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SYSTEMATIC REVIEW

Association Between Temporal Spatial Parameters and Overuse Injury History in Runners: A Systematic Review and Meta-analysis

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Abstract

Background Temporal spatial parameters during running are measurable outside of clinical and laboratory environments using wearable technology. Data from wearable technology may be useful for injury prevention, however the association of temporal spatial parameters with overuse injury in runners remains unclear.

Objective To identify the association between overuse injury and temporal spatial parameters during running.

Data Sources Electronic databases were searched using keywords related to temporal spatial parameters, running, and overuse injury, and authors' personal article collections through hand search.

Eligibility Criteria for Selecting Studies Articles included in this systematic review contained original data, and analytically compared at least one temporal spatial parameter (e.g. cadence) between uninjured and retrospectively or prospectively injured groups of runners. Articles were excluded from this review if they did not meet these criteria or measured temporal spatial parameters via survey.

Study Appraisal and Synthesis Method The internal validity of each article was assessed using the National Institutes of Health Quality Assessment Tool for Observational Cohort and Cross-Sectional Studies. Meta-analyses were conducted for temporal spatial parameters if data existed from at least three separate cohorts of the same prospective or retrospective design. Data were pooled and analyzed using an inverse variance fixed-effect model.

Results Thirteen articles which tested a total of 24 temporal spatial parameters during running were included in the review. Meta-analyses were conducted on four temporal spatial parameters using data from eleven retrospective studies. Healthy runners and those with a history of overuse injury had a similar average stride time (mean difference: 0.00 s, 95% CI − 0.01 to 0.01 s), contact time (mean difference: 0.00 s, 95% CI 0.00 to 0.01 s), cadence (mean difference: 0.3 steps per minute (spm), 95% CI − 1.8 to 2.5 spm), and stride length (mean difference 0.00 m, 95% CI − 0.05 to 0.05 m) during running.

Limitations Data pooled for meta-analyses were limited to retrospective design studies. Studies included in the systematic review had low methodological consistency.

Conclusion Based on pooled results from multiple studies, stride time, contact time, cadence, and stride length averages are not distinguishable between runners either with or without a history of overuse injury. More prospective studies are required to determine the association of temporal spatial parameters with overuse injury development in runners.

Systematic Review Registration Registry and Number CRD42018112290.

Key Points

- This review determined that average stride time, contact time, cadence, and stride length during running are not different between injured and uninjured runners based on the combined findings from previous studies.
- Additional prospective studies are needed to determine the role of temporal spatial parameters during running in overuse injury development.
- Practitioners should exercise caution when using temporal spatial parameters to determine a runner's injury risk.

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1 Introduction

Running is a popular recreational activity among adults. In the United Kingdom, running was the most common mode of physical activity reported by adults [1]. While running is associated with many health benefits, it may also lead to overuse injuries. As many as 80% of runners are estimated to experience an overuse injury each year [2]. Aspects of a runner's anatomy, training program, and running biomechanics are thought to contribute to the development of overuse injuries [3]. Investigations of overuse injuries in runners have identified biomechanical risk factors for injury [4]. However, many runners are unaware of running biomechanics that may contribute to injury [5], such as a large peak hip adduction angle [6]. Additionally, many runners may be unaware if their running technique includes biomechanical risk factors for injury.

The use of wearable technology is an emerging area which may be utilized by runners to identify the presence of a biomechanical risk factor for injury in their running technique. Wearable technology is a US$ 27 billion industry that is dominated by fitness trackers and smart-watches [7]. Recreational runners are a targeted group of consumers for wearable devices such as the Garmin Forerunner®, Apple Watch®, RunScribe™, etc. Some of these wearable devices are able to provide biomechanical information about a user's running technique, however they are typically limited to measurement of simple temporal spatial parameters [8]. Temporal spatial parameters describe running technique in terms of time and space variables. Examples of temporal spatial parameters include running speed and distance, as well as running stride characteristics, such as step width, step length, and cadence. Moderate to excellent reliability and validity of temporal spatial parameters measured by some of these devices have been reported [9, 10]. Thus, temporal spatial parameters measured by wearable devices that have a reasonable level of reliability and validity may be useful for identifying runners' injury risk.

Temporal spatial parameters during running have been linked to biomechanical risk factors for injury in healthy runners. Previous studies have altered lower extremity biomechanics during running in healthy adults by altering their temporal spatial parameters [11]. For example, both a narrower step width [12] and decreased cadence [13] during running increased peak hip adduction angle in healthy runners. An increased peak hip adduction angle during running has been identified as a prospective risk factor for patellofemoral pain and iliotibial band syndromes in female runners [6, 14]. However, the association of habitual temporal spatial parameters during running with overuse injury is not well known. An association between overuse injury and temporal spatial parameters, especially with decreased cadence, has been hypothesized [11, 15, 16]. However, the association of temporal spatial parameters during running with overuse injury in runners remains unclear. Thus, the capability of temporal spatial parameters to assist in overuse injury prevention and rehabilitation efforts in runners also remains unclear.

Temporal spatial parameters can be easily recorded during running using wearable devices. Analysis of temporal spatial parameters recorded using wearable devices could potentially alert runners and clinicians to the presence of biomechanical risk factors for overuse injury. Thus, investigating the association between temporal spatial parameters and overuse injury in runners is warranted. Therefore, the purpose of this systematic review and meta-analysis of the literature was to identify the association between overuse injury and temporal spatial parameters during running in recreational runners.

2 Methods

This systematic review analyzed prospective and retrospective investigations which analyzed temporal spatial parameters during running between runners with and without overuse injuries. This systematic review was registered on PROSPERO online database of systematic reviews; the protocol registration number is CRD42018112290. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used.

2.1 Article Selection

An extensive literature search was conducted using CINAHL, Medline, PubMed, SCOPUS, and SPORTDiscus databases. Search terms were: (cadence OR "step rate" OR "step length" OR "stride length" OR speed OR velocity OR "step width" OR "stance time" OR "contact time" OR "swing time") AND (run OR running OR runner) AND (injury OR injured OR injuries). Articles which contained one or more of the search terms and were published from January 1980 to November 2018 were identified. Additionally, authors manually searched their personal article libraries and study references for relevant articles.

Articles that contained original data, analytically compared a temporal spatial parameter between groups, had a retrospectively or prospectively injured cohort, and included participants of at least 14 years of age who were operationally defined as runners were included in this systematic review. Alternatively, those articles that did not meet these criteria, were conference abstracts, non-English language, measured temporal spatial parameters using a survey or during sprinting, or did not include a control group were excluded from this review. Two reviewers (RB&AW)

independently screened articles for the inclusion criteria. First, all identified articles were screened based on the article title. Remaining articles were screened based on the abstract. Finally, the full text was screened if the article title and abstract provided insufficient information to establish eligibility for inclusion in the systematic review.

After screening for eligibility, the two reviewers met to dispute and come to a consensus on disagreements in article selection. In cases where a consensus was not established, a third reviewer (KF) made the final decision. Once a consensus was reached, the two reviewers independently screened the selected articles in their entirety to determine eligibility. Articles that the reviewers agreed met the inclusion criteria were entered into this systematic review and meta-analysis.

2.2 Quality Assessment

The internal validity of each article was independently assessed by two reviewers (RB&CR) using the National Institutes of Health (NIH) Quality Assessment Tool for Observational Cohort and Cross Sectional Studies [17]. The tool assesses the ability of each study to make conclusions about the link between temporal spatial parameters during running and overuse injury. Flaws in the design and methodology of the study can increase its risk of bias and decrease internal validity. All 14 items of the Quality Assessment Tool were used to assess the articles in this review. Reviewers answered each question as either 'Yes', 'No', 'Cannot Determine', 'Not Applicable', or 'Not Reported' based on their critical review for each study. After each article was assessed using the tool, reviewers met to dispute and come to a consensus on disagreements. To compare the risk of bias across studies, answers to Quality Assessment Tool questions were weighted. Questions to the tool answered with a 'Yes' were given a score of 1, while 'No', 'Not Applicable', 'Cannot Determine', and 'Not Reported' answers were given a score of 0. The total score for each study was used to classify the risk of bias as either low (10–14), moderate (5–9), or high (0–4). For item 12 of the quality assessment we assumed, unless indicated otherwise, that the raters in prospective studies were blinded to the injured status of runners as measurements were recorded prior to injury. Alternatively, we assumed that raters in studies that grouped runners based on current injury or injury history were not blind to injury status.

2.3 Data Extraction

For the meta-analysis, the mean and standard deviations of temporal spatial outcome variables for injured and uninjured groups were extracted from each study. Additionally, the number of participants, participant demographics, and the measurement tool used to record temporal spatial parameters were extracted from each study. Exploratory meta-analyses were conducted on each temporal spatial parameter that had data from at least three separate cohorts. Differences in temporal spatial parameters between groups of runners with or without an overuse injury may either have contributed to or resulted from the injury. Thus, data were pooled separately for prospective and retrospective design studies to distinguish between causality. The extracted data were entered into Review Manager 5.3 for statistical analysis (RevMan, Copenhagen, Denmark). Data were analyzed using an inverse variance fixed-effect model with mean differences between the injured and uninjured group. The 95% confidence intervals (CI) for the mean differences were calculated, with $p < 0.05$ indicating that the true mean difference was different from zero. Both a χ^2 statistic with corresponding p value and an I^2 statistic were calculated and used to describe the total variation across studies due to heterogeneity as opposed to random chance. Values of I^2 of 25% are considered low, 50% are considered moderate and 75% are considered high heterogeneity [18]. Study weights were calculated as the inverse of the standard error.

3 Results

After screening for inclusion and exclusion criteria, 13 articles reporting on 11 different cohorts were included in this systematic review and meta-analysis (Fig. 1). Temporal spatial parameters were measured using a variety of methods and running conditions. Out of the 13 studies, 2 were prospective cohort designs [19, 20], 10 were retrospective designs [21–30], and 1 was both a prospective and retrospective design [31]. In most of the studies, the injured group consisted of runners with a mix of various overuse injuries [19, 20, 22–24, 26, 28, 31], while 5 studies focused on specific overuse injuries [21, 25, 27, 29, 30]. Of these five, four studies compared runners with patellofemoral pain syndrome to uninjured control groups [21, 25, 29, 30], and one study compared runners with and without a history of plantar fasciitis [27]. Runners in the control groups had no history of overuse injury [21, 22, 24, 25, 31], no recent injury [23, 26, 30], or were not injured at the time of testing [27–29].

3.1 Quality Assessment

Bias scores for manuscripts included in the systematic review ranged from a 3 (high risk of bias) to 12 (low risk of bias) out of 14 possible points (Table 1). Two studies were rated as having a low risk of bias [19, 20], while 9 studies were rated as having a moderate risk of bias [21–27], and one study was rated as having a high risk of bias [28]. One study was rated as having both a low risk of bias, and

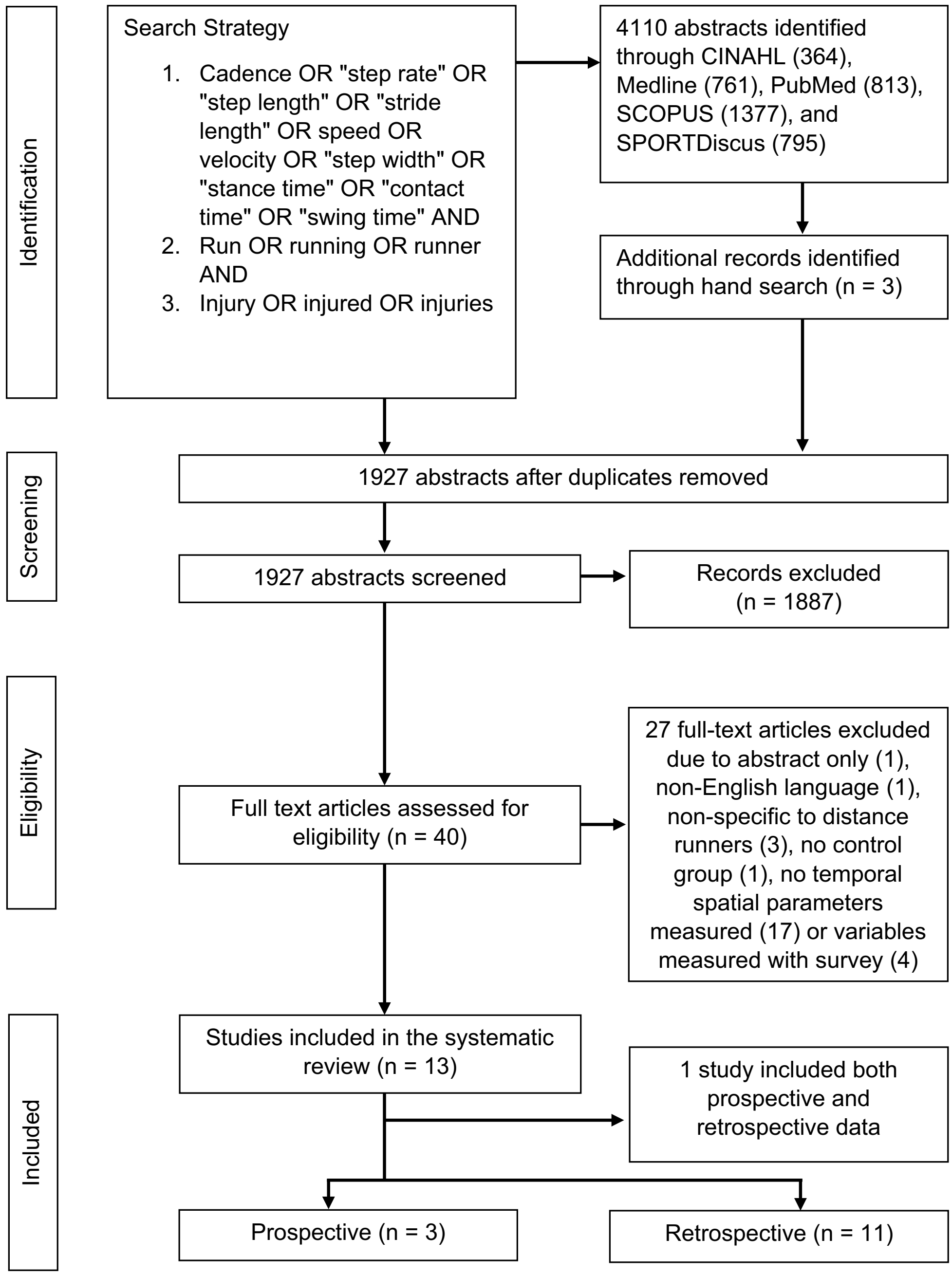

Fig. 1 Flow diagram of the article selection process

a moderate risk of bias in the analysis of prospective and retrospective injury data, respectively [31]. Most of the studies included in the review did not consider different levels of overuse injury severity (item 8), or potential confounding variables such as height and weight (item 14) in their analysis. All the studies in this review included inclusion and exclusion criteria, thus clearly specifying the study population (item 2). However, inclusion and exclusion criteria were not uniformly applied to all study participants in cases where participants in the injured group were currently injured (item 4). Additionally, most studies did not report the participation rate of eligible runners (item 3). Some items on the NIH Quality Assessment Tool delineated between prospective and retrospective studies. For example, loss to follow-up (item 13) was not relevant to non-prospective studies. Additionally, only cross-sectional studies did not measure the exposure of interest and outcomes separately (item 6).

3.2 Meta-analysis

Studies included in this review compared a total of 24 different temporal spatial parameters during running between runners with and without overuse injuries. However, only stride time, contact time, cadence, and stride length were

Table 1 Answers to the National Institutes of Health Quality Assessment Tool

References	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Item 12	Item 13	Item 14
Bredeweg et al. [20]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Bredeweg et al. [19]	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Duffey et al. [21]	Yes	Yes	NR	No	No	No	Yes	No	Yes	No	Yes	No	NA	No
Futrell et al. [28]	Yes	Yes	NR	No	No	No	Yes	No	No	No	No	No	NA	No
Heiderscheit et al. [29]	Yes	Yes	NR	No	Yes	No	Yes	No	Yes	No	Yes	No	NA	No
Hreljac et al. [22]	Yes	Yes	NR	Yes	No	Yes	Yes	No	No	No	No	No	NA	Yes
Luedke et al. [31] prospective	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Luedke et al. [31] retrospective	Yes	Yes	NR	Yes	Yes	Yes	Yes	No	No	No	Yes	No	NA	No
Mann et al. [23]	Yes	Yes	NR	Yes	Yes	Yes	Yes	No	Yes	No	Yes	No	NA	No
Meardon et al. [24]	Yes	Yes	NR	Yes	No	Yes	Yes	No	Yes	No	Yes	No	NA	No
Messier et al. [25]	Yes	Yes	NR	No	No	No	Yes	No	Yes	No	Yes	No	NA	No
Peng et al. [26]	Yes	Yes	NA	Yes	No	Yes	Yes	No	Yes	No	Yes	No	NA	No
Ribeiro et al. [27]	Yes	Yes	NA	No	Yes	No	Yes	Yes	Yes	No	No	No	NA	No
Willson et al. [30]	Yes	Yes	NA	No	Yes	No	Yes	No	Yes	No	Yes	No	NA	No

Item 1: Was the research question or objective in this paper clearly stated?; Item 2: Was the study population clearly specified and defined?; Item 3: Was the participation rate of eligible persons at least 50%?; Item 4: Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study pre-specified and applied uniformly to all participants?; Item 5: Was a sample size justification, power description, or variance and effect estimates provided?; Item 6: For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?; Item 7: Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?; Item 8: For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or exposure measured as continuous variable)?; Item 9: Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?; Item 10: Was the exposure(s) assessed more than once over time?; Item 11: Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?; Item 12: Were the outcome assessors blinded to the exposure status of participants?; Item 13: Was loss to follow-up after baseline 20% or less?; Item 14: Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?

NR not reported, *NA* not applicable

reported from at least three studies of similar prospective or retrospective design. Therefore, only stride time, contact time, cadence, and stride length data from retrospective design studies were entered into the meta-analyses (Table 2). Contact time was the largest meta-analysis, with 12 group comparisons and data from 517 individuals. Stride time and stride length meta-analyses were composed of 8 and 9 group comparisons and data from 224 and 206 individuals, respectively. The meta-analysis for cadence originally included 5 group comparisons and 383 individuals. However, the cadence data from Peng et al. [26] were removed due to inconsistencies between reported cadence, swing time, and stance time. Therefore, the final meta-analysis for cadence included 3 group comparisons and 283 individuals. Meta-analyses of stride time (mean difference: 0.00 s, 95% CI − 0.01 to 0.01 s), contact time (mean difference: 0.00 s, 95% CI 0.00 to 0.01 s), cadence (mean difference: 0.3 steps per minute [spm], 95% CI − 1.8 to 2.4 spm), and stride length (mean difference 0.00 m, 95% CI − 0.05 to 0.05 m) during running revealed no differences between the pooled injured and uninjured groups of runners ($p > 0.05$) (Figs. 2, 3, 4, 5). I^2 statistics indicated low to moderate effects of heterogeneity, warranting no further examination.

4 Discussion

For this systematic review and meta-analysis, we sought to identify the association between temporal spatial parameters during running and overuse injury risk in recreational runners. Temporal spatial parameters during running are of interest because they are easily measured outside of laboratory environments with affordable technology such as wearable devices. However, the link between temporal spatial parameters during running and overuse injury risk is not well understood. Our systematic review included 13 studies that compared 24 specific temporal spatial parameters between runners with and without overuse injuries [19–28, 31]. In most cases, temporal spatial parameters during running were similar between injured and uninjured runners. However, some differences in temporal spatial parameters between injured and uninjured groups of runners were reported, which are detailed in the following paragraphs [20, 24, 29, 31]. While there were not enough data for a prospective meta-analysis, four meta-analyses were completed with data from retrospective designed studies. Retrospective data from 11 studies were pooled and entered into meta-analyses to provide quantitative insight into the association of contact time, stride time, cadence, and stride length during running to overuse injury. Meta-analyses indicated no statistical difference in stride time, contact time, cadence, and stride length during running between runners with and without previous or current overuse injuries.

4.1 Contact Time

Contact time measures the duration of time the foot is in contact with the ground during each stride. Contact times during running were similar between injured and uninjured groups of runners in every study included in the meta-analysis. Thus, contact time during running is not consistently different between runners with or without a history of overuse injury. Prospectively, there were also no differences in contact time for a mixed group of male and female runners who went on to report an injury compared to those who remained uninjured [19, 20]. However, a sub-group analysis indicated that a small group of male runners ($N = 11$) who later encountered a running-related injury to their lower extremity had a shorter contact time than uninjured male runners by 24 ms [20]. While this difference in contact time is small, only 10% of the total contact time, the cumulative effect over a long run may be influential to injury risk. For example, a 24 ms difference in contact time each step could result in approximately 94,680 ms of cumulative contact time difference after running 3 miles. Contact time partially explained lower extremity stiffness during running in a previous study [32]. As contact time during running decreased, lower extremity stiffness increased in healthy male runners [32]. A related variable, knee stiffness, was recently identified as a prospective risk factor for overuse injuries in runners [33]. Maximum knee stiffness during running was greater in runners who were later diagnosed with an overuse injury compared to uninjured runners [33]. It was hypothesized that stride length, running surface, and body weight may contribute to maximum knee stiffness during running [33]. Biomechanical risk factors for overuse injury may differ between male and female runners [34]. While contact time during running differed between injured and uninjured males prospectively, it did not differ between injured and uninjured females [20]. Thus, shorter contact times during running may be more of a prospective risk factor for injury in male runners than in female runners. However, more prospective evidence for the role of contact time during running in overuse injury development is needed. Based on the findings from our meta-analysis of retrospective data, there was no difference in contact time between runners with and without a history of overuse injury.

4.2 Stride Time

Stride time during running was compared between runners with and without a history of overuse injury in four studies [23, 24, 26, 29]. Stride time is a combination of contact time and the time spent in swing phase during the running gait cycle. Thus, stride time and contact time are related. Runners with a history of overuse injury had similar stride times during running compared to control groups [23, 24,

Table 2 Designs of included studies

Reference	Participants	Injury	Footwear	Running velocity	Running surface	Measurement tools	TSP variables
Prospective design studies							
Bredeweg et al. [20]	Controls: 176 (66 male) Injured: 34 (11 male)	Injury to lower extremity or back	Personal	2.2 m/s[a] 2.5 m/s[a,b] 2.8 m/s[M]	Treadmill	Force plate	Cadence, stride length, contact time
Bredeweg et al. [19]	Controls: 176 (66 male) Injured: 34 (11 male)	Injury to lower extremity or back	Personal	2.2 m/s[a] 2.5 m/s[a,b] 2.8 m/s[b]	Treadmill	Force plate	Step length, contact time, and symmetry angle of each (angle formed by the left and right side vectors)
Luedke et al. [31]	Controls: 54 (12 male) PFP: 3 (1 male) Shin injury: 11 (8 male)	Shin injury and PFP	NR	3.0 m/s[c,d] 3.8 m/s[c,d]	Outdoor track	Commercial wearable device	Cadence
Retrospective design studies							
Hreljac et al. [22]	Controls: 20 (12 male) Injured: 20 (12 male)	Injury at or below the knee	Personal	4 m/s[c,d]	Runway	Force plate	Contact time
Luedke et al. [31]	Controls: 29 (8 male) Injured: 39 (13 male)	Non-specific running injury	NR	3.0 m/s[c,d] 3.8 m/s[c,d]	Outdoor track	Commercial wearable device	Cadence
Mann et al. [23]	Controls: 46 (33 male) Injured: 44 (33 male)	Non-specific running injury	NR	3.0 m/s[c,d]	Treadmill	Plantar pressure insole	Cadence, stride length, contact time, flight time, stride time, contact time as a percentage of stride time, and the variability of each
Meardon et al. [24]	Controls: 9 (NR) Injured: 9 (NR)	Non-specific running injury	NR	3.5 m/s[c,d]	Indoor track	Uni-axial accelerometer	Stride time, stride time variability
Peng et al. [26]	Controls: 50 (NR) Injured: 50 (NR)	Non-specific running injury	Personal	3.8 m/s[c,d] 2.9 m/s[d] 2.7 m/s[c]	Treadmill	3D motion capture	Cadence, stride length, step length, contact time, stride time, swing time, step width
Cross-sectional design studies							
Futrell et al. [28]	Controls: 32 (25 male) Injured: 93 (45 male)	Non-specific running injury	Standard[d] Personal[c]	2.6 m/s[c,d]	Treadmill	Force plate	Cadence
Duffey et al. [21]	Controls: 99 (75 male) PFP: 70 (48 male)	PFP	Personal	3.4 m/s[c,d]	Runway	Force plate	Contact time
Heiderscheit et al. [29]	Controls: 8 female PFP: 8 female	PFP	Standard	2.4 m/s[c,d] 2.7 m/s[d] 2.6 m/s[c]	Treadmill	3D motion capture	Stride time, stride length, and variability of each
Messier et al. [25]	Controls: 20 (14 male) PFP: 16 (12 male)	PFP	Personal	3.5 m/s[d] 3.2 m/s[c]	Runway	Force plate	Contact time
Willson et al. [30]	Controls: 13 female PFP: 10 female	PFP	Standard	3.7 m/s[c,d]	Runway	3D motion capture Force plate	Step length, contact time
Ribeiro et al. [27]	Controls: 30 (19 male) Acute PF: 15 (9 male) Chronic PF: 15 (10 male)	PF	Standard	3.3 m/s[c,d]	Runway	Plantar pressure insole	Contact time

NR did not report, *PFP* patellofemoral pain, *PF* plantar fasciitis, *TSP* temporal spatial parameters

[a]Female

[b]Male

[c]Injured

[d]Controls

26, 29]. Additionally, injured and uninjured groups of runners have similar variability in stride time at the beginning of a run [23, 24, 29]. However, another measure of variability, stride time consistency, differed between injured and uninjured runners over a prolonged run [24]. Specifically, injured runners had a lower overall stride time consistency throughout the prolonged run compared to uninjured runners [24]. A lower overall stride time consistency indicates that stride times throughout the prolonged run were more random in the injured group compared to the uninjured group [35]. The lower stride time consistency was suggested to represent altered neuromuscular control in runners with a previous injury [24]. Previous studies have reported either an increased or decreased movement variability during running in injured runners compared to uninjured runners [36, 37]. A degree of variability during running can be expected, but there may be an optimal amount to decrease the risk of overuse injury. However, additional evidence is needed to understand the association of variability in temporal spatial parameters with overuse injury risk. For the temporal spatial parameter of stride time, there was no difference between pooled data from studies which compared runners with a history of overuse injury to healthy runners.

4.3 Cadence

Cadence during running was compared between runners with and without a history of overuse injury in four studies [23, 26, 28, 31]. In all studies, runners with and without a history of injury had a similar cadence during running. In a prospective study, high school cross country runners with a cadence less than 167 spm had greater odds of incurring a shin injury over a competitive season compared to those with a cadence above 173 spm [31]. However, these thresholds may not extend to a broader running population due to the small sample size, as only 11 runners sustained a shin injury in this study. Nevertheless, this study illustrates an alternate method to assess injury risk associated with temporal spatial parameters using thresholds instead of averages. The etiology of overuse injuries in runners is hypothesized to be multifactorial [38]. Therefore, individuals with similar injuries or injury history may exhibit unique biomechanical risk factors during running. As such, analyzing group averages may mask the variation in biomechanical risk factors during running associated with injury development [39]. Assessing injury risk in runners who exceed thresholds of temporal spatial magnitudes may isolate biomechanical risk factors for analysis. Future studies are needed to determine the associated injury risk of temporal spatial parameters during running that exceed thresholds. Our meta-analysis indicates that average cadence is not different between runners with and without a history of injury.

4.4 Stride Length

Stride length during running is the distance covered over a complete gait cycle, from heel strike to the subsequent heel strike of the ipsilateral limb. Stride length during running was similar between injured and uninjured groups of runners in all studies included in this meta-analysis [23, 26, 29]. Thus, stride length during running is not consistently different between runners with or without a history of overuse injury. However, there is limited evidence for an association of increased stride length variability in runners with patellofemoral pain syndrome. Stride length variability during running was similar between runners with and without a history of various lower extremity injuries [23]. However in another study, runners with patellofemoral pain syndrome had greater stride length variability during running at their preferred speed compared to healthy runners [29]. This was hypothesized to be a result of altered muscle strength and activation characteristics during movement associated with patellofemoral pain [29]. However, the same runners exhibited a similar stride length variability during running at a standardized speed regardless of injury status [29]. Thus, additional evidence is needed to elucidate the link between stride length variability during running and overuse injury risk. The findings from our meta-analysis indicate no difference between runners who had a previous injury to healthy controls in stride length during running.

4.5 Clinical Significance

Technological advances in wearable devices have made the collection and storage of temporal spatial parameters during running available to a wide audience of runners. An injured runner's temporal spatial parameters from previous runs may be potentially useful to clinicians for treatment. Our findings suggest that stride time, contact time, cadence, and stride length are not associated with a history of overuse injury in runners. However, more prospective evidence is required to determine if temporal spatial parameters during running are associated with overuse injury development. In cross-sectional studies, alterations of temporal spatial parameters during running, such as step width, stride length, and cadence also altered biomechanical risk factors for overuse injury in healthy runners [12, 13, 40, 41]. Recent efforts to alter biomechanical risk factors for injury through modifying one temporal spatial parameter, cadence, using wearable technology have been successful in the short term. Runners with high instantaneous vertical loading rates were able to decrease loading rates during running through an intervention focused on increasing running cadence [42]. The success of this intervention was driven by feedback from a commercial wearable device worn during the participants' normal running

Study or Subgroup	Injured Mean	Injured SD	Injured Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Fixed, 95% CI
Heiderscheit et al. [29] PS injured limb	0.743	0.03	8	0.728	0.039	8	10.7%	0.02 [-0.02, 0.05]
Heiderscheit et al. [29] PS uninjured limb	0.742	0.03	8	0.727	0.039	8	10.7%	0.02 [-0.02, 0.05]
Heiderscheit et al. [29] SS injured limb	0.736	0.034	8	0.731	0.04	8	9.4%	0.01 [-0.03, 0.04]
Heiderscheit et al. [29] SS uninjured limb	0.736	0.033	8	0.731	0.039	8	9.9%	0.01 [-0.03, 0.04]
Mann et al. [23]	0.732	0.043	44	0.744	0.044	46	38.5%	-0.01 [-0.03, 0.01]
Meardon et al. [24]	0.74	0.04	9	0.7	0.04	9	9.1%	0.04 [0.00, 0.08]
Peng et al. [26] preferred speed	0.71	0.12	50	0.74	0.03	50	10.6%	-0.03 [-0.06, 0.00]
Peng et al. [26] standard speed	0.47	0.3	50	0.55	0.27	50	1.0%	-0.08 [-0.19, 0.03]
Total (95% CI)			**185**			**187**	**100.0%**	**-0.00 [-0.01, 0.01]**

Heterogeneity: Chi² = 12.74, df = 7 (P = 0.08); I² = 45%
Test for overall effect: Z = 0.14 (P = 0.89)

Mean difference IV, Fixed, 95% CI

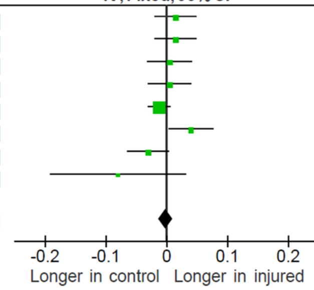

Fig. 2 Forest plot of stride time (s) during running. *SD* standard deviation, *IV* inverse variance, *CI* confidence interval, *PS* preferred speed, *SS* standard speed

Study or Subgroup	Injured Mean	Injured SD	Injured Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Fixed, 95% CI
Duffey et al. [21]	0.258	0.025	99	0.252	0.03	70	29.2%	0.01 [-0.00, 0.01]
Hreljac et al. [22]	0.216	0.021	12	0.22	0.021	12	7.6%	-0.00 [-0.02, 0.01]
Mann et al. [23]	0.276	0.024	44	0.283	0.033	46	15.2%	-0.01 [-0.02, 0.00]
Messier et al. [25] left limb	0.251	0.028	16	0.251	0.031	20	5.8%	0.00 [-0.02, 0.02]
Messier et al. [25] right limb	0.248	0.028	16	0.242	0.022	20	7.6%	0.01 [-0.01, 0.02]
Peng et al. [26] PS left limb	0.29	0.12	50	0.29	0.12	50	1.0%	0.00 [-0.05, 0.05]
Peng et al. [26] PS right limb	0.31	0.1	50	0.31	0.12	50	1.1%	0.00 [-0.04, 0.04]
Peng et al. [26] SS left limb	0.2	0.15	50	0.23	0.14	50	0.7%	-0.03 [-0.09, 0.03]
Peng et al. [26] SS right limb	0.21	0.15	50	0.23	0.15	50	0.6%	-0.02 [-0.08, 0.04]
Ribeiro et al. [27] acute	0.23	0.028	30	0.234	0.021	30	13.7%	-0.00 [-0.02, 0.01]
Ribeiro et al. [27] chronic	0.24	0.025	15	0.234	0.021	30	9.9%	0.01 [-0.01, 0.02]
Willson et al. [30]	0.232	0.02	10	0.229	0.021	13	7.6%	0.00 [-0.01, 0.02]
Total (95% CI)			**442**			**441**	**100.0%**	**0.00 [-0.00, 0.01]**

Heterogeneity: Chi² = 6.47, df = 11 (P = 0.84); I² = 0%
Test for overall effect: Z = 0.33 (P = 0.74)

Mean difference IV, Fixed, 95% CI

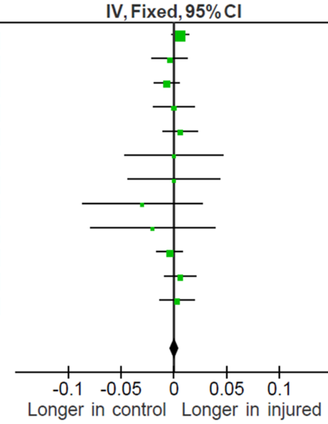

Fig. 3 Forest plot of contact time (s) during running. *SD* standard deviation, *IV* inverse variance, *CI* confidence interval, *PS* preferred speed, *SS* standard speed

Study or Subgroup	Injured Mean	Injured SD	Injured Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Fixed, 95% CI
Futrell et al. [28]	164	9.5	93	165	8.9	32	34.4%	-1.00 [-4.64, 2.64]
Luedke et al. [31]	169.7	6.8	39	169.8	7.6	29	37.3%	-0.10 [-3.59, 3.39]
Mann et al. [23]	164.4	10	44	162	9.4	46	28.3%	2.40 [-1.61, 6.41]
Total (95% CI)			**176**			**107**	**100.0%**	**0.30 [-1.84, 2.43]**

Heterogeneity: Chi² = 1.59, df = 2 (P = 0.45); I² = 0%
Test for overall effect: Z = 0.27 (P = 0.78)

Mean difference IV, Fixed, 95% CI

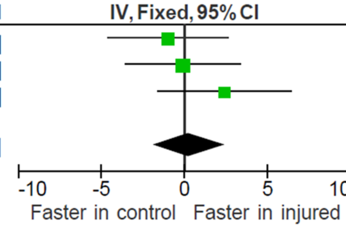

Fig. 4 Forest plot of cadence (steps per minute) during running. *SD* standard deviation, *IV* inverse variance, *CI* confidence interval

routine 'in-field', or outside of the laboratory setting [42]. However, practitioners should exercise caution in introducing feedback from wearable devices in gait retraining interventions as long-term improvements in running mechanics have not been established.

Commercial wearable technology may also be able to alert a runner if they exhibit an injurious gait pattern during running. However, the wearable technology commonly used by runners is limited to measuring temporal spatial parameters. As this meta-analysis indicates, average contact time, stride time, cadence, and stride length during running are similar between injured and uninjured groups of runners. However, there is limited evidence to suggest that injured runners have an increased variability in stride length and lower stride time consistency compared to uninjured runners [24, 29]. However, it is not known whether these differences existed prior to injury. Additionally, limited prospective evidence suggests that

Study or Subgroup	Injured Mean	Injured SD	Injured Total	Control Mean	Control SD	Control Total	Weight	Mean difference IV, Fixed, 95% CI
Heiderscheit et al. [29] PS injured limb	1.92	0.22	8	1.98	0.17	8	7.8%	-0.06 [-0.25, 0.13]
Heiderscheit et al. [29] PS uninjured limb	1.91	0.22	8	1.98	0.17	8	7.8%	-0.07 [-0.26, 0.12]
Heiderscheit et al. [29] SS injured limb	1.98	0.09	8	1.97	0.12	8	26.8%	0.01 [-0.09, 0.11]
Heiderscheit et al. [29] SS uninjured limb	1.98	0.09	8	1.97	0.12	8	26.8%	0.01 [-0.09, 0.11]
Mann et al. [23]	2.205	0.32	44	2.174	0.323	46	16.4%	0.03 [-0.10, 0.16]
Peng et al. [26] PS left limb	1.53	0.52	50	1.47	0.63	50	5.7%	0.06 [-0.17, 0.29]
Peng et al. [26] PS right limb	1.53	0.52	50	1.47	0.62	50	5.8%	0.06 [-0.16, 0.28]
Peng et al. [26] SS left limb	1.6	1.14	50	1.82	1.13	50	1.5%	-0.22 [-0.66, 0.22]
Peng et al. [26] SS right limb	1.59	1.14	50	1.82	1.13	50	1.5%	-0.23 [-0.67, 0.21]
Total (95% CI)			**276**			**278**	**100.0%**	**0.00 [-0.05, 0.05]**

Heterogeneity: Chi² = 3.67, df = 8 (P = 0.89); I² = 0%
Test for overall effect: Z = 0.02 (P = 0.98)

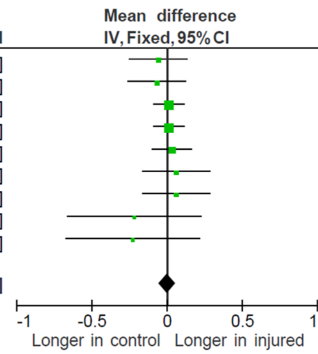

Fig. 5 Forest plot of stride length (m) during running. *SD* standard deviation, *IV* inverse variance, *CI* confidence interval, *PS* preferred speed, *SS* standard speed

a shorter contact time and a slow cadence during running may increase the risk for overuse injury [20, 31].

4.6 Limitations

Due to the small number of studies identified by this systematic review, only retrospective studies were entered into the meta-analysis. By design, retrospective studies are limited as findings cannot be attributed to injury causation. However, prospective findings for average contact time, stride length, and cadence align with some of our findings from retrospective meta-analyses. Specifically, average contact time, stride length, and cadence were similar between male and female runners who experienced an overuse injury compared to those who remained uninjured [20]. This review highlighted specific findings from previous studies that reported significant differences in stride time consistency and stride length variability between injured and uninjured runners. These highlighted findings are limited as there are insufficient data to draw conclusions in a meta-analysis with findings from other studies. Future studies are needed to examine potential differences in temporal spatial variability between injured and uninjured runners.

Another limitation is the variability in methodology of the included studies. There was no consistency among studies in the tools used to measure temporal spatial parameters, or the number of running trials collected. Running speeds were also variable, with some studies collecting temporal spatial parameters at the runners' preferred speed [19–21, 23–26, 28, 29] and others at various standardized speeds which were monitored by either timers [22, 27], marker trajectories [30], pacers [31], or treadmill settings [19, 20, 26, 29]. Factors such as running speed, running experience, body mass, height and leg length have been associated with temporal spatial parameters [16, 43]. Thus, future studies should address these confounding variables in their analysis of temporal spatial parameters during running. There was also variability in the inclusion criteria among studies. Runners were deemed 'injured' only after a certain injury, such as patellofemoral pain syndrome, was professionally diagnosed in some studies [25]. In other studies, runners were deemed 'injured' after reporting at least one previous running-related injury in their lifetime [22, 24]. As such, we are unable to draw specific conclusions regarding the association of temporal spatial parameters to individual injuries. Studies that control for features of overuse injuries, such as type, severity, and time since the injury occurred are warranted to better understand the link between temporal spatial parameters and running-related injuries. Additionally, groups were comprised of a mix of both men and women in some studies, while others only included female runners, or analyzed male and female runners separately. Men and women exhibit differences in lower extremity biomechanics during running [44]. These sex differences may also extend to temporal spatial parameters during running. Future studies should analyze the link between temporal spatial parameters and overuse injury in male and female runners separately. Finally, most studies included in this review had a moderate risk of bias. Future studies should consider reporting the participation rate of eligible persons, providing a power analysis to justify sample size, and blinding raters to participants' injury status to improve internal validity.

5 Conclusion

Current evidence suggests that, on average, runners with either a history of injury or current injury have similar stride time, contact time, cadence, and stride length during running compared to uninjured runners. There were too few prospective studies that examined the association of temporal spatial parameters during running with overuse injury risk to conduct a meta-analysis. Investigations that assess the relationship between temporal spatial parameters during running and overuse injuries are translatable to the clinic and the field. Therefore, future biomechanical studies investigating overuse injuries in runners should incorporate temporal spatial parameters.

Data Availability Statement All data generated or analyzed during this review are included in this published article.

Compliance with Ethical Standards

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Conflict of interest Richard Brindle, Jeffrey Taylor, Coty Rajek, Anika Weisbrod, and Kevin Ford declare that they have no conflicts of interest relevant to the content of this review.

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