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Review

The impact of previous musculoskeletal injury on running gait variability: A systematic review

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ABSTRACT

Background: Growing evidence suggests that identifying movement variability alterations in pathological vs. healthy gait may further understanding of injury mechanisms related to gait biomechanics; however, in the context of running and musculoskeletal injuries the role of movement variability remains unclear.
Research question: What is the impact of a previous musculoskeletal injury on running gait variability?
Methods: Medline, CINAHL, Embase, Cochrane library and SPORTDiscus were searched from inception until February 2022. Eligibility criteria were (a) included a musculoskeletal injury group, (b) compared running biomechanics data to a control group, (c) measured movement variability for at least one dependent variable, (d) provided a statistical between-group comparison of variability outcomes. Exclusion criteria were neurological conditions impacting gait, upper body musculoskeletal injuries and age < 18 years old. A summative synthesis was performed instead of a meta-analysis due to methodological heterogeneity.
Results: Seventeen case-control studies were included. The most common deviations in variability observed among the injured groups were: (1) high and low knee-ankle/foot coupling variability and (2) low trunk-pelvis coupling variability. Significant ($p < 0.05$) between-group differences in movement variability were identified in 8 of 11; 73% of studies of runners with injury-related symptoms, and 3 of 7; 43% of studies of recovered or asymptomatic populations.
Significance: This review identified limited to strong evidence that running variability is altered in adults with a recent history of injury for specific joint couplings only. Individuals with ankle instability or pain employed altered running strategies more often than those who have recovered from injury. Altered variability strategies have been proposed to contribute to future running-related injuries, therefore these findings are relevant to clinicians managing active populations.

1. Introduction

Previous injury in the past 12 month is one of the strongest risk factors for future running-related injuries [1]. Abnormal biomechanical profiles can emerge after sustaining an initial injury [2,3], and this may explain why previous history of injury confers an elevated risk of future injuries, not only to the original site but also to the surrounding structures [4].

Numerous biomechanical studies have identified differences between populations with and without a history of musculoskeletal injury [2,3], however kinematic and kinetic analyses alone has not led to a clear understanding of injury mechanisms in running gait. To gain further insight into this relationship, the subtle biomechanical adjustments that occur in gait are increasingly being examined in the context of movement variability [5], a branch of motor control.

The abundant degrees of freedom available in human movement lead to inherent variations in the performance of a repetitive task, known as movement variability [6]. The subtle variations in running gait patterns

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can be beneficial to runners, as some variability may protect against overuse injury by dispersing mechanical load through musculoskeletal structures and increasing tissue adaptation time [7]. Movement variability can also reflect the health of the neuromuscular system and its capacity to adjust and control gait parameters [8], a critical function for runners that enables them to maximise running economy while also mitigating injury risk.

Runners with a history of musculoskeletal injury often exhibit altered variations in gait biomechanics when compared to injury-free runners [5,9]. As no normative parameters exist for movement variability, excessively high or low variations relative to a control group are considered deviations from 'optimal' motor control. Rather than being beneficial it is posited that altered movement variability strategies that occur following an initial injury are detrimental and contribute to future injuries [4]. Movement variability can be calculated from biomechanical running data (e.g., kinematic, kinetic, spatiotemporal and coordination) using linear, coordinative, or nonlinear tools to quantify variability outcomes. Linear variability measures absolute or relative variability around a reference point (e.g., mean or median), typically using either standard deviation or coefficient of variation [10]. Coordination variability quantifies the absolute or relative variability of two interacting joints or segments [5], and three common tools used to measure pathological gait are vector coding; the variability of angle-angle plots [11], continuous relative phase; the variability of angle-velocity plots [12], and discrete relative phase; the variation of segments or joints at a key time point of interest [13]. Nonlinear variability quantifies the temporal or organisational structure of variations in a system over time. Tools used in nonlinear studies include fractal analysis, Lyapunov exponent and sample entropy [14,15].

Previous studies of running gait variability in relation to overuse injury have often yielded contradictory results. In studies of patellofemoral pain, both high [16] and low movement variability [5] have been identified, despite authors using similar analysis techniques. Variability that is excessively high or low can potentially contribute to future running-related injuries. However, it is unclear why results differ among studies of the same injury type. Due to the contradictory findings, the differential impact of stage of injury (e.g., current injury-related symptoms or recovered) will be considered in this review.

Inconsistent findings in the current literature highlight the distinct need to systematically review and synthesize extant results. Previous review papers have investigated movement variability in relation to aging and falls [17], neurological disorders [18,19], ACL injury [20], or combined running variability results with results of other tasks such as jumping or a cut task [9]. Findings from these review papers have limited applicability to running gait variability in populations who have previously sustained a musculoskeletal injury. No systematic review to date has been conducted to examine the impact of prior injury running gait variability.

The aim of this systematic review was twofold, (1) to identify potentially maladaptive variations in movement variability by identifying any common deviations that occur in injured populations, and (2) to examine the impact of injury stage in relation to running gait variability.

2. Methods

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines [21]. Details for this review were prospectively registered on PROSPERO (42018107022).

2.1. Search strategy

Two reviewers (SJB and SMB) independently evaluated the search strategy and eligibility criteria of the studies. Electronic health database searches were conducted using Medline, CINAHL, Embase, Cochrane library and SPORTDiscus from inception until January 2022. Medline search terms and operators applied in the databases were: (run* OR sprint* OR jog*) AND (biomech* OR kinematic* or kinetic*) AND (variability OR motor control OR coordinat* OR dynamic system* OR chaos theor* OR sequenc*). Keywords were adapted to specific databases and results were limited to human studies and by English language. Articles were imported to Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia) and duplicates removed. Disagreements were resolved via consensus or consultation with a third reviewer (SE). Article references were manually checked to ensure all relevant studies were screened. A full Medline search strategy is presented in Supplementary Item 1.

2.2. Selection criteria

Studies were eligible for inclusion if they (a) included adults > 18 years old with a history of musculoskeletal injury to the lower limb or lumbopelvic region, (b) compared running biomechanics data to an injury-free control group, (c) measured movement variability for at least one dependent variable, and (d) provided a statistical comparison of injury vs. injury-free groups for each outcome variable.

Musculoskeletal injury was defined as an acute or chronic injury episode, that could have affected the locomotor system and led to altered movement variability. Movement variability of gait biomechanics is assessed in three distinct ways: (1) the amount or magnitude of variations (i.e., linear tools) [22], (2) variability of the interaction between joints or segments (i.e., coordination variability) [23], and/or (3) the temporal structure or organisation of their variation over time (i.e., non-linear tools) [24]. An overview of each of these methods is provided in Supplementary Item 3. Each method measures a distinct aspect of movement variability; therefore, we determined it was of value to include studies that used any of the aforementioned variability measures in their methodology. Exclusion criteria were papers that investigated neurological conditions impacting gait, upper body or cervical spine injuries. Single-case control studies, intervention studies, review papers, editorials, book chapters, conference abstracts and studies that were published in a language other than English were also excluded.

2.3. Quality assessment

The quality of included studies was assessed using the Quality Assessment Tool for Observational Cohort and Cross-sectional Studies [25]. Two reviewers (SJB and SMB) independently reviewed studies against each item and if a consensus could not be reached, a third reviewer (SE) independently reviewed the paper.

2.4. Data extraction

The following information was extracted from the articles: participant characteristics, instrumentation and data collection procedures, biomechanical variables assessed during running protocol, movement variability outcomes, and results. Data items were independently extracted and cross-checked for accuracy by two reviewers (SJB and SMB) with a modified Cochrane Collaboration data collection form.

2.5. Data analysis

Probability values ($p < 0.05$) were used to determine whether movement variability differed in those with and without a musculoskeletal injury. Due to the substantial heterogeneity in study populations, experimental protocol and analysis techniques across the studies, it was not appropriate to conduct a meta-analysis. All biomechanical variables and significant between-group differences in movement variability outcomes are presented in Supplementary Item 2.

To identify potentially maladaptive movement variability strategies, a best evidence synthesis was conducted of the biomechanical variables identified across the injury groups. Level of evidence (LOE) categories [26] were defined as follows: (1) strong evidence, if consistent findings among three or more studies, including a minimum of two high-quality studies; (2) moderate evidence, if consistent findings among two or more studies, including at least one high-quality study; (3) limited evidence, if consistent findings from at least one high-quality or two low- or moderate-quality studies; and (4) very limited evidence, if findings consistent from one low- or moderate- quality study.

3. Results

3.1. Search results

The initial search identified 1065 citations after 511 study duplicates were removed. Two researchers independently screened titles and abstracts, and 36 full-text articles were retrieved. Full text screening excluded a further 19 articles. The PRISMA flow diagram (Fig. 1) presents the study selection process. Ultimately 17 eligible studies were identified for inclusion in this review.

3.2. Study characteristics

The included studies were conducted in a variety of countries. These included Brazil [27], Germany [28], Iran [29], Luxembourg [30], and the United States of America [31,11,12,32,33–41]. These studies consisted of retrospective [30], cross-sectional [27,33,34,36,38–40], and case-control [31,11,12,28,29,32,35,37,41], study designs. This review assessed running gait variability after musculoskeletal injury, and the specific injury types identified among included articles were inversion ankle sprain [11,28,32,36,37], patellofemoral pain syndrome [31,29,33,35], iliotibial band (ITB) syndrome [34,38], low back pain [12,27,41], and general running-related injuries [30,39,40].

Variability outcomes were quantified using linear, coordination and nonlinear tools. Linear measures were standard deviation [28,31] and coefficient of variation [30,35,39]. Coordination variability techniques included deviation phase [29,32], vector coding [11,27,33–37], and continuous relative phase [31,12,38,41]. Detrended fluctuation analysis is a measure of nonlinear variability used in two studies [30,39]. Details of study and participant characteristics are provided in Table 1.

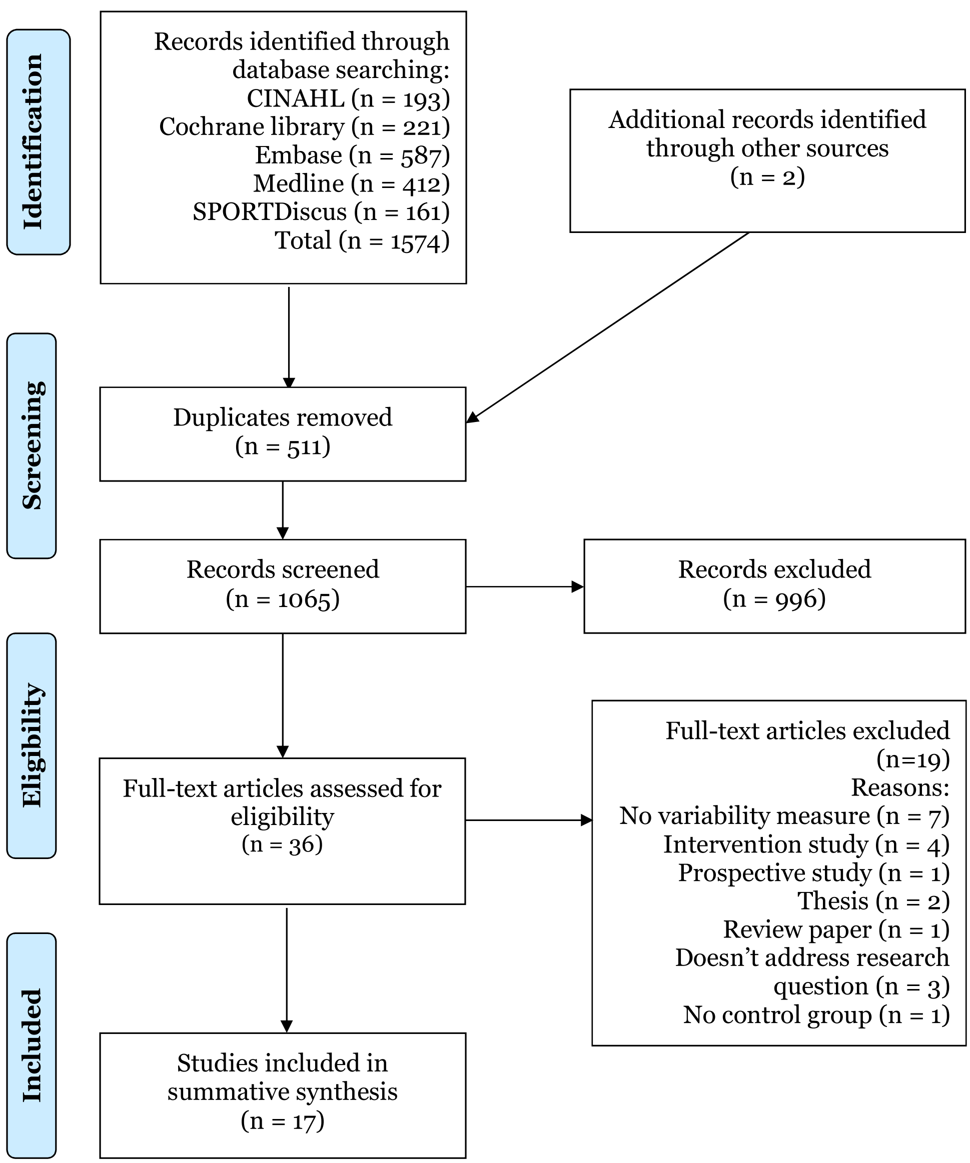

Fig. 1. Preferred reporting items for systematic review and meta-analysis flow diagram representing the article search process.

Table 1
Characteristics for each included study.

Author (Year)	Study Design	Injury Studied	Population	Sample Size	Sex	Injury Group Mean (SD)	Control Group	Running Mode & Data Acquisition	Shoes	Running Protocol (Speed in Km/h)	Biomech Variable Type	Variability Outcome Measure
Drewes (2009)[32]	Case-control	Chronic ankle instability	University students	Injury: 7 Control: 7	Male & Female	Age: 24.6 (4.2) Height: 172.6 (9.4) Weight: 70.9 (8.1)	Matched by sex & age	Treadmill, 3D motion analysis – 120 Hz	Barefoot	Fixed speed 9.7, three to five 15-second trials	Inter-segmental coupling	Deviation phase of standard deviation
Hamacher (2016)[28]	Case-control	Chronic ankle instability	Recreational athletes	Injury: 12 Control: 12	Male & Female	Age: 24.0 (3.0) Height: NR Weight: 69.5 (12.0)	Matched by sex, age, weight & physical activity level	Treadmill, 3D motion analysis –200 Hz	Lab issued shoes	Fixed speed, 10, single one-minute trial & 30 seconds of data acquisition	Joint kinematics	Standard deviation
Herb (2020) [36]	Cross-sectional	Chronic ankle instability	Recreational athletes	Injury: 15 Control: 13	Male & Female	Age: 26.9 (6.8) Height: 171.7 (6.3) Weight: 73.5 (10.7)	Matched by physical activity level	Treadmill, 3D motion analysis – 250 Hz	Lab shoes	Fixed speed 9.7, Three 15-second trials	Joint coupling	Vector coding
Kwon (2020) [37]	Case-control	Chronic ankle instability	General population	Injury: 17 Recovered: 17 Control: 17	Male & Female	Age: 22.3 (2.5) Height: 168.6 (8.7) Weight: 74.8 (11.9) Age: 22.7 (2.4) Height: 171.0 (8.1) Weight: 73.9 (15.0)	Matched by sex	Instrumented treadmill, 3D motion analysis – 120 Hz	Lab issued shoes	Fixed speed 9.6, Single ten second trial	Joint coupling	Vector coding
Lilley (2018) [11]	Case-control	Chronic ankle instability	Recreational athletes	Injury: 13 Control: 14	Male & Female	Age: 23.8 (5.1) Height: 174.0 (11) Weight: 74.9 (15.0)	Matched by physical activity level	Treadmill, 3D motion analysis – 250 Hz	Lab issued shoes	Fixed speed 9.7, Three 15 second trials	Joint coupling	Vector coding
Cunningham (2014)[33]	Cross-sectional	Patellofemoral pain	Recreational runners	Injury: 21 Control: 20	Female	Age: 25.8 (6.1) Height: 163.0 (0.0) Weight: 57.1 (6.5)	Matched by age, height, weight & run mileage	Instrumented treadmill, 3D motion analysis – 300 Hz	Lab issued shoes	Self-selected pace, injury: 10.4 & control: 9.1 for a single15-minute trial	Joint coupling	Vector coding
Haghighat (2021)[29]	Case-control	Patellofemoral pain	General population	Injury: 17 Control: 17	Female	Age: 25.9 (3.9) Height: 163.0 (0.0) Weight: 59.7 (10.8)	Matched by age, height, weight & test leg (left or right)	Treadmill, 3D motion analysis – 200 Hz	Lab issued shoes	Self -selected, injury: 7.6, control: 8.0 & fixed 9.7. Each trial 30 seconds	Inter-segmental coupling	Deviation phase of continuous relative phase
Heiderscheit (2002)[35]	Case-control	Patellofemoral pain	General population	Injury: 8 Control: 8	Female	Age: 24.0 (6.0) Height: 171.0 (0.0)	Matched by sex & age	Treadmill, 3D motion analysis – 240 Hz	Lab issued shoes	Self-selected, injury: 9.3, control: 9.8 & fixed 9.7. Each trial 15 seconds	Joint coupling & spatiotemporal	Vector coding & coefficient of variation

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Table 1 (*continued*)

Author (Year)	Study Design	Injury Studied	Population	Sample Size	Sex	Injury Group Mean (SD)	Control Group	Running Mode & Data Acquisition	Shoes	Running Protocol (Speed in Km/h)	Biomech Variable Type	Variability Outcome Measure
						Weight: 70.1 (11.4)						
Mutchler (2020)[31]	Case-control	Patellofemoral pain	Recreational runners	Injury: 6 Control: 6	Female	Age: 21.0 (0.6) Height: 162.0 (0.0) Weight: 66.1 (7.9)	Matched by age, sex, run mileage & foot strike (rearfoot) pattern	Treadmill, 3D motion analysis – NR	Lab issued shoes	Self-selected, injury: 7.1, control: 7. 7, to knee pain or fatigue	Joint kinematics & inter-segmental coupling	Standard deviation & continuous relative phase
Hafer (2017) [34]	Cross-sectional	ITB syndrome	Recreational runners	Injury or Recovered: 13 Control: 12	Female	Age: 30.2 (7.0) Height: 163.0 (0.1) Weight: 56.2 (7.4)	Matched sex, run mileage, run speed & foot strike (rearfoot) pattern	Treadmill, 3D motion analysis – 8 Hz	Lab issued shoes	Self-selected, Injury: 10.8 & control: 11.9, to fatigue	Inter-segmental coupling	Vector coding
Miller (2008) [38]	Cross-sectional	ITB syndrome	Recreational runners	Recovered: 8 Control: 8	NR	Age: 27.5 (9.0) Height: 170.1 (6.9) Weight: 68.7 (15.9)	Matched by age (± 4 yrs)	Treadmill, 3D motion analysis – 120 Hz	Own running shoes	Self-selected, injury:10.2, control: 12.4 to fatigue	Inter-segmental coupling	Continuous relative phase
Pelegrinelli (2020)[27]	Cross-sectional	Low back pain	Recreational runners	Injury or asymptomatic: 13 Control: 13	Male	Age: 32.5 (6.1) Height: NR Weight: NR	Matched by recent training load & foot strike (rearfoot) pattern	Treadmill, 3D motion analysis – 240 Hz	Own running shoes	Fixed speed 11.9, ten running cycles captured	Inter-segmental coupling	Vector coding
Seay (2014) [41]	Case-control	Low back pain	Recreational runners	Injury: 14 Recovered: 14 Control: 14	NR	Age: 35.7 (10.9) Height: 170.9 (11.5) Weight: 73.9 (13.4) Recovered group Age: 32.6 (9.4) Height: 171.0 (10.3) Weight: 71.4 (9.7)	Matched by age & run mileage	Treadmill, 3D motion analysis – 240 Hz	NR	Fixed speed 2.8–13.9, increased by 1.5 every 30 secondsfor six trials	Intra-segmental coupling	Standard deviation & continuous relative phase
Seay (2011) [12]	Case-control	Low back pain	Recreational runners	Injury: 14 Recovered:14 Control: 14	NR	Age: 35.7 (10.9) Height: 170.9 (11.5) Weight: 73.9 (13.4) Recovered group Age: 32.6 (9.4) Height: 171 (10.3)	Matched by age & run mileage	Treadmill, 3D motion analysis – 240 Hz	NR	Fixed speed 2.8–13.9, increased by 1.5 every 30 seconds for six trials	Inter-segmental coupling	Standard deviation & continuous relative phase

(*continued on next page*)

Table 1 (*continued*)

Author (Year)	Study Design	Injury Studied	Population	Sample Size	Sex	Injury Group Mean (SD)	Control Group	Running Mode & Data Acquisition	Shoes	Running Protocol (Speed in Km/h)	Biomech Variable Type	Variability Outcome Measure
						Weight: 71.4 (9.7)						
Mann (2015) [42]	Retrospective case-control	Running-related injuries	Recreational runners	Recovered: 44 Control: 46	Male & Female	Age: 40.0 (10.0) Height: 176.0 (0.0) Weight: 70.0 (9.0)	Matched by age, running experience & footwear	Treadmill, Runalyser – pressure sensitive insole system	Pressure sensitive insole inserted into own shoes	Self-selected, injury:10.8, control: 10.5, 80–120% two-minute trial acquisition	Spatiotemporal parameters & strike index	Coefficient of variation & detrended fluctuation analysis
Meardon (2011) [39]	Cross-sectional	Running-related injuries	Recreational runners	Recovered: 9 Control: 9	NR	Age: 29.3 (10.3) Height: 170.6 (9.3) Weight: 66.3 (7.8)	Matched by sex & training volume	300-metre overground track, uni-axial accelerometer & BioRecorder – 1000 Hz	NR	Self-selected, injury:12.5, control: 12.6, trial mean 19 ± 3 laps	Spatiotemporal	Coefficient of variation & detrended fluctuation analysis
Paquette (2017) [40]	Cross-sectional	Running-related injuries	Recreational runners	Recovered: 23 Control: 21	Male & Female	Age: 28.0 (7) Height: 172.0 (0.1) Weight: 66.3 (11.4)	Matched by years of running experience & two-year training load	Treadmill, 3D motion analysis – 240 Hz	Usual running shoes	Self-selected 75% maximum, injury: 10.4, control: 11.2, 40-minute trial	Joint kinematics	Standard deviation

ITB, iliotibial band. 3D, three-dimensional. Hz, hertz. KM/ H, kilometres per hour. Age, years. Height, centimetres. Weight, kilograms. NR, not reported.

3.3. *Quality assessment findings*

Study quality was found to be moderate for seven studies (7 of 17; 41%), high for seven studies (7 of 17; 41%) and low for three studies (3 of 17; 18%). Authors reached full consensus on quality assessment items (SJB and SMB). A common potential source of bias was sample size justification (item 5: 3 of 17; 29% of studies), that relates to type 1 error. Other sources of potential bias included poor control and/or reporting of potential confounders (item 14: 8 of 16; 47% of studies), heterogenous study population (item 4: 4 of 17; 23%) and lack of assessor blinding (item 13: 17 of 17; 100% of studies). Table 2 presents the quality assessment findings for each study.

3.4. *Summary of findings*

Between-group differences in movement variability were identified for knee-ankle/foot coupling (LOE: strong) [31,11,33,38] and trunk-pelvis coupling (LOE: limited) [12,29]. No between group differences in shank-rearfoot variability were found in the five studies that investigated this variable (LOE: strong) [32,34,36–38]. Similarly, at least two studies found no differences in either stride time [39,42] or thigh-shank coupling [34,38] variability after injury (LOE: limited). For the remaining variables, results were mixed and level of evidence very limited, as findings were supported by single studies. An overview of variability results for each specific variable can be found in Table 3 and further details of results in Supplementary Item 2.(Table 4).

Of the studies that included participants with injury-related symptoms at the time of testing, including pain and ankle instability [31,11,12,28,29,32,33,35,36,37,41], 8 of 11; 73% reported a significant difference for at least one variable used to examine the movement variability of running biomechanics [31,11,12,28,29,33,35,37]. Of the studies that examined previous musculoskeletal injuries [12,30,37–41], 3 of 7; 43% reported significant differences in running variability relative to a control group [30,37,38].

4. Discussion

The first aim of this systematic review was to identify common deviations in running variability employed by injured populations, using level of evidence groups to categorize findings from each study. Results were generally very limited, as the majority of biomechanical variables used to examine variability were only examined in a single study. Of the variables that were used in two or more studies, results indicate that altered variability is most often employed by injured runners in knee-ankle/foot (LOE: strong) [31,11,33,38] and trunk-pelvis couplings [12,29] (LOE: limited). Conversely, no between-group differences in movement variability were reported for shank-rearfoot coupling (LOE: strong) [32,34,36–38], stride time (LOE: limited) [39,42] or thigh-shank coupling (LOE: limited) [34,38] during running tasks. Overall, results suggest that running variability strategies differ between injured and injury-free populations, but only in particular joint couplings.

Knee-ankle/foot was the most commonly altered joint coupling identified in this review, with both relatively high and low variability employed by injured runners for this variable [31,11,33,38]. Low variability was reported in a study of chronic ankle instability [11] and high variability in studies of ITB syndrome [38] and patellofemoral pain [31,33]. This could suggest that injury type has a differential impact on running variability. For example, knee pain could necessitate the exploration of alternate and potentially less painful movement patterns (i.e., high variability), while the internal constraints of excessive ankle instability could explain a less variable coordination pattern proximally. Alternatively, high or low variability could precede the index injury among injury prone groups [16].

Trunk-pelvis variability was also identified as a potential movement variable of interest in this review. The results suggest that runners with patellofemoral pain or low back pain employ less trunk-pelvis variability

Table 2
Quality assessment judgement for each of the 14 domains of study quality, and the overall quality assessment results.

	Quality assessment items 1–14															
Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	/14	Quality rating
Cunningham (2014)[33]	Y	Y	Y	Y	N	Y	N	N	Y	N	Y	N	NA	Y	8	High
Drewes (2009)[32]	Y	Y	Y	Y	N	Y	N	N	Y	N	Y	N	NA	N	7	Moderate
Hafer (2017)[34]	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	NA	N	9	High
Haghighat (2021)[29]	Y	Y	Y	Y	N	Y	N	N	Y	N	Y	N	NA	Y	8	Moderate
Hamacher (2016)[28]	Y	Y	Y	Y	N	Y	N	N	N	N	Y	N	NA	Y	7	Moderate
Heiderscheit (2002)[35]	Y	Y	Y	N	Y	Y	N	N	Y	N	Y	N	NA	N	6	Low
Herb (2014)[36]	Y	Y	Y	Y	N	Y	N	N	Y	N	Y	N	NA	N	7	Moderate
Kwon (2020)[37]	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	N	NA	Y	7	Moderate
Lilley (2017)[11]	Y	Y	Y	N	N	Y	N	N	Y	N	Y	N	NA	N	6	Low
Mann (2015)[42]	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	N	NA	Y	9	High
Meardon (2011)[39]	Y	Y	Y	N	N	Y	N	N	Y	N	Y	N	NA	N	6	High
Miller (2008)[38]	Y	Y	Y	N	N	Y	N	N	Y	N	Y	N	NA	Y	7	Moderate
Mutchler (2020)[31]	Y	Y	Y	Y	Y	Y	N	N	Y	N	Y	N	NA	Y	9	High
Paquette (2017)[40]	Y	Y	Y	Y	Y	Y	N	Y	Y	N	Y	N	NA	Y	10	High
Pelegrinelli (2020)[27]	Y	Y	Y	Y	N	Y	N	N	Y	N	Y	N	NA	N	7	Moderate
Seay (2014)[41]	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	N	NA	Y	9	High
Seay (2011)[12]	Y	Y	Y	Y	N	Y	N	Y	Y	N	Y	N	NA	Y	9	High

Key: 1. Study objective defined, 2. Study population defined, 3. Study attrition ≥ 50%, 4. Study population homogenous, 5. Same size justified, 6. Exposure measured prior to outcome, 7. Time frame sufficient, 8. Different levels of exposure, 9. Exposure defined & methods reliable, 10. Repeat measurements of exposure, 11. Outcome measure defined, 12. Assessor blinded to outcome, 13. Follow-up rate, 14. Statistical analysis, NA; Not applicable

Table 3
Results of best evidence synthesis for deviations in movement variability for specific biomechanical variables, identified among injury groups.

Biomechanical variable	Significant between-group difference	Level of evidence [26]
Shank–Rearfoot[32,34,36–38]	Nil[32,34,36–38]	Strong
Knee–Foot/Ankle[31,11,33,38]	Low[11] or High[31,33,38]	Strong
Trunk–Pelvis[12,29]	Low[12,29]	Limited
Stride time[39,42]	Nil[39,42]	*Limited*
Thigh–Shank[34,38]	Nil[34,38]	*Limited*
Foot contact angle[40]	Nil[40]	Very limited
Ankle joint angle[28]	High[28]	Very limited
Knee joint angle[31]	Low[31]	Very limited
Knee–Foot/Ankle[35]	Nil[35]	Very limited
Shank–Ankle[37]	Low[37] or High[37]	Very limited
Thigh–Rearfoot[38]	Low[38]	Very limited
Thigh–Shank[35]	Low[35]	Very limited
Hip–Ankle[11]	Low[11]	Very limited
Hip–Knee[31]	High[31]	Very limited
Pelvis–Thigh[29]	Low[29]	Very limited
Pelvis–Thigh[34]	Nil[34]	Very limited
Trunk–Thigh[29]	Low[29]	Very limited
Lumbar-Pelvis[27]	Nil[27]	*Very limited*
Lumbar–Thorax[27]	Nil[27]	Very limited
Trunk–Trunk[40]	Nil[40]	Very limited
Stride length[35]	High[35]	Very limited
Stride duration[35]	Nil[35]	Very limited
Strike index[42]	High[42]	Very limited
Contact time[42]	Nil[42]	Very limited
Flight time[42]	Nil[42]	Very limited
Duty factor[42]	Nil[42]	Very limited
Stride frequency[42]	Nil[42]	Very limited

High/low variability relative to a control group. Nil, no significant difference in movement variability in injured group vs. control group.

than injury-free populations [12,29]. Low trunk-pelvis variability has previously been identified during walking tasks in studies of low back pain [43] and patellofemoral pain [29], suggesting that low trunk-pelvis variability is also present at slower speeds.

Shank-rearfoot coupling variability was not significantly different between groups in four studies of chronic ankle instability [32,34,36,37] and a study ITB syndrome [38]. This suggests that coordination variability between the shank-rearfoot is often similar in adults with and without an injury. Three of the five studies that examined the shank-rearfoot variable identified altered variability for other lower extremity couplings [11,37,38], such as knee-ankle and thigh-shank joints/segments. This could indicate that injury-related alterations in variability tend to occur at more proximal segments during running tasks.

This systematic review is the first to examine common movement strategies in studies of injured populations during running tasks. Due to substantial number of different variables included across the studies, results were mostly very limited. Of the 24 biomechanical variables identified across the studies, only six were used in two or more studies. To strengthen evidence relating to the impact of musculoskeletal injuries on specific variables of interest during running tasks, further studies are needed. The findings from this review can direct future researchers investigating the impact of injury on running variability and the summary of variables aids in addressing the issue of outcome variable heterogeneity in current variability research.

The second aim of this study was to examine the potential differential impact of stage of injury. Between-group differences in running variability (injury group versus control group) were identified in 73% (n = 8 of 11) of studies of populations with current injury symptoms [31,11,12,28,29,33,35,37], and 43% (n = 3 of 7) of those that investigated asymptomatic or recently recovered populations [30,37,38]. This result suggests that altered running variability may arise to compensate for injury-related symptoms such as pain or ankle instability. Findings are consistent with previous studies of current shoulder and low back pain during the performance of functional tasks [44,45].

Injury-related symptoms identified in this review were current anterior or lateral knee pain, low back pain and ankle instability. Results support the notion that injury-related symptoms motivate the neuromuscular system to explore alternative motor strategies to reduce painful input and protect musculoskeletal structures from further injury [46,47]. Altered movement strategies could be of benefit short-term by allowing the continuation of running, but when continued over a longer period it is posited that relatively high/low variability can increase the risk of future injuries [5,16]. This is important as most current injuries in this review are chronic (ongoing > 3 months), therefore maladaptive movement variability strategies have been employed over a prolonged time period. A potential relationship between altered movement variability and future running-related injuries has been previously identified in a prospective study of recreational runners [16], which could mean that altered variability precedes injury in some populations.

Asymptomatic or recovered injuries were only found to impact

Table 4
Results of summative synthesis comparing running gait variability in populations after musculoskeletal injury to control comparators.

Author (year)	Musculoskeletal injury type	Acute or chronic	Injury-related symptoms	Symptoms quantified	Injury-related symptoms at testing	Biomechanical variable type	Variability outcome measure	Difference in run gait variability?	If yes, high or low
Drewes (2009) [32]	Ankle inversion sprain	Chronic	Ankle instability	FADI, < 90%	Yes	Lower limb coupling	Coordination	No	NA
Hamacher (2016)[28]	Ankle inversion sprain	Chronic	Ankle instability	No	Yes	Ankle kinematics	Linear	Yes	High
Herb (2020) [36]	Ankle inversion sprain	Chronic	Ankle instability	FAAM, < 80%	Yes	Lower limb coupling	Coordination	No	NA
Kwon (2020) [37]	Ankle inversion sprain	Chronic	Ankle instability	FAAM, < 90%	Yes	Lower limb coupling	Coordination	Yes	Low
			Recovered	NA	No	Lower limb coupling	Coordination	Yes	Low & high
Lilley (2018) [11]	Ankle inversion sprain	Chronic	Ankle instability	FAAM, < 85%	Yes	Lower limb coupling	Coordination	Yes	Low
Cunningham (2014)[33]	Patellofemoral pain	NR	Anterior knee pain	NPRS, ≥ 3/10	Yes	Lower limb coupling	Coordination	Yes	High
Haghighat (2021)[29]	Patellofemoral pain	Chronic	Anterior knee pain	NPRS, ≥ 3/10	Yes	Lower limb or trunk coupling	Coordination	Yes	Low
Heiderscheit (2002)[35]	Patellofemoral pain	NR	Anterior knee pain	VAS, 1.9/10 & 2.4/10	Yes	Lower limb coupling	Coordination	Yes	Low
						Spatiotemporal	Linear	Yes	High
Mutchler (2020)[31]	Patellofemoral pain	Chronic	Anterior knee pain	VAS, 0.6–4.7/10	Yes	Knee kinematics	Linear	Yes	High
						Lower limb coupling	Coordination	Yes	High
Hafer (2017) [34]	ITB syndrome	NR	Lateral knee pain	NPRS, 0–6/10	Yes & no	Pelvis & lower limb coupling	Coordination	No	NA
Miller (2008) [38]	ITB syndrome	NA	Recovered	NA	No	Lower limb coupling	Coordination	Yes	Low & high
Pelegrinelli (2020)[27]	Low back pain	Chronic	Low back pain	VAS, 0–2.4/10	Yes & no	Trunk & pelvis coupling	Coordination	No	NA
Seay (2014) [41]	Non-specific back pain	Chronic	Low back pain	VAS, 0.8/10	Yes	Trunk & pelvis coupling	Coordination	No	NA
			Recovered	NA	No			No	NA
Seay (2011) [12]	Non-specific back pain	Chronic	Low back pain	VAS, 0.8/10	Yes	Trunk & pelvis coupling	Coordination	Yes	NA
			Recovered	NA	No			No	NA
Mann (2015) [42]	Running-related injury	Both	Recovered	NA	No	Spatiotemporal	Linear	No	NA
				NA		Foot strike index	Nonlinear	Yes	High
Meardon (2011)[39]	Running-related injury	Both	Recovered	NA	No	Spatiotemporal	Nonlinear	No	NA
Paquette (2017)[40]	Running-related injury	Both	Recovered	NA	No	Ankle kinematics	Linear	Yes	High

FAAM, The Foot and Ankle Ability Measure. FADI, The Foot and Ankle Disability Index. ITB, iliotibial band. LBP, low back pain. NA, not applicable. NPRS, numerical pain rating scale. NR, not reported. PFP, patellofemoral pain. VAS, visual analog scale. High or low variability relative to control group. Chronic, injury persists > 3 months. Difference in run gait variability, defined as significant ($p < 0.05$) difference in at least one outcome measure of variability compared to a control group.

running gait variability in a small number of studies [30,37,38]. Significant findings were mainly found in studies of specific lower limb injuries (e.g., patellofemoral pain and ITB syndrome) [37,38], and not studies of recovered low back pain or a general running-related injuries [12,30,38–41]. Of these studies, 43% (3 of 7) investigated running-related injuries [30,39,40]. Heterogeneity among running-related injuries could mask differences between groups, and as such the impact of previous or asymptomatic injuries on running variability could be under-stated in this review.

Though not investigated specifically in this review, it is interesting to note that differences in movement variability were identified between the recovered or asymptomatic and acute injury-related symptoms groups [12,41]. In previous low back pain studies, significant differences in movement variability were found when running data were compared to current low back pain groups, while no findings were reported using the control group as the comparator [12,41]. Taken together with results from this review, this may suggest a continuum of responses exists between acute injury, recovered and injury-free groups. Altered movement variability strategies potentially persist even after the resolution of injury-related symptoms in some injury populations [6,48,49]. Further research is warranted to determine the impact of altered movement variability before, during and after musculoskeletal injuries, including prospective research.

Studies in this review used group-level analysis to explore between group differences in variability. Group-level analyses compare the mean difference in movement variability outcomes (e.g., knee joint angle variability). Though a standard approach in studies of motor control, group-level analyses could potentially overlook the individual nature of variability responses. Analysis of intra-individual (within-person) variability before and after injury may also be important to identify relevant factors that contribute to inefficiencies in the kinetic chain during running gait, and potential clinical implications.

5. Limitations

This review was limited to a summative synthesis due to the substantial heterogeneity in study populations, experimental tasks, and outcome measures used across the studies. Another limitation is the underlying assumption that optimal movement variability parameters are represented by control groups. As no normative parameters currently exist, deviations from 'normal' movement variability strategies in motor control research are defined relative to data from control groups. Given that included studies were either retrospective or cross-sectional in design, it can't be ruled out that participants in the control groups may also deviate from 'optimal' running variability parameters but have not yet developed an injury.

Prospective studies within injury groups of interest are required to establish normative variability values and to establish whether a cause-effect relationship exists between variability and injury. Publication and language bias are also considered limitations of this review.

6. Conclusions

Adults with a current or recent history of musculoskeletal injury often employ different running variability strategies compared to injury-free populations, but only for certain joint couplings. Altered movement variability may contribute to future running-related injuries, therefore these findings are of relevance to clinicians who manage active populations. Further studies are needed to determine whether altered movement variability can identify injury-prone runners prior to sustaining an initial injury.

Conflict of interest

The authors declare that there is no conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.01.018.

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