difference in internal knee abduction moment in a mixed-sex population of recreational runners developing any RRI (ES = 0.20) [39].

Limited evidence indicated greater internal knee abduction moment impulses in a mixed-sex population of experienced runners developing patellofemoral pain (ES = 1.28) [49].

Limited evidence indicated greater knee joint stiffness in a mixed-sex population of recreational runners developing any RRI (ES = 0.07) [39].

3.4.3 Spatiotemporal Characteristics

Inconsistent evidence was found in two studies for step rate. Specifically, limited evidence indicated lower step rate in a mixed-sex population of cross-country runners developing shin injury [50]. Limited evidence indicated no significant difference in step rate in runners of the same study cohort developing anterior knee pain [50] and in male and female novice runners developing any RRI (ES = 0.05–0.44) [41].

Limited evidence indicated shorter ground contact times in male novice runners developing any RRI in one study (ES = 0.57–0.84) [41] and higher asymmetry between limbs in ground contact times in male and female runners developing any RRI in one study (ES = 0.02) [44].

Very limited evidence indicated a significantly lower time to vertical plantar peak force underneath the lateral heel in a mixed-sex population of novice runners developing patellofemoral pain in one study (ES = 0.56) [45].

4 Discussion

This systematic review identified no conclusive biomechanical mechanism to explain the development of RRIs. Given the limited number of published studies and the considerable heterogeneity of the studied populations, methodologies, and outcome variables within the included studies, caution is warranted when interpreting or generalizing the findings of individual studies within this relatively novel research area.

4.1 Biomechanical Factors Related to the Development of Running-Related Injuries (RRIs)

4.1.1 Kinematics

Limited evidence with large ES for greater peak hip adduction in female recreational runners developing patellofemoral pain [35] and iliotibial band syndrome [36] is supported by retrospective research, highlighting its role in the biomechanical etiology of these injuries in female runners. From a biomechanical perspective, the magnitude of hip adduction has previously been related to strain on the iliotibial band [51] and patellofemoral joint stress [52]. Interestingly, hip adduction was not related to RRI risk in a mixed-sex population of cross-country runners [37]. This inconsistency may be explained by the small sample size, different study population and short follow-up period used in the latter study, or the fact that the studies by Noehren et al. [35, 36] focused on only one specific pathology within a female population.

Limited evidence with large ES for greater peak knee internal rotation in female recreational runners developing iliotibial band syndrome [36] is consistent with retrospective research in a similar population [53]. Greater knee internal rotation may lead to greater strain on the iliotibial band due to its attachments to Gerdy's tubercle, and greater compression of the iliotibial band against the lateral femoral epicondyle [36]. However, the magnitude of difference between groups was relatively small (3.7°) and the ability to detect transversal plane knee kinematics clinically as well as in laboratory settings can be questioned.

Smaller peak knee flexion with medium ES in runners who developed Achilles tendinopathy [38] is consistent with cross-sectional research [54]. However, this finding should be interpreted with caution due to the small sample size, high number of drop-outs, and lack of statistical tests. Theoretically, a smaller peak knee flexion may indicate reduced efficiency in absorbing load at the knee [55] and may induce more tension in the calf and Achilles tendon [38]. Interestingly, findings from Hein et al. [38] are inconsistent with Messier et al. [39], who reported no significant differences with very small ES in peak knee flexion in recreational runners developing any RRI. This might imply that peak knee flexion can be a risk factor for Achilles tendinopathy, but not for all RRIs.

Conflicting evidence was reported for peak ankle eversion velocity, while inconsistent evidence was identified for greater peak ankle eversion, peak rearfoot eversion and smaller ankle eversion range of motion. As such, current prospective evidence does not support a persistent and widespread belief that ankle and rearfoot eversion is related to an increased risk for RRIs [56]. These findings are in line with retrospective evidence in patellofemoral pain [23], while contradictory findings have been reported in runners with iliotibial band syndrome [24].

Very limited evidence with very large ES for smaller peak ankle dorsiflexion in runners developing Achilles tendinopathy [38] is not supported by cross-sectional research [54]. This prospective evidence should be interpreted with caution given the lack of statistical analysis applied in this study. The biomechanical rationale remains speculative and could be related to other compensatory movement patterns across the lower extremity (e.g., rearfoot eversion).

4.1.2 Kinetics

The role of vertical average and/or instantaneous loading rate in the development of RRIs is inconsistent and not in line with retrospective studies reporting greater vertical loading rates in runners with a history of tibial stress fracture [57, 58] and plantar fasciopathy [59]. This discrepancy could be attributed to the fact that the prospective studies focused on all RRIs, while the retrospective studies focused on specific RRIs. It could be possible that vertical loading rate is only relevant to specific RRIs such as tibial stress fracture [57, 58] and plantar fasciopathy [59]. The strong evidence for no significant difference with very small to small ES for vertical impact peak in relation to RRIs is in line with retrospective findings [60]. Methodological differences (population, follow-up period, data analysis) between studies may limit the ability to generalize current research findings. The role of vertical loading rate may be variable among sexes and injury definition. Limited evidence with large ES indicates a greater vertical loading rate in male novice runners [41], while moderate evidence for no significant difference with very small to small ES was found in female recreational runners [42, 43] and mixed-sex populations of cross-country runners [37, 40]. Limited evidence with large to very large ES indicated greater average and instantaneous loading rate in female recreational runners developing any RRI, when comparing runners who required medical attention with runners who had never sustained an injury before, while this effect was not observed when comparing injured and non-injured runners [42]. The theoretical rationale behind these findings is that musculoskeletal structures are viscoelastic in nature and do not respond very well to more impulsive loads compared to more gradual loads [61–63]. However, current prospective evidence does not necessarily support this rationale.

Inconsistent evidence for peak braking force is in line with retrospective studies [64–68]. Differences in follow-up duration, sample sizes, and data collection procedures should be taken into account when interpreting these results. Further research is needed to understand why these inconsistent findings exist.

The inconsistent and/or conflicting evidence identified for most of the plantar pressure variables is in line with a recent review by Mann et al. [69] summarizing prospective and retrospective studies. The large variability in methods to make subdivisions of plantar areas, and the enormous number of variables included in the data analysis, could contribute to this inconsistency.

The link between peak external knee adduction moment and RRI risk is inconsistent [37, 39]. However, limited evidence with very large ESs for greater internal knee abduction moment impulses was found in a mixed-sex population of experienced runners developing patellofemoral pain, supporting retrospective findings [49]. Since Stefanyshyn et al. [49] had a low injury rate (7.5%, with only six injured runners), the results are rather preliminary and should be interpreted with caution. Increased frontal plane knee joint angular impulses could lead to increased patellofemoral joint stress across repetitive running cycles [49].

Finally, limited evidence for greater knee joint stiffness in the sagittal plane [39] is in line with retrospective findings in runners with a history of a tibial stress fracture [70]. However, the small difference in knee joint stiffness between groups (2%) with very small ES calls into question the clinical significance of this result. In addition, greater knee joint stiffness was more common in runners with higher body weights (≥ 80 kg). Greater knee joint stiffness may support the findings of Hein et al. [38] where a reduced peak knee flexion was found, suggesting less energy dissipation, which could lead to excessive loading of structures of the lower extremity [39].

4.1.3 Spatiotemporal Characteristics

Step rate was inconsistently associated with RRIs [41, 50]. It should be noted that one out of two studies [50] was not adequately powered to demonstrate a risk relationship between step rate and anterior knee pain. To the best of our knowledge, no retrospective or cross-sectional studies have compared runners with and without RRIs. Regardless, the absence of evidence linking step rate to injury prospectively or retrospectively is interesting considering the large body of work that has now evaluated the influence of altering step rate on biomechanics [71] and pain [72–75].

Other spatiotemporal factors, such as ground contact time [41, 44], were only supported by limited evidence with large ES in male runners, but not in female runners. Typically, shorter ground contact times are related to a higher step rate [76]. Therefore, the findings associating a shorter ground contact time in male runners with an RRI may partially contradict the potentially beneficial effects of an increased step rate identified in this review [50]. In combination with the higher vertical loading rates, these shorter ground contact times might suggest a stiffer landing pattern in the male injured runners. However, to the best of our knowledge, no study has directly evaluated the role of leg stiffness on the incidence of RRIs.

4.2 Considerations when Interpreting the Results

4.2.1 Methodological Considerations

Most studies did not properly report their method of recruitment or used convenience sampling, such as recruiting an entire team of runners. This limits the ability to generalize the results to a broader running population. Seventy-five percent of the included studies had low risk of bias. Runners with different age, sex, performance level, level of experience, foot strike pattern, and running exposure were included in the 16 prospective studies of this systematic review. Caution is therefore warranted when extrapolating results from one study to other populations of runners. Future prospective studies should focus on clearly defining all these factors to facilitate between-study comparisons. Multiple studies had a limited sample size (19–400; 6/16 studies with < 100 participants), often resulting in a relatively low number of injured runners (6–199), which reduced the statistical power of the results. Future studies could focus on strategies (e.g., multicenter studies with standardized methodologies) to increase sample sizes and statistical power.

Some studies focused on RRIs in general [37, 39–44, 46], whilst others focused on specific injuries including patellofemoral pain, iliotibial band syndrome, medial tibial stress syndrome, Achilles tendinopathy, and plantar fasciopathy [35, 36, 45, 47–51]. Generic risk factors for RRIs may exist, but findings from this review indicate that certain risk factors may be associated with specific RRIs. Pooling all injuries together might therefore under- or overestimate the relevance of specific biomechanical risk factors for specific RRIs [43]. Future prospective studies with larger sample sizes should aim to identify risk factors for specific injuries.

Various definitions of RRIs used across studies may influence injury rates [13, 77]. Injury was defined based on physical complaints in three studies [42, 45, 49], need to interrupt training or competition in two studies [39, 50], and a combination of physical complaints, interruption of training, and seeking medical assistance in eight studies [37, 38, 41, 43, 44, 46–48]. Several studies failed to adequately define an RRI [35, 36, 40]. The lack of a uniform definition of RRIs across prospective studies may limit the generalization of results and therefore under- or overestimate the true burden of RRIs, and/or the relevance of a biomechanical risk factor. A recent Delphi study [15] has defined an RRI as “running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional” [15]. This consensus definition may help to bring uniformity to future prospective studies on RRIs and facilitate between-study comparisons.

The length of follow-up plays an important role in capturing RRIs in prospective research. A follow-up of at least 6 months has been recommended [15, 16], but only seven studies in this systematic review fulfilled this criterion. Furthermore, all included studies assume that biomechanical risk factors remain constant during the time of follow-up, which may not be the case [78]. Given the chronic presentation of many RRIs, a more continuous monitoring at regular intervals may be a better indicator to report overuse injuries [77].

4.2.2 Methodology of Measurements

Measurements were either obtained by running barefoot [38, 45–47] or with their own or standard running shoes [35–37, 39–44, 48–50] on a treadmill [41, 43, 44, 48] or overground on a runway [35–40, 42, 45–47, 49, 50], at preferred [37, 39, 43, 45–48], fixed [35, 36, 38, 40–42, 44, 49] or both at preferred and fixed running speeds [50]. All modalities possess some constraints potentially influencing the final outcomes and hampering between-study comparisons. Future studies should attempt to replicate the real-life running situation as much as possible when measuring running biomechanics.

To measure kinematics, all studies used three-dimensional motion analysis. This is considered the gold standard for a biomechanical running analysis, although considerable differences might exist between models being used to measure biomechanical variables. Increasing evidence exists to support the use of two-dimensional motion analysis [79–82] and wearables [83, 84] as a valid and reliable alternative. Since both methods are less complex, less expensive, and take less time than three-dimensional motion analysis, multicenter “big data” studies could be conducted to increase statistical power. Additionally, these methods may make it more feasible to measure runners in their natural environment, rather than in an artificial laboratory-based setting.

A large number of biomechanical variables were investigated in the included prospective studies. However, it should be noted that these variables are not necessarily the only biomechanical variables that can be clinically relevant in causing RRIs. Some variables may be easier to measure and therefore more studies could have focused on specific variables (e.g., kinetics). Moreover, all prospective studies in this systematic review reporting ankle or foot kinematics considered the foot as one rigid segment, hereby neglecting its complex multi-segmental anatomy and biomechanical function [28]. It could be possible that the role of foot kinematics in the etiology of RRIs is underestimated based on the methodological approaches being used. Another remarkable finding of our systematic review was that all prospective studies focused on lower extremity kinematics, but more proximal regions (e.g., pelvis and trunk kinematics) were not studied. This is an important limitation of current prospective literature considering previous cross-sectional studies have reported altered pelvis and trunk kinematics in runners with RRIs [85, 86]. In addition, the positioning of the trunk can have an influence on lower extremity joint loading during running [87–89].

4.2.3 Data Analysis

All included studies used a group-based approach to statistically analyze and interpret the role of the biomechanical variables. Considering the injured and non-injured groups as two homogeneous samples may fail to discover significant relationships between biomechanical variables and RRIs [21, 90], as several studies have shown the existence of specific subgroups or "clusters" based on running kinematics within both injured [91] and non-injured runners [90]. The classical group-based statistical approach may therefore flatten out the presence of individual clinically relevant biomechanical presentations [21]. Future prospective studies should explore the validity of using more advanced statistical methodologies using subgroup analysis designs, and ensuring they are adequately powered to do so [92].

Biomechanical data were mostly reported as peak values, representing the maximum or minimum value within a time-varying curve during the stance phase. By reducing multi-dimensional time-varying biomechanical data to zero-dimensional data (peak values), our further understanding of more subtle alterations in biomechanical data across the whole running cycle might be compromised [21, 93, 94].

Repetitive overloading of specific tissues during running can be the end result of a combination of movements in different planes at different points within the kinetic chain [21]. However, all prospective studies included in this systematic review that evaluated kinematics focused on individual lower extremity joints, and not on the interaction between different adjacent and non-adjacent joints (e.g., joint coupling). A growing body of retrospective evidence supports the theory that a more advantageous window of movement coordinative variability is essential in relation to overuse injuries of the lower extremity [21, 95, 96]. Alterations across both ends of this spectrum of movement coordinative variability are hypothesized to lead to a reduction in the movement strategies available for an individual and increase the risk for repetitive overuse of specific musculoskeletal tissues [21, 95]. However, this theory has not yet been validated in prospective studies.

Finally, running injuries are not only caused by biomechanical factors, but also by an interaction of multiple modifiable and non-modifiable factors [18, 97–100]. For example, running exposure (workload) is an essential factor involved in injury development [18, 101, 102], but the interaction with biomechanical risk factors has not yet been investigated in prospective studies. It could be hypothesized that biomechanical risk factors might decrease the ability to tolerate an increase in workload before an injury occurs [21, 102, 103]. A biomechanical risk factor for RRIs should be interpreted within a multifactorial biopsychosocial context, and must not be perceived as a predictor to sustain an RRI for an individual [104]. Only Messier et al. [39] used a multifactorial approach, including training behaviour, physiological, biomechanical, and psychological factors. Although the traditional reductionist approach has significantly increased our understanding of potential contributing risk factors, more complex model approaches are currently recommended to further understand the etiology of sport injuries [97].

4.3 Clinical Implications of Biomechanical Risk Factors

Even though identifying risk factors is only one step within a larger framework of injury prevention [105–107], an accurate clinical interpretation of the findings of this systematic review is necessary to achieve the goal of injury reduction in runners. First, it must be noted that the identification of biomechanical risk factors does not implicate that a general "perfect" biomechanical running style would exist [21]. Second, there is no clear definition of what exactly is too much or too little for any biomechanical risk factor. As a consequence, a clinician should not try to find or use cut-off values with a "one-size-fits-all" approach for the whole population. The biomechanical risk factors reported in this systematic review should therefore be interpreted within a multidimensional biopsychosocial framework with expert clinical reasoning when aiming to reduce injury risk with targeted interventions in an individual runner [21, 108].

Gait retraining interventions could be considered as part of the solution when managing or preventing running injuries [72]. Tailoring running retraining strategies to each individual is needed to optimise outcomes [72]. Primary injury prevention interventions for runners have only been studied to a limited extent [109, 110], in comparison with the larger scientific base of evidence for effective overuse injury prevention in other sports [111]. Future studies should further evaluate the role of specific intervention strategies to successfully modify the biomechanical variables associated with RRIs and decrease injury risk.

5 Conclusion

Despite persistent and widespread beliefs, current prospective evidence relating biomechanical variables with RRI risk is inconsistent and largely dependent on the population and injuries being studied. Existing findings related to kinematics, kinetics, and spatiotemporal variables during running require confirmation via further high-quality prospective studies before clinical recommendations can be made. A balanced interpretation with comprehensive clinical reasoning is necessary to apply current prospective evidence in a clinical setting.

Compliance with Ethical Standards

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