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REVIEW ARTICLE

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Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review

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Movement variability during repetitive performance of a dynamic activity (eg, running, jumping, kicking) is considered an integral characteristic of optimal movement execution; however, its relationship with musculo-skeletal injury is not known. The primary aim of this study was to review published comparison trials to determine whether movement variability differs between uninjured controls and subjects with a lower limb musculo-skeletal injury. A systematic search of online databases; MEDLINE, Sports Discus, Scopus, and Web of Science was conducted from July to November 2016. Studies were selected if they (a) included participants with a lower limb injury, (b) compared injured participants to uninjured controls, (c) examined movement variability for at least one dependent variable, and (d) provided a statistical between-group comparison when comparing measures of movement variability. Studies were excluded if they (a) investigated neurological disorders, (b) examined musculo-skeletal injury in the upper extremity or spine, and (c) used nonlinear measures to examine variability (ie, complexity). A significant difference between injured and uninjured populations was reported in 73% of the included studies, and of these, 64% reported greater movement variability in the injured group. This is the first systematic review with a best-evidence synthesis investigating the association between movement variability and musculo-skeletal injury. Findings suggest that movement variability in those with a musculo-skeletal injury differs from uninjured individuals. Interestingly, there was an overall trend toward greater movement variability being associated with the injured groups, although it should be noted that this trend was not consistent across all subcategories (eg, injury type). For a clearer insight into the clinical application of variability, greater methodological homogeneity is required and prospective research is recommended.

KEYWORDS
biomechanics, control, coordination, injury

1 | INTRODUCTION

Variability in human movement can be defined as the natural variations in motor control strategies employed when performing multiple repetitions of the same task.[1] This phenomenon was aptly described by Bernstein in 1967 as "repetition without repetition".[2] Traditionally in biomechanical analysis, variability has been treated as an error in movement, where the person attempts to reproduce the same exact movement but cannot, or noise arising from technical or measurement sources.[3-5] However, intra-individual variation in movement patterns between repetitive actions (eg, stride cycle, hop task) is now considered an integral characteristic of any motor task[6] allowing flexible adaptations to stresses placed on the human body.[7] As such it is thought that movement variability has a functional role to play with respect to musculo-skeletal injury.[1,8,9]

Movement variability can be assessed in terms of both the amount of variability and the structure of variability, which functionally represent different aspects of movement variability[10] and can vary independently of one another.[11] To quantify the amount of movement variability, linear statistical tools are utilized (eg, standard deviation, coefficient of variation), whereas to quantify the structure of variability, nonlinear tools are utilized (eg, sample entropy, Lyapunov exponent).[11] While it would be of value to systematically review the literature on both forms of analysis, there are currently far fewer studies on the structure of variability, preventing robust conclusions from being drawn. Therefore, this review solely examines those articles investigating the difference in the amount of movement variability between injured and uninjured populations.

It has been postulated within the framework of dynamic systems theory[12] that reduced variability during movement might lead to repetitive loading on a specific tissue structure resulting in excessive stress and eventual injury.[11] Several authors have provided further support for the association between injury and reduced variability in various injured groups including chronic ankle instability[13] and patellar tendinopathy.[14]

However, in direct contrast it has also been suggested that greater variability is associated with injury.[7,9] In accordance with general motor program theory, variations in movement may represent aberrant neuromuscular motor control[15] resulting in poorly controlled actions which may lead to excessive stress and injury.[9] In support of this theory, numerous studies have found greater variability in a number of different injury groups including athletic groin pain,[16] chronic ankle instability,[17] and iliotibial band syndrome.[18] With such contrasting evidence in the literature, there is a clear need for a systematic review investigating movement variability and its relationship with injury. To date, this has not been conducted.

Both discrete (eg, peak knee moment) and continuous measures (eg, 0%-100% of the knee moment waveform) have been examined when investigating inter-trial variability. Given that analysis of the whole continuous waveform has been shown to be more effective at detecting differences between groups[19,20] it would be useful to explore whether findings on movement variability are also affected by the type (discrete vs continuous) of analysis employed.

The primary aim of this systematic review was to investigate published comparison trials to determine whether the amount of movement variability in dynamic tasks differs between groups with lower limb musculo-skeletal injury and uninjured controls. In light of the diverse range of methods used, the secondary aim of this review was to provide methodological recommendations for future research.

Summary Box

What is already known

- Linear modeling of variability (deviations in motor output around a mean) has long been used in the study of motor skills and often termed as error or noise movement during a task.
- Dynamic systems theory provides a contrasting view that variability may be seen as an individuals' attempt to adapt the performance of a task to the changing array of internal and external constraints acting on the system.
- Many different analysis techniques have been used to measure movement variability and as yet no consensus has been reached as to the most appropriate or sensitive method for a given task.

New findings

- There was an overall trend toward greater movement variability being associated with the injured groups, although it should be noted this trend was not consistent across all subcategories (eg, injury type).
- Specific methodological factors were identified that may help improve the sensitivity to detect between-group differences in movement variability.
- Prospective research needs to be conducted to determine whether alterations in movement variability precede or follow an injury.

2 | METHODOLOGY

2.1 | Protocol and registration

This systematic review was registered (42016039113) with Prospero (Centre for Reviews and Dissemination), University of York, on 13/5/2016. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement was used.[21]

2.2 | Search strategy

A systematic search of the literature was undertaken independently by two authors (SB, SG) between June and September 2016 for clinical trials, case-comparison and cohort studies comparing movement variability between injured populations and uninjured controls. Databases, searched from inception until September, 01 2016, included MEDLINE, Sports Discus, Scopus, and Web of Science. The terms applied in all database searches are presented in Table 1. These were combined using relevant Boolean terms and limits of English language, and human population were placed on searches.

TABLE 1 Search terms

Population	injur* OR musculoskeletal
Outcome	Variability
Variables	Biomech* OR kinetic OR kinematic OR motor control OR coordination OR dynamic systems
NOT	upper* OR spine OR lumbar* OR arm OR back OR heart rate OR animal* OR Cadaver* OR rat* OR monkey OR frog OR robot* OR modelling OR pharma* OR mice OR cat* OR fish* OR DNA OR gene OR RNA

*Broadens a search by finding words that start with the same letters

2.3 | Selection criteria

Three authors (SB, SG, and KM) determined the selection criteria, as listed in Table 2, before commencing the search. This review only addresses measures that assess the amount of variability in movement, determined by linear analysis techniques applied to a time series (eg, standard deviation, coefficient of variation, linear variation, range, and circular variants of these metrics when examining coordination variability). This review does not examine nonlinear analysis techniques (eg, entropy measures and Lyapunov exponent) that investigate the structure of variability throughout a time series.

All studies investigating the amount of movement variability in lower extremity musculo-skeletal injuries were included in this review. Musculo-skeletal injury was defined as any acute or chronic injury episode that would have influenced both the peripheral (tissue damage) and central (spinal cord and brain) movement systems which may have led to altered movement patterns and variability of movement patterns. While it may be argued that patients who have undergone anterior cruciate ligament reconstruction (ACLR) are in fact recovered, we have included this population in this review. This is justified as potentially patho-mechanical movement strategies remain evident in this population 6 or more months following surgery.[22]

The two authors (SB and SG) independently applied the selection criteria when reviewing titles and abstracts and a full review of a manuscript was performed if selection was unclear. Disagreements were resolved by discussion or third-party consultation (KM). Reference lists of selected studies were examined to identify further relevant studies.

2.4 | Data extraction and analysis

Data extraction was performed independently by the authors (SB and SG) using predefined data fields and then cross-checked for accuracy. Data identified for qualitative analysis included type and location of musculo-skeletal injuries, analysis techniques implemented, dependent variables utilized, and physical tasks performed. The principle quantitative measure extracted for this review was the probability value used to identify significant between-group differences within a study. All of the variables examined within this review are listed within Appendix 1 along with the significant findings reported in the related studies. A meta-analysis of the studies was not possible due to the limited reporting of values and data for any one biomechanical measure. A qualitative analysis was therefore implemented to provide a best-evidence synthesis, and where possible, a subgroup analysis between studies was performed.[23-27] Where one study utilized various methodological approaches (e.g. tasks examined included both run and walk conditions, the dependent variables examined included both kinematic and spatiotemporal, or the analysis technique included both continuous point-by-point and discrete-point measures), all components were considered separately for analysis in the results section of this review.

2.5 | Assessment for risk of bias

A modified version of the Downs and Black's checklist[28] as proposed by Trac et al 2016[29] was used to assess study quality (subscales include reporting, external validity, internal validity, selection bias, and power). This version changed the scoring of question 27 from 5 to 2, making 29 the total score of the 27 questions.[29] Studies were appraised independently (SB and SG).

3 | RESULTS

3.1 | Overview of findings

The search method employed in this review identified 1053 studies. After titles and abstracts were reviewed, 69 studies

TABLE 2 Selection criteria for literature search

Inclusion criteria	Exclusion criteria
• Participants with a lower limb musculo-skeletal injury • Compared injured participants to uninjured controls • Examined the amount of movement variability for at least one dependent variable • Utilized linear tools to measure the amount of movement variability • Provided a statistical between-group comparison when comparing linear measures of movement variability	• Investigated neurological disorders • Examined musculo-skeletal injury in the upper extremity or spine • Utilized nonlinear measures to examine variability (i.e, complexity)

were retrieved; duplicates were then removed, leaving 37 studies for a full review. Of these 37 studies, 20 were excluded for the following reasons: (a) investigated variability using nonlinear approaches only (measures of complexity) (n = 7), (b) provided no control group (n = 5), (c) provided no inferential statistical comparison of movement variability (n = 3), (d) did not measure variability (n = 2), (5) were review papers (n = 2), or (e) not relevant (n = 1). This left 17 papers included for review from the database searches. *Pearling* of article bibliographies revealed an additional five studies adhering to the inclusion criteria. A final 22 papers were incorporated in this systematic review, which included the findings from 295 injured subjects and 319 uninjured controls. Figure 1 presents a flow diagram of study inclusion.

Quality appraisal scores using the modified Downs and Black's checklist,[29] presented in full in Appendix 2, ranged from 11 to 14 out of a possible 29 points with a median score of 12. No study received a point on the criterion scoring external validity (questions 11, 12, and 13). Also criterion not fulfilled by any study included questions related to blinding, follow-up of patients' post-intervention, and compliance with the intervention (questions 14, 15, 17 and 19). Discrepancies in scores were based on points attained under the "reporting" and "power" subscales. Eighteen studies[14,16,17,18,30-32,34,36-43,45,46] scored a point for clearly describing included subjects (criterion 3). Four studies[16,18,32,37] scored a point for reporting adverse outcomes resulting from performance of the task (criterion 8). Eighteen studies[14,16,17,18,30-32,34,36-43,45,46] scored a point by reporting actual probability values (criterion 10). Ten studies[16,18,30,33,34,38,39,41,43,45] scored a point for reporting calculation of sample size (criterion 27).

A summary of the main subject and analysis characteristics extracted for each study is presented in Table 3. Overall findings revealed that 73% (n = 16/22) of studies reported a statistically significant difference in at least one dependent variable used to examine movement variability between injured subjects and uninjured controls. Injured subject groups demonstrated greater variability in 64% (n = 14/22) of the studies,[16,17,18,30-32,35-37,42,43,45-47] reduced variability in 27% (n = 6/22),[13,14,18,30,35,47] and no difference between groups was evident in 27% (n = 6/22).[33,34,38-41] Table 4 presents the percentage of studies reporting greater, less, or no difference in variability when comparing injured subjects to uninjured controls.

3.2 | Subject characteristics

3.2.1 | Findings by injury type

A wide variety of different injury types were identified within the studies. Subject groups consisted of either individuals with a single specific injury or various lower limb injuries. In the studies investigating single specific injuries, 88% (n = 14/16) reported significant between-group differences. Of these, greater variability was evident in 75% (n = 12/16),[16,17,18,30-32,35-37,42,43,46] reduced variability in 31% (n = 5/16),[13,14,18,30,35] while 13% (n = 2/16) reported no significant differences between injured and uninjured groups.[33,38] Table 4 presents the breakdown of findings when specific injury types were group together.

Non-specific lower extremity injury types were reported in six studies and included running-related injuries (n = 5)[34,39-41,45] and injury proneness (n = 1).[47] A significant between-group difference was reported in 33% (n = 2/6) of these studies. When the injured group was compared to uninjured controls, greater variability was evident in 33% (n = 2/6),[45,47] reduced variability reported in 17% (n = 1/6),[47] and no difference in 67% (n = 4/6).[34,39-41]

3.2.2 | Findings by region location

Within the various subject groups, injury was spread across three lower limb regions (ankle, knee and hip). Injury at the knee joint was most commonly investigated. This was examined in 46% (n = 10/22) of studies[14,18,32,35,37,38,42,43,45,46] with significant findings evident in 90% of these (n = 9/10). In the injured group, greater variability was evident in 80% (n = 8/10) of the studies,[18,32,35,37,42,43,45,46] reduced variability in 30% (n = 3/10),[14,18,35] and no between-group differences in 10% (n = 1/10).[38]

The ankle was the next most commonly examined injury location with 23% (n = 5/22) of all studies.[13,17,30,33,36] Significant between-group findings were evident in 80% of these (n = 4/5) studies, with greater variability reported in the injured group in 60% (n = 3/5),[17,30,36] reduced variability in 40% (n = 2/5),[13,30] and no difference in 20% (n = 1/5).[33]

Injury at the hip region was examined in only 9% (n = 2/22) of all studies with both of these (100%) (n = 2/2) reporting that injured subjects demonstrated greater variability when compared to controls.[16,31]

Groups consisting of injury across multiple lower limb regions (eg, foot stress fracture, patellofemoral pain and hip pain) were examined in 23% (n = 5/22) of studies, and 80% reported no significant difference in variability between groups.[34,39-41] One study reported mixed findings with the injured group demonstrating increased and reduced variability when compared to uninjured controls.[47]

3.2.3 | Findings in relation to pain

Pain was reported in 27% (n = 6/22) of the studies. Within these studies that reported pain, 83% (n = 5/6) found greater variability was evident in the injured group compared to the uninjured group,[17,31,32,37,43] while one study reported no between-group differences.[38] Two of these studies assessed subjects' pain levels using a visual analogue scale during the

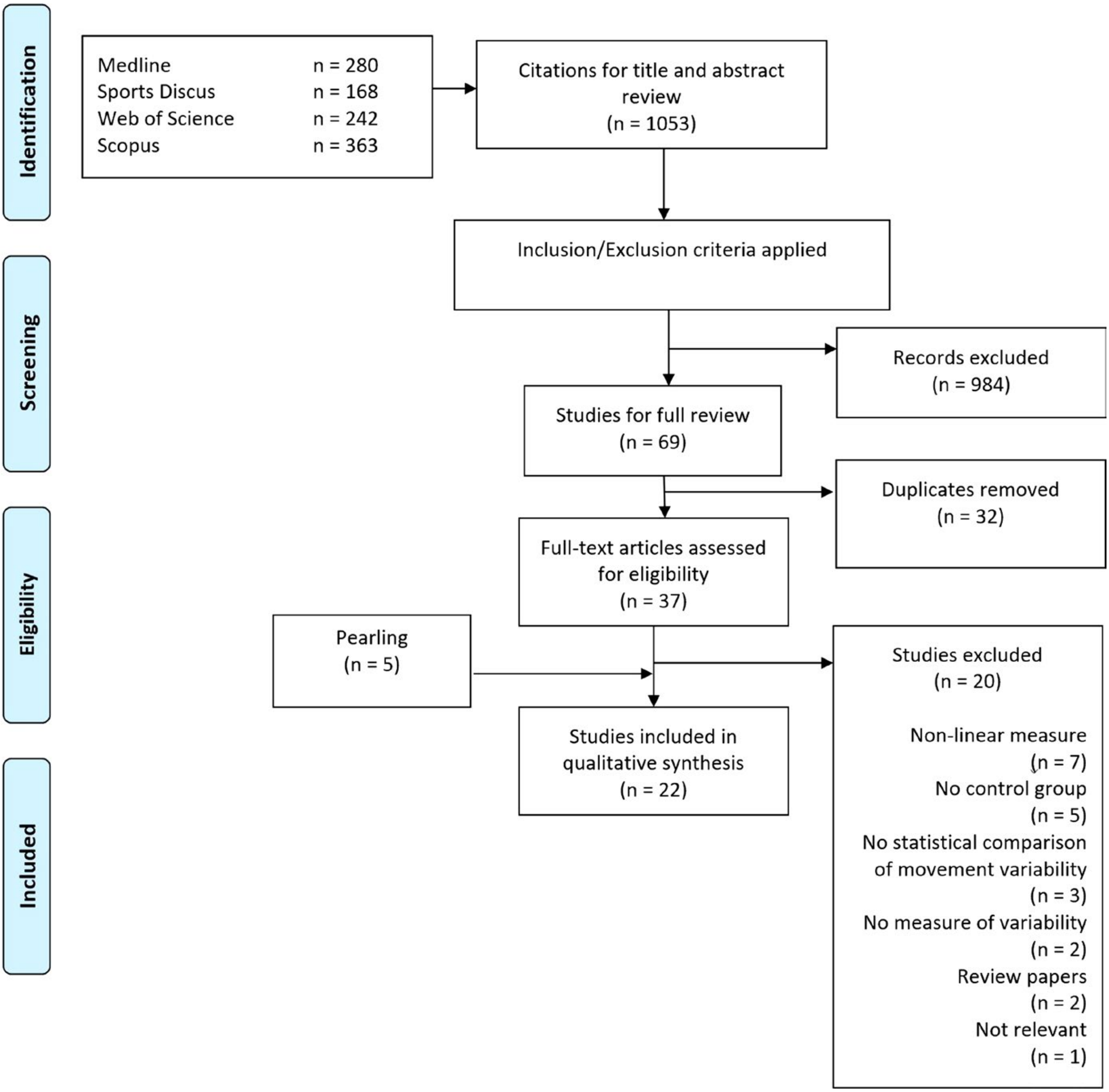

FIGURE 1 PRISMA flow diagram of search strategy

task performed.[32,37] Four studies reported pain, as assessed by orthopedic examination[38] or a subjective questionnaire which included a subscale for pain[17,31,43] but did not assess pain rating/level during the task.

Injured subject groups were reported as pain free at the time of testing in 55% (n = 12/22) of studies.[14,16,18,30,33,34,39-42,45,47] Of these studies, significant findings were reported in 58% (n = 7/12). In the injured groups reporting no pain, greater movement variability in the injured group was evident in 42% (n = 5/12),[18,30,40,45,47] less variability in 33% (n = 4/12),[14,17,30,47] and no between-group difference in 42% (n = 5/12).[33,34,39,40,41]

Four papers did not report on pain levels as part of the selection criteria or during the performance of the task.[13,35,36,46]

3.3 | Findings by analysis type

In the reviewed studies, movement variability was examined in both continuous and discrete measures. Continuous measures refer to analysis of the entire biomechanical waveform (0-100%), while discrete measures refer to individual points on the waveform (eg, peak knee moment, knee angle at peak ground reaction force, time to peak hip angle). It should be noted that in both cases, the analysis could be of a single joint/

TABLE 3 Summary of subject and analysis characteristics

	Subject characteristics						Analysis characteristics				
Author	**Group**	**Injured**	**Uninjured**	**Impaired region**	**Variability analyzed**	**Pain present**	**Task performed**	**Number of trials**	**Additional technique**	**Variability metric**	**Significant Finding**
ACLR											
Van Uden et al. 2003[42]	ACLR	13	7	Knee	Knee- ankle	No	Single leg hopping	10 seconds	CRP	SD	>Knee-Ankle
Cordeiro et al. 2015[43]	ACLR	8	9	Knee	Knee	Yes	Instep soccer kick	3 kicks	-	SD	>Knee
Pollard et al. 2015[46]	ACLR	10	10	Knee	Hip-knee	NR	45° side-step cut	4 cut trials	VC	SD	>Hip-Knee
Gribbin et al. 2016[35]	ACLR	22	15	Knee	Hip-knee	NR	Run/walk	10 strides	VC	VCV	>Hip-Knee <Hip-Knee
Ligamentous											
Kipp and Palmieri-Smith 2012[17]	CAI	11	11	Ankle	Ankle	Yes	Single leg land	5 trials	FPCA	SD	>Ankle
Brown, Bowser, and Simpson 2012[30]	CAI	46	24	Ankle	Trunk, hip, knee, ankle	No	2 leg jump—single leg land (3 directions)	10 trials each condition	-	CV	>Trunk <Hip, Knee
Hamacher, Hollander, and Zech 2016[36]	CAI	12	12	Ankle	Ankle	NR	Run	40 strides	-	SD	>Ankle
Drewes et al. 2009[33]	CAI	7	7	Ankle	Shank, rearfoot	No	Run/walk	21 run strides 14 walk strides	CRP	DP	=
Herb et al. 2014[13]	CAI	13	15	Ankle	Shank, rearfoot	NR	Run/walk	3 strides	VC	VCV	<Ankle
Tendon											
Kulig, Joiner, and Chang 2015[14]	PT	9	9	Knee	Hip, knee, ankle	No	Land (from jump spike)	3 -6 trials	-	CV	<Ankle
Overuse injury											
James, Dufek, and Bates 2000[47]	INJURY Prone	10	10	Lower limb	Hip, knee, ankle	No	Land	10 each condition	-	SD	>Ankle <Ankle
Ferber, Davis, and Williams 2005[34]	RRI	11	11	Lower limb	Tibia-rearfoot	No	Run	5 trials	VC	SD	=

(Continues)

TABLE 3 (Continued)

	Subject characteristics						Analysis characteristics				
Author	Group	Injured	Uninjured	Impaired region	Variability analyzed	Pain present	Task performed	Number of trials	Additional technique	Variability metric	Significant Finding
Mann et al. 2015[39]	RRI	44	46	Lower limb	Spatiotemporal	No	Run	161 strides	-	CV	=
Paquette, Milner, and Melcher 2016[41]	RRI	23	21	Lower limb	Ankle	No	Run	5 foot strikes @ 10 min intervals	-	SD	=
Maclean, Emmerik, and Hamill 2010[45]	RRI	9	9	Knee	Tibia-calcaneus, knee-rearfoot	No	Run	10 seconds In each condition	VC	SD	>Tibia-calcaneus
Meardon, Hamill, and Derrick 2011[40]	RRI	9	9	Lower limb	Temporal	No	Run	661 strides	-	SD, CV	=
Miller et al. 2008[18]	ITBS	8	8	Knee	Thigh-tibia, thigh-foot, tibia-foot, knee-foot	No	Run	10 seconds @ 2 min intervals	CRP	SD	>Knee-Foot <Thigh-Foot, Tibia-Foot
Hein et al. 2012[38]	ITBS	18	18	Knee	Hip-knee, knee-ankle,	Yes	Run	5 stance phases	CRP	SD	=
Heiderscheit, Hamill, and Emmerik 2002[37]	PFPS	8	8	Knee	Thigh-leg, knee-ankle	Yes	Run	15 strides	VC	CV	>Stride length
Cunningham et al. 2014[32]	PFPS	11	19	Knee	Knee-ankle	Yes	Run	5 strides	VC	Mean, SD	>Knee-Ankle
Edwards et al. 2016[16]	AGP	10	7	Hip	Ankle, knee, hip, trunk	No	Side-step cut	10 cut trials	-	CV	>Trunk
Osteoarthritis											
Chiu, Lu, and Chou 2010[31]	THA	20	10	Hip	Hip-knee, knee-ankle	Yes	Walk	10 meters	CRP	SD	>Hip-Knee, Knee-Ankle
		Mean/ Median					Mean/Median				
		15/11	13/10				Strides	85/14			
							Trials	6/5			

ACLR, anterior cruciate ligament reconstruction; CAI, chronic ankle instability; PT, patellar tendinopathy; RRI, running-related injury; ITBS, iliotibial band syndrome; PFP, patellofemoral pain; AGP, athletic groin pain; THA, total hip arthroplasty; NR, not reported; CRP, continuous relative phase; VC, vector coding; VCV, vector coding variability; FPCA, functional principal component analysis; SD, standard deviation; CV, coefficient of variation; DP, deviation phase greater than (>), less than (<) and equal to (=) symbols signify finding of injured subject group as compared to uninjured controls.

segment measure (eg, knee moment) or between two joints/segments (eg, hip-knee relative phase angle). Irrespective of whether a continuous or discrete measure was examined for variability, in line with the inclusion criteria of this review only studies employing linear statistical tools were utilized (eg, standard deviation and coefficient of variation).

Continuous measures were examined for variability in 68% (n = 15/22) of studies.[13,17,18,30-38,42,45,46] Significant findings were reported in 73% (n = 11/15). Greater variability in the injured group was evident in 67% (n = 10/15) of the studies,[17,18,30-32,35,36,42,45,46] reduced variability in 20% (n = 3/15),[13,30,35] and no difference observed between the two groups in 27% (n = 4/15).[33,34,37,38]

Variability was examined in continuous waveforms using various continuous measurement types including vector coding (n = 7),[13,32,34,35,37,45,46] continuous relative phase (n = 5),[18,31,33,38,42] ensemble curves of individual joint/segmental angles at each percent of the task cycle (n = 2),[30,36] and principal component analysis of discrete variables over predetermined continuous time periods (eg, 300 ms) (n = 1).[17] Table 4 presents the breakdown of findings when variability was examined in continuous and discrete measures, and a

TABLE 4 Percentage of studies that showed greater, less, or no variability when comparing injured and uninjured controls[a]

Study category (n)	Greater variability % (n)	Less variability % (n)	No difference in variability % (n)
All studies (22)	64 (14)	27 (6)	27 (6)
Injury type			
Single specific injury types (16)	75 (12)	31 (5)	13 (2)
CAI (5)[13,17,30,33,36]	60 (3)	40 (2)	20 (1)
ACLR (4)[35,42,43,46]	100 (4)	25 (1)	0
PFPS (2)[32,37]	100 (2)	0	0
ITBS (2)[38,18]	50 (1)	50 (1)	50 (1)
AGP[16]	100 (1)	0	0
Hip OA[31]	100 (1)	0	0
Patellar tendinopathy[14]	0	100 (1)	0
Various lower limb injury (6)[34,39-41,45,47]	33 (2)	17 (1)	67 (4)
Injury by region			
Hip (2)[16,31]	100	0	0
Knee (10)[14,18,32,35,37,38,42,43,45,46]	80 (8)	30 (3)	10 (1)
Ankle (5)[13,17,30,33,36]	60 (3)	40 (2)	20 (1)
Pain			
Pain (6)[17,31,32,37,38,43]	83 (5)	0	17 (1)
Pain free (12)[14,16,18,30,33,34,39,40,41,42,45,47]	42 (5)	33 (4)	42 (5)
Analysis types			
Continuous measures (15)[13,17,18,30-38,42,45,46]	67 (10)	20 (3)	27 (4)
Continuous measure types			
Vector coding (7)[13,32,34,35,37,45,46]	57 (4)	29 (2)	29 (2)
Continuous relative phase (5)[31,33,38,18,42]	60 (3)	0	40 (2)
Discrete measures (10)[14,16,17,18,37,39,40,41,43,47]	40 (4)	30 (3)	40 (4)
Task			
Cyclic (15)[13,18,31-42,45]	53 (8)	20 (3)	40 (6)
Non-cyclic (7)[14,16,17,46,30,43,47]	86 (6)	43 (3)	0
Variable			
Kinematic (20)[13,14,16,17,18,30-39,41-43,45,46]	60 (12)	25 (5)	30 (6)
Spatiotemporal (3)[37,39,40]	33 (1)	0	67 (2)
Kinetic (3)[16,17,47]	33 (1)	33 (1)	67 (2)

[a] As some studies report significant findings of both lesser and greater variability or some studies utilized multiple methodological approaches (tasks, dependent variable types, or analysis techniques), the total sum of percentages do not always equal 100% as one study may have been included for results under various subsections. CAI, chronic ankle instability; ACLR, anterior cruciate ligament reconstruction; PFPS, patellofemoral pain syndrome; ITBS, iliotibial band syndrome; AGP, athletic groin pain; OA, osteoarthritis.

further breakdown of the different types of continuous measures employed (eg, vector coding and continuous relative phase).

The second approach used to quantify movement variability involved discrete point analysis, which examined, for example, maximum/minimum metrics to represent the whole waveform. This technique was used in 45% (n = 10/22) of studies,[14,16,17,18,37,39-41,43,47] and significant findings were reported in 60% (n = 6/10) of these studies. Greater variability was evident in 40% (n = 4/10),[16,37,43,47] reduced variability in 30% (n = 3/10),[14,18,47] and no difference reported in 40% (n = 4/10).[17,39-41]

3.4 | Findings by task

There were a wide variety of tasks used to examine movement variability including running, walking, jumping, landing, side-step cutting, and kicking a ball. To enable synthesis of findings, the tasks were categorized into cyclic (end of one movement cycle is beginning of the next) or non-cyclic (distinct beginning and end) movements. Tasks that were cyclic in nature (running, walking or continuous single leg hopping) were utilized in 68% (n = 15/22) of studies.[13,18,31-42,45] Significant differences between the injured and uninjured groups were reported in 53% (n = 9/15) of these studies. In the injured group, greater variability was evident in 53% (n = 8/15),[18,31,32,35-37,42,45] reduced variability in 20% (n = 3/15),[13,18,35] and no between-group difference reported in 40% (n = 6/15).[33,34,38-41] Movement variability was examined during a run condition in 87% (n = 13/15) of these studies with 46% (n = 6/13) reporting greater variability in the injured group when compared to controls,[18,32,35-37,45] while 8% (n = 1/13) reported reduced variability,[18] and 54% (n = 7/13) found no difference between groups.[13,33,34,38-41] Running was performed on a treadmill in 77% (n = 10/13) of the studies,[13,18,32,33,35-37,39,41,45] a runway in 15% (n = 2/13),[34,38] and a 300-meter indoor track in 8% (n = 1/13).[40] Run conditions were either set at a fixed (n = 7)[13,33,35-38,45] or self-selected speed (n = 7).[18,32,34,37,39-41] The average fixed speed was 10.4 km/h, and the average self-selected speed for injured and uninjured control groups was 11.3 km/h. The length of the run condition ranged from 15-second trials to exhaustive 40-min runs**.**

Non-cyclic tasks were utilized in 36% (n = 7/22) of studies. A variety of different tasks were employed including a land (n = 4/7),[17,14,30,47] side-step cut (n = 2),[16,46] and a soccer instep kick (n = 1).[43] Significant differences in movement variability between injured groups and uninjured controls were identified in 100% (n = 7/7) of these studies. Greater variability was evident in the injured group in 86% (n = 6/7)[16,17,30,43,46,47] and reduced variability in 43% (n = 3/7).[14,30,47]

3.5 | Findings by variables

Three types of dependent variable were utilized to examine movement variability between injured and uninjured subjects: kinematic, spatiotemporal, and kinetic. Kinematic variables were examined in 91% (n = 20/22) of studies[13,14,16,18,30-39,41-43,45,46] and 70% (14/20) of these reported significant findings. Greater variability was evident in the injured group in 60% (n = 12/20) of these studies,[16,18,30-32,35,36,42,43,45,46] reduced variability in 25% (n = 5/20),[13,14,18,30,35] and no between-group differences in 30% (n = 6/20).[33,34,37-39,41]

Spatiotemporal variables (eg, foot contact time, stride time, stride length, stride frequency, and flight time) were used to examine movement variability in 14% (n = 3/22) of the studies. Greater variability in the injured group was reported in 33% of the studies (n = 1/3)[37] and no between-group difference in 67% (n = 2/3).[39,40]

Kinetic variables (eg, ground reaction forces, impulses, and joint moments) were examined in 14% (n = 3/22) of studies. One study report both significantly increased and decreased measures of variability in the injured group when compared to controls,[47] while no significant between-group difference was evident in 67% (n = 2/3).[16,17]

4 | DISCUSSION

To date, this is the first systematic review to investigate whether there is a difference in movement variability between populations with a lower limb musculo-skeletal injury compared with uninjured controls. The overall findings suggest that injured populations tend to deviate from "normal" ranges of movement variability (as quantified in the uninjured control groups); 73% of studies reported significant between-group differences in at least one measure of variability assessed, when comparing injured subject groups to uninjured controls.[13,14,16,18,30-32,35-37,42,43,45-47] The application of dynamic systems theory to help understand injury and movement variability has led to the hypothesis that an optimum range of variability exists for human movement, outside of which is associated with increased risk of injury.[7,9] The focus in much of the literature has been that reduced variability has a greater association with injury.[12,54] However, in direct contrast to this hypothesis the findings from this systematic review found a trend toward increased variability in injured groups, as 64% of studies reporting significant between group differences reported greater variability in the injured group when compared to the uninjured controls.[16,18,30-32,35-37,42,43,45-47] This was compared to 27% that reported less variability in the injured group. The varied findings from this review may be explained by the "optimal" theory proposed by Hamill et al,[9] where either too little or too much movement variability may be related to increased risk of injury. This however should not be confused with the inverted U theory presented by Stergiou et al,[7] which examines the temporal structure of movement signals. The theory proposed by Hamill et al[9] presents the relationship between motor performance and variability as a "U"-shaped association where either too little or too much is thought to have a detrimental impact on performance and may be associated with pathological populations. However, it is worth noting that to date, no research has presented both significantly higher variability and lower variability in the injured group in comparison with the control group within the same variable.

There are a number of potential reasons why greater movement variability was identified in the injured groups. Firstly, as a causative risk factor for injury, it is possible that greater variability reflects a decrease in neuromuscular control leading to poorly controlled movement.[15] This in turn may result in tissues (muscle, tendon, cartilage, and bone) being subjected to unaccustomed strain and load, which if sustained overtime, or occurs at extremes in either force applied or the associated motion, may lead to injury.[7,9] If greater movement variability does represent a risk factor for injury, then exercise interventions should focus on improving neuromuscular control. However, the retrospective design of the studies in the present review does not allow this causative relationship between altered movement variability and injury to be concluded.

Secondly, with injury pain provides an organismic influence, and the greater movement variability evident in injured populations may reflect an unstable compensatory movement mechanism being utilized to reduce loading on the sensitized and painful tissues.[51,53,55] Pain causes changes in the body at both central (spinal cord and brain)[50,51] and peripheral levels (activation within and between muscles)[51] altering movement variability[11,56] and proprioceptive control of movement.[53] This view is in line with dynamic systems theory, which suggests that movement patterns spontaneously arise through processes of self-organization as a result of several factors (eg, task, environment, and organismic) acting on the individual.[52,54] While such a change in movement mechanics may achieve a short-term goal of protection from further pain and or injury, this may not be ideal as a long-term movement solution[51]; therefore, interventions would have to aim at decreasing variability to "normal" levels seen in uninjured populations.

A third explanation is that once the tissue damage resulting from an injury has healed and the pain has resolved, variability may represent the exploration of movement solutions by the neuromuscular system to re-optimize movement in the presence of altered neuromuscular capacity (eg, reduced muscular strength) and/or in the presence of pain-induced changes to the body schema (the brain's representation of the body).[57] In fact, it has been previously observed that pain-induced compensatory movement adaptations may even persist with recovery and the resolution of pain.[53,58] If this latter explanation is the case, then rehabilitation interventions should not aim to decrease movement variability, as indicated above, as it potentially represents the natural recovery process. To determine whether variability should be targeted in rehabilitation, there is a clear need for intervention studies investigating the efficacy of increased/decreased variability-targeted rehabilitation. Furthermore, prospective research is required to conclusively determine the relationship between variability and injury.

Throughout this review, several studies produced contrasting findings for the same injury. For example greater,[36] less variability[13] and no difference in variability[33] were identified at the ankle joint when examining chronic ankle instability. It is hard to identify exactly why these inconsistencies are evident; however, it may be a reflection of the various muscular and mechanical adaptations that occur in response to injury and pain,[51] the different tasks examined (eg, jump land, running, walking) and/or different measurement types utilized (eg, continuous relative phase and vector coding). In fact even within individual studies when examining the same group for the same task, two authors identified both greater variability and less variability when examined at multiple joints/segments.[18,30] While it is unclear why both less and greater variability can be observed in populations with the same injury type it may be a reflection of the muscular and mechanical adaptations that occur in response to injury and pain.[51] Collectively, these findings may indicate that the current application of dynamic systems theory to injuries requires revision.

4.1 | Subject characteristics

Examining movement variability in a single specific injury group (eg, chronic ankle instability) or injury at a specific region (eg, hip, knee, and ankle) appeared to be more sensitive in detecting an influence on variability than if examined in a non-specified group (eg, general lower extremity running-related injury comprising multiple injury types and/or across multiple injury regions). Where 75% of studies examining a single specific injury identified significant between-group differences, only 33% using a non-specific injury group reported significant findings. Similarly, 89% of the studies that examined one injury location found a significant difference in variability between groups compared to just 20% of the studies that examined a subject population consisting of several injury locations.

This is perhaps not surprising as examining a heterogeneous group may mask findings between individuals within that group.[20] For example, Ferber et al[34] included subjects with a variety of running-related injuries, including patellofemoral pain syndrome, and reported no significant between-group difference, while Heiderscheit et al[37] and Cunningham et al[32] included only subjects with patellofemoral pain syndrome and both studies reported significant between-group differences.

4.2 | Analysis type

Findings from this review possibly favor examining variability in continuous measures, with 73% of studies examining a continuous waveform reporting significant differences between injured subjects and uninjured controls. This is in comparison with 60% of the studies examining discrete point data. In accordance with this finding, Kipp & Palmieri-Smith[17] examined variability in both discrete and continuous measures and found that differences in variability between injured and uninjured groups were only detectable in continuous measures. Variability was examined in a number of continuous data analysis techniques within this review; these included the variation in continuous relative phase, vector coding, and principle component analysis. With the variety of approaches utilized, no trend was identified regarding their sensitivity. Further, no study within this review directly compared different continuous analysis techniques.

4.3 | Task

When tasks were categorized into cyclic or non-cyclic movements, the non-cyclic tasks appeared more sensitive at detecting differences in variability between injured and uninjured groups. All studies examining non-cyclic tasks reported significant between-group differences. In comparison, only half of those that examined cyclic tasks reported significant between-group differences. There are possibly three explanations for this finding. Firstly, this may simply represent a methodological/statistical phenomenon, in which the methods utilized are more suitable at detecting differences during non-cyclic tasks in comparison with cyclic tasks. Secondly, the greater detection of variability in non-cyclic tasks may be related, at least in part, to cyclic tasks, such as walking or running, being practiced more often.[1] As such, at the time of testing subjects may have already explored alternative movement strategies for these cyclic tasks and have adopted a less variable movement solution. In contrast, non-cyclic tasks such as landings and cutting maneuverers are generally less practiced. This may result in alternative movement strategies still being explored at the time of testing resulting in greater variability.[59] Finally, non-cyclic tasks (eg, landing and change in direction) typically demonstrate greater ground reaction forces and loading than cyclic tasks (eg, running and hopping). The greater detection of variability in non-cyclic tasks may therefore be reflective of greater compensation being utilized in comparison with cyclic tasks to offload the injured tissues.

It is worth noting, but probably unrelated to the previous point, that the median number of strides examined for cyclic tasks was 14 and the median number of trials for non-cyclic tasks was 5 with an interquartile range of 25.50 and 6.25, respectively. Within this review, no study provided justification for the number of trials examined. Previous research examined the number of trials required to reliably examine movement variability during walking[49,60] and running[49] identifying that up to 20 trials are required for walking and 8 trials are required for running, similar to the median number of trials examined by studies in this review. However, caution should be applied here in adopting the findings of Sangeux et al[60] and Hafer and Boyer[49] as the number of trials required has been shown to be task dependent,[49] and is likely specific to the population being examined, and these studies were examined in healthy participants. Future research should therefore look to investigate the number of trials needed to reliably examine movement variability during specific tasks and in specific populations. This should ideally be conducted not with just statistical reliability, as in Sangeux et al[60] and Hafer and Boyer,[49] whereby the number of trials was determined based on the magnitude of variability staying within a given range (eg, within 10% of a 15-stride mean or 10% relative precision) as the number of trials is increased. Rather the number of trials required should be determined with regard to how many trials are required to detect differences with an appropriately high effect-size in the amount of variability between subjects of interest (eg, in injured subjects with chronic ankle instability vs uninjured controls).

4.4 | Variables

Within the reviewed studies, kinematic, kinetic, and spatiotemporal measures were all utilized as dependent measures to compare movement variability between injured subjects and uninjured controls. Kinematic measures were the most commonly examined in 91% of studies and 70% of these reported a significant between-group difference. In comparison, spatiotemporal and kinetic measures were each only examined in 14% of studies and 33% of these studies identified a significant difference between the two groups. When studies compared both kinetic and kinematic variables significant between-group differences were only evident in kinematic variables.[16,17] These findings at present would suggest that kinematic variability might be the most sensitive to differences between groups. This was somewhat surprising as kinetic measures reflect more closely the forces associated with injuries. This is difficult to explain as there is generally greater intrasubject variability in kinetic measures.[48] Previous research has demonstrated that kinetic measures also have proportionally higher between-subject variability[48] which inhibits the ability to detect difference between groups. However, to date no research has examined the variability in kinetic variability measurements so it remains uncertain why kinematic variability might be the most sensitive to differences between groups.

These findings have numerous methodological implications. Firstly, when examining movement variability, it may be more appropriate for researchers to investigate a single specific injury type thus avoiding any possible masking of findings. Secondly, continuous analysis of data may be more sensitive than discrete-point analysis in detecting significant between-group differences. Finally, kinematic movement variability measured during non-cyclic tasks appeared to be most consistent in detecting significant between-group differences.

4.5 | Limitations of review

Given the large heterogeneity in study methodologies and metrics examined, this review was limited to a qualitative analysis of the literature. The qualitative approach adopted here results in papers being categorized as either finding greater variability or less variability if any *one* measure, of all the measures assessed, has greater or less variability, respectively. In contrast, for a paper to be categorized as having no effect on variability, *none* of the measures assessed must differ between the injured and uninjured controls. This introduces a bias in the reporting process that needs to be considered when interpreting the findings. For full report of findings, please see Appendix 1.

Another limitation to this review is the underlying assumption that a "normal" magnitude of variability exists and is associated with healthy individuals. As with all cross-comparison studies, it may be that the "healthy" subjects also have an abnormal level of variability but have not been exposed to the volume or intensity required to develop an injury.

Secondary to the above point, it is not possible to state an overall "normal" range of variability within this qualitative review because of the wide variety of tasks, injury groups, and analysis methods employed.

Finally, this review also only included linear magnitude-based representations of variability and excluded research investigating nonlinear measures of variability (eg, entropy and Lyapunov exponent). Future systematic reviews should be conducted investigating the latter with respect to lower limb injury once a sufficient number of studies have been conducted in this area.

4.6 | Limitations of studies

Limitations of the studies reviewed include poor control and/or reporting of possible confounding factors (including fatigue, gender, pain, and running speed), biased examination of multiple comparisons without controlling for family wise errors, and a lack of justification for the number of trials analyzed when examining between trial variability. The later point is of importance as it is currently unknown how many trials are required to obtain reliable and meaningful measures. Other limitations include the use of the coefficient of variation metric in several studies[14,30,37,39,40] which may result in findings of variability that are artificially inflated when the variables examined are of a small magnitude. Also the plethora of measurements types utilized within this review impedes the cross-comparison and synthesis of findings between studies. A consensus should be reached for the standardization of analysis types. Finally, the lack of large normative databases currently limits the utility of variability as a clinical measure. To encourage the adoption of best research practice, and allow the use of variability as a clinical measure, open-access databases should be encouraged. This would not only enhance the transparency of research but also allow the investigation and direct comparison of these different methodologies.

4.7 | Perspective

The overall findings from this review suggest that deviation from normal ranges of movement variability may be associated with injury. Interestingly, a trend was identified with injured populations exhibiting greater movement variability when compared to uninjured controls. This trend was particularly evident in injured population groups reporting pain and ligamentous injury and as such future research should explore the association between pain and variability and sensorimotor control and variability. There is a clear need to repeat many of the studies within this review, using appropriate methodologies, to determine whether there is a consistency in the findings of variability between those with and without injury. In order to enhance the sensitivity to detect between-group differences in variability, future research should consider examining variability using a subject group with a clearly defined injury type and/or injury location. Furthermore, it would appear advantageous to examine non-cyclic tasks utilizing continuous waveform methods of analysis, with a focus on kinematic measures. Finally, prospective research needs to be conducted to determine whether alterations in movement variability precede or follow an injury.

CONFLICT OF INTEREST

Samuel Baida, Shane Gore, Andrew Franklyn-Miller, and Kieran Moran declare they have no conflict of interest relevant to the content of this review.

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APPENDIX 1

Variables measured and significant findings

Author	Variables examined	Significant finding
Van Uden et al. (2003)[48] ACLR	Knee and ankle sagittal plane angular displacements	> operated limb, sagittal plane, ankle-knee coupling ($P = .001$)
Cordeiro et al. (2015)[43] ACLR	Knee sagittal plane kinematics: ROM, angular velocity, angular acceleration, angular position at maximum velocity. Temporal: duration time to peak velocity and to peak acceleration, time of max angular velocity, duration time to contact.	> operated limb, maximum extension angle ($P < .012$) > peak velocity ($P > .033$)
Pollard et al. (2015)[46] ACLR	Intralimb coupling angles; hip rotation-knee abd/add, hip flex/ext-knee abd/add, hip rotation-ankle IN/EV, knee abd/add-knee flex/ext, knee abd/add-ankle IN/EV, knee abd/add-knee rotation, knee flex/ext-knee rotation.	> hip rotation-knee abd-add ($P = .04$) > hip flex/ext-knee abd-add ($P = .05$) > knee abd/add-knee flex/ext ($P < .01$) > knee abd/add-knee rotn ($P = .03$)
Gribbin et al. (2016)[35] ACLR	Intralimb joint couples; hip frontal-knee frontal, hip frontal-knee sagittal, hip frontal-knee transverse, hip sagittal-knee frontal, hip sagittal-knee transverse, hip transverse-knee frontal	WALK > hip frontal-knee frontal 24%-32% gait cycle (midstance) (cohen's d 11.7) > hip frontal-knee frontal 49%-53% gait cycle (late stance) (cohen's d 4.5) > hip frontal-knee transverse 51%-58% gait cycle (late stance) (cohen's d 7.3) > hip sagittal-knee transverse 53%-55% gait cycle (late stance) (cohen's d 7.69) > hip sagittal-knee transverse 67%-69% gait cycle (swing) (cohen's d 35.85) > hip transverse-knee frontal 27%-29% gait cycle (midstance) (cohen's d 14.9) > hip transverse-knee frontal 45%-47% gait cycle (late stance) (cohen's d 12.0) < hip sagittal-knee frontal 25%-31% gait cycle (midstance) (cohen's d -2.3) < hip sagittal-knee transverse 25%-30% gait cycle (midstance) (cohen's d -2.69) RUN > hip sagittal-knee transverse swing (not reported)
Kipp and Palmieri-Smith (2012)[17] CAI	Ankle sagittal and frontal plane; touchdown, maximum, minimum angle. Ankle sagittal and frontal peak moment. Sagittal and frontal principal components kinematic and kinetic time series data	= touchdown angle, max/min angle sagittal/frontal plane = peak moments, kinetic PC scores > kinematic sagittal PC 3 (100 ms pretouchdown) > kinematic frontal PC 1 (through entire 300 ms)
Brown, Bowser, and Simpson (2012)[30] CAI	3D kinematics ankle, knee, hip, trunk	PRE-INITIAL > (FAI) trunk LF ($P = .006$) < (FAI) knee IR/ER ($P = .007$) < (coper) knee IR/ER ($P = .001$) < (MAI) hip flex ($P = .006$) < (FAI) hip flex ($P = .001$) < (coper) ($P = .006$) < coper anterior ($P = .007$) STANCE < FAI knee IR/ER ($P = .003$) < MAI hip flex ($P = .003$) < FAI hip flex ($P < .001$) < Coper hip flex ($P = .001$) < MAI hip abd/add ($P = .003$) <FAI lateral ($P = .003$) < MAI anterior ($P = .006$) < FAI anterior ($P = .005$)

(Continues)

APPENDIX 1 (Continued)

Author	Variables examined	Significant finding
Hamacher, Hollander, and Zech (2016)[36] CAI	Ankle sagittal and frontal plane angles	> injured ankle frontal plane 11%-24% stance ($P < .001$) > injured ankle frontal plane 77%-83% swing ($P = .005$) > injured ankle frontal plane 92%-97% swing ($P = .007$) > unaffected ankle frontal plane 66%-69% swing ($P = .023$)
Drewes et al. (2009)[33] CAI	Rear-foot inversion-eversion, shank rotation. Coupling shank rotation rear-foot inversion-eversion	= No significant differences in DP measures between groups during walking or jogging ($P > .05$)
Herb et al. (2014)[13] CAI	Joint coupling rear-foot and shank	WALK < injured ankle rear-foot-shank late stance, toe off, early swing (not reported)
Kulig, Joiner, and Chang (2015)[14] Patellar tendon	Lower extremity contact angle, sagittal plane hip, knee and ankle	< injured limb ankle DF initial contact ($P = .01$)
James, Dufek, and Bates (2000)[47] Injury prone	Hip, knee, ankle; peak joint moments, time to peak moment values, impact impulse	> injured limb 100% jump height peak AJM ($P < .05$) < injured limb 50% jump height time to peak AJM ($P < .05$)
Ferber, Davis, and Williams (2005)[34] RRI	Intralimb couple; rear-foot eversion/inversion - tibial internal/external rotation	= No significant differences in variability in joint coupling between groups
Mann et al. (2015)[39] RRI	Strike Index, contact time, stride time, flight time, duty factor, stride length, stride frequency	= No significant differences in variability found between groups
Paquette, Milner, and Melcher (2016)[41] RRI	Sagittal plane foot contact ankle	= No significant differences in variability of sagittal plane foot contact ankle between groups
Maclean, Emmerik, and Hamill (2010)[45] RRI	Intralimb couples; tibia transverse-calcaneus frontal, knee sagittal-rearfoot frontal, knee frontal-rear-foot frontal, knee transverse-rear-foot frontal	> Injured limb tibial transverse-calcaneus frontal early stance ($P = .004$; ES = 0.30)
Meardon, Hamill, and Derrick (2011)[40] RRI	Stride time	= No significant differences in variability of stride time between groups at the beginning of the run
Miller et al. (2008)[18] ITBS	Intralimb couples; thigh frontal (abd/add) -tibia transverse (IR/ER), thigh frontal-foot transverse (IN/EV), tibia transverse-foot transverse (IN/EV), knee sagittal (Flex/Ext) -foot frontal (abd/add), knee frontal (abd/add) -foot transverse	> knee flex/ext-foot abd/add complete stride ($P = .02$) > knee flex/ext-foot abd/add swing ($P = .04$) > knee flex/ext-foot abd/add stance ($P = .02$) < tibial IR/ER-foot IN/EV heel strike ($P = .04$) ^ discrete measure
Hein et al. (2012)[38] ITBS	Intralimb coupling; hip sagittal-knee sagittal, hip frontal-knee sagittal, knee sagittal-ankle sagittal, knee sagittal-ankle sagittal	= No significant differences in variability of dependent measures found between groups during stance phase, intervals of stance phase or continuously during
Heiderscheit, Hamill, and Emmerik (2002)[37] PFP	Stride duration and length. Within limb coupling; thigh transverse-leg transverse, thigh sagittal-leg sagittal, knee transverse-ankle transverse (IN), knee sagittal-ankle transverse (IN), knee sagittal-ankle sagittal	> stride length preferred running speed ($P = .03$, ES 0.30)
Cunningham et al. (2014)[32] PFP	Coupling angle variability; knee valgus/varus (KV) -ankle inversion/eversion (AI), knee valgus/varus-ankle plantar/dorsi flexion (AF), knee flexion/extension (KF) -ankle inversion/eversion, knee flexion/extension-ankle plantar/dorsi flexion, knee internal/external rotation (KR), knee internal/external-ankle plantar/dorsi flexion	> KF-AF Q1 ($P = .020$; cohen's d 0.97) > KR-AI Q2 ($P = .049$; 0.80) > KR-AF Q2 ($P = .038$; 0.85) > KV-AF Q4 ($P = .010$; 1.09) > KV-AF Q5 ($P = .008$: 1.12) > KV-AF stance ($P = .008$: 1.21) > KV-AI stride ($P = .031$; 0.89)
Edwards et al. (2016)[16] AGP	3D kinematics ankle, knee, hip, L5-S1 and T12-L1. Peak net internal ankle, knee and hip joint moments. Peak ground reaction force (vertical, minima, posterior)	> Knee internal-external rotation *F*wa > Hip internal-external rotation Fwa > T12-L1 right-left rotation ($P < .05$)

(Continues)

APPENDIX 1 (Continued)

Author	Variables examined	Significant finding
Chiu, Lu and Chou (2010)[31] THA	Interjoint coordination variability; hip-knee, knee-ankle	> surgical limb hip-knee sagittal plane presurgery ($P = .019$) > surgical limb knee-ankle sagittal plane presurgery ($P = .008$) > surgical limb knee-ankle sagittal plane 6 weeks post-op ($P = .036$)

ACLR, anterior cruciate ligament reconstruction; CAI, chronic ankle instability; RRI, running related injury; ITBS, iliotibial band syndrome; PFP, patellofemoral pain; AGP, athletic groin pain; THA, total hip arthroplasty; > greater than; < less than; = no between group difference; ROM, range of motion; abd, abduction; add, adduction; flex, flexion; ext, extension; IN, inversion; EV, eversion; rotn, rotation; PC, principal component; max, maximum; min, minimum; FAI, functional ankle instability; MAI, mechanical ankle instability; IR, internal rotation; ER, external rotation; LF, lateral flexion; DP, deviation phase; DF, dorsi-flexion; AJM, ankle joint moment; ES, effect size; T12, thoracic vertebrae 12; L1, lumbar vertebrae 1, *F*wa, first local minimum of the vertical ground reaction force after peak vertical ground reaction force.

APPENDIX 2

Quality appraisal checklist [19]

	Reporting										
	Q1	2	3	4	5	6	7	8	9	10	
Author											
van Uden et al. 2003)[42]	1	1	1	1	1	1	1	0	1	1	9
Cordeiroet al. (2015)[43]	1	1	0	1	1	1	1	0	1	1	8
Pollard et al. (2015)[46]	1	1	0	1	1	1	1	0	1	1	8
Gribbin et al. (2016)[35]	1	1	1	1	1	1	1	0	1	0	8
Herb et al. (2014)[13]	1	1	1	1	1	1	1	0	1	0	8
Kipp and Palmieri-Smith (2013)[17]	1	1	1	1	1	1	1	0	1	1	9
Brown, Bowser,and Simpson (2012)[30]	1	1	1	1	1	1	1	0	1	1	9
Hamacher, Hollander, and Zech (2016)[36]	1	1	1	1	1	1	1	1	0	1	9
Drewes et al. (2009)[33]	1	1	1	1	1	1	1	0	1	0	8
Kulig, Joiner, and Chang (2015)[14]	1	1	1	1	1	1	1	0	1	1	9
James, Dufek, and Bates (2000)[47]	1	1	0	1	1	1	1	0	1	0	7
Ferber, Davis, and Williams (2005)[34]	1	1	1	1	1	1	1	0	1	1	9
Mann et al. (2015)[39]	1	1	1	1	1	1	1	0	1	1	9
Paquette, Milner, and Melcher (2016)[41]	1	1	1	1	1	1	1	0	1	1	9
Maclean, Emmerik, and Hamill (2010)[45]	1	1	0	1	1	1	1	0	1	1	8
Meardon, Hamill, and Derrick (2011)[40]	1	1	1	1	1	1	1	0	1	1	9
Miller et al. (2008)[18]	1	1	1	1	1	1	1	1	1	1	10
Hein et al. (2012)[38]	1	1	1	1	1	1	1	0	1	1	9
Heiderscheit, Hamill and Emmerik (2002)[37]	1	1	1	1	1	1	1	1	1	1	10
Cunningham et al. (2014)[32]	1	1	1	1	1	1	1	1	1	1	10
Edwards et al. (2016)[16]	1	1	1	1	1	1	1	1	1	1	10
Chiu, Lu, and Chou (2010)[31]	1	1	1	1	1	1	1	0	1	1	9
										Mean	9
										Median	9

External				Internal bias								Confounding							Power	
11	12	13		14	15	16	17	18	19	20		21	22	23	24	25	26		27	Total
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	1	0	1	0	1	2	0	0	0	0	0	0	0	1	11
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	10
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	12
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	13
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14
0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
			0								3							0		12
			0								3							0		12