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REVIEW

WILEY

Monitoring lower limb biomechanical asymmetry and psychological measures in athletic populations—A scoping review

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Abstract

Background: Lower limb biomechanics, including asymmetry, are frequently monitored to determine sport performance level and injury risk. However, contributing factors extend beyond biomechanical and asymmetry measures to include psychological, sociological, and environmental factors. Unfortunately, inadequate research has been conducted using holistic biopsychosocial models to characterize sport performance and injury risk. Therefore, this scoping review summarized the research landscape of studies concurrently assessing measures of lower limb biomechanics, asymmetry, and introspective psychological state (e.g., pain, fatigue, perceived exertion, stress, etc.) in healthy, competitive athletes.

Methods: A systematic search of MEDLINE, Embase, CINAHL, SPORTDiscus, and Web of Science Core Collections was designed and conducted in accordance with PRISMA guidelines. Fifty-one articles were included in this review.

Results: Significant relationships between biomechanics ($k=22$ studies) or asymmetry ($k=20$ studies) and introspective state were found. Increased self-reported pain was associated with decreased range of motion, strength, and increased lower limb asymmetry. Higher ratings of perceived exertion were related to increased lower limb asymmetry, self-reported muscle soreness, and worse jump performance. Few studies ($k=4$) monitored athletes longitudinally throughout one or more competitive season(s).

Conclusion: This review highlights the need for concurrent analysis of introspective, psychological state, and biomechanical asymmetry measures along with longitudinal research to understand the contributing factors to sport performance and injury risk from biopsychosocial modeling. In doing so, this framework of biopsychosocial preventive and prognostic patient-centered practices may provide an actionable means of optimizing health, well-being, and sport performance in competitive athletes.

KEYWORDS
injury risk, limb symmetry, sport performance, sport psychology

1 | INTRODUCTION

Neuromuscular function and lower limb biomechanics are often monitored in athletic populations to optimize performance, minimize the risk of injury, and identify potential deficiencies in movement patterns.[1–7] A variety of biomechanical and performance assessments ranging from vertical jump tasks, musculoskeletal strength or power, sprint or change of direction speed, balance, and other sport-specific movements are commonly utilized.[8,9] While the relative importance of an assessment can vary greatly from one sport to another,[9] comparing lower limb asymmetries may be an important marker which can be broadly applied across most assessments and sports.[8,10]

The existence of lower limb biomechanical asymmetries has been related to athletic performance or increased injury risk,[8,10–13] but one of the most common applications remains benchmarking return-to-sport (RTS) readiness.[14–17] It is well-established that a lower limb injury results in a variety of biomechanical lower limb asymmetries, and these inter-limb differences can continue throughout a seemingly successful rehabilitation and well after RTS.[18–22] Moreover, as athletes progress through their rehabilitation journey, the observed asymmetries can be closely aligned with a variety of psychosocial variables that reflect the athlete's introspective psychological state (e.g., pain, rating of perceived exertion (RPE), sleep quality, anxiety, fear, etc.) and readiness to RTS.[23–27] For instance, lower limb asymmetries related to factors such as strength,[25] jumping kinetics,[24] and gait,[26] among others, have been shown to be related to self-reported introspective state throughout their path of RTS. Therefore, from a RTS perspective, the association between lower limb asymmetries and an athlete's introspective state is well established.

Unfortunately, the relationship between lower limb asymmetry and the introspective psychological state of healthy athletes who are either free of injury or have successfully returned to sport is less clear and often poorly assessed. Oftentimes, pain and other introspective psychological factors are dichotomized such that the relevance of these psychosocial factors on health and well-being is placed in rehabilitation and the injured athlete, and largely ignored in healthy and actively competing athletes. However, the occurrence of pain is not synonymous with injury, pain may persist even after the athlete has overcome their injury, and elite athletes often display a high tolerance for pain and/or coping mechanisms that help them modulate their pain so that they can continue to train and compete.[28,29] Logically, it would make more sense to contextualize psychosocial factors, such as pain, and their relationship to biomechanical factors like lower limb asymmetry on a continuum, rather than treating these health-related factors as irrelevant in those athletes who are healthy and competing.

This scoping review aimed to highlight the literature that included measures of both lower limb biomechanics, specifically those related to within- and between-limb asymmetry, and introspective psychological state in non-injured, competitive athletes, and competitive athletes who RTS after injury. Specifically, we aimed to (i) identify primary aims/designs of studies collecting both asymmetry and introspective metrics, (ii) map the biomechanical asymmetry metrics and introspective outcomes collected together and examine previously reported relationships of introspective state with lower limb biomechanical asymmetries, and (iii) identify gaps while providing recommendations for future research.

2 | METHODS

Given the gaps in knowledge surrounding the relationship between biomechanics, asymmetry assessments, and the introspective state of the healthy athlete, we selected a scoping review methodology for this work.[30,31] It was expected that this framework could support mapping potential relationships and identifying gaps that could support future primary research or systematic reviews in the area.[32] This scoping review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines[32] and the corresponding PRISMA-ScR checklist can be found in Appendix A: Table A1.

2.1 | Eligibility criteria

Studies were included in the present scoping review if the population consisted of healthy, competitive athletes (i.e., categorized as national, professional/elite, collegiate, or other competitive athletes (e.g., semiprofessional/sub-elite, club-level, etc.)),[33] they had at least one assessment of lower limb biomechanical (e.g., kinetics or kinematics) or performance-based (e.g., inter- or intra-limb strength differences) asymmetry, and at least one self-reported measure of introspective psychological state (e.g., pain, RPE, sleep quality, anxiety, fear, etc.). Articles were excluded if, (i) it was a systematic review, meta-analysis, or conference abstract, (ii) the population consisted of recreational athletes,[33] (iii) only lower limb biomechanical (e.g., kinetics or kinematics) or performance-based asymmetry were measured without data or reporting on the self-reported introspective state, or vice-versa, and (iv) the study only reported on athletes undergoing a RTS progression (i.e., had yet to return to their sport).

2.2 | Search strategy and screening

A systematic search was completed using the following five databases: Web of Science Core Collections, SPORTDiscus, CINAHL, MEDLINE, and Embase. To optimize the overall scope of the literature search, a personalized search strategy was employed for each database utilizing the following overarching topics: lower limb, asymmetry, movement/mechanics, athlete, and self-report. The complete search strategy and specific syntax used for each database are presented in Appendix B. The systematic search was conducted on November 22, 2021, and the included studies were sequentially imported to Covidence for screening upon the removal of duplicates. The removal of duplicates was then verified by an individual reviewer (J.K.) to ensure that no additional articles were removed inadvertently by the software. Five reviewers (J.K., Z.M., M.R., E.W., S.M.) independently completed title and abstract screening using Covidence. Each article was independently screened by two reviewers, and any conflicts were resolved in consultation with a third reviewer (D.K.). Subsequently, full-text screening to determine inclusion in the study was completed by five independent reviewers (J.K., E.W., A.P., S.K., S.M.). As before, each article was screened by two reviewers and any conflicts were resolved in consultation with a third reviewer (D.K.).

2.3 | Data charting and synthesis

Upon the completion of full-text screening, data were extracted independently by two reviewers (Z.M., M.R., A.P., S.K., S.M.), with a final consensus check by a third (J.K. or E.W). The number of extracted articles is denoted with "k", while the number of participants within a study is denoted with "n". Based on the study aims, data were extracted surrounding the (i) study design and aim, (ii) biomechanical asymmetry metrics and self-reported introspective measures, and (iii) observed relationships between introspective state with lower limb biomechanical asymmetries. Specifically, study designs were summarized as cross-sectional or repeated measures, with studies that employed a quasi- or true experimental study design, based on a hierarchy proposed by Harris and colleagues,[34] identified for the purposes of distinguishing the potential causality of highlighted relationships. Additionally, study aim was grouped into one of six themes which emerged as, (i) performance assessments, (ii) injury risk assessments, (iii) effects of fatigue, (iv) training with pain, (v) comparing healthy, competitive athletes to injured, and (vi) the effect of previous injury history on performance or risk of reinjury. The biomechanical assessment and testing methodology, along with the self-reported introspective state measure (e.g., pain, RPE, fatigue, anxiety, etc.) and questionnaire were extracted from these studies. Finally, studies that reported a statistically significant relationship between lower limb biomechanics variables and the introspective state of the athlete was extracted in this scoping review. Specifically, we extracted effect size metrics whenever possible to elucidate the magnitude of such relationships (e.g., r – associations; Cohen's d – standardized difference between two group means; partial eta squared – effect size metric often used for ANOVA; Hazard Ratio – effect size measure relating to probability statistics). These data and connections were summarized in a Network Graph using NetworkX Python package.[35]

3 | RESULTS

3.1 | Search results and screening

A total of 3871 articles were identified using our search strategy. After the removal of duplicate articles, 2484 studies remained for the title and abstract screening. After full-text screening of 286 articles, 51 articles[14,36–85] were ultimately included in the present scoping review. The rationale for exclusion at the full-text level can be found in Figure 1. The most frequent reason for exclusion was "assessed the effect of an intervention during return-to-sport" ($k=108$), followed by "wrong population" ($k=65$), indicating the study sample did not consist of healthy and actively participating competitive athletes.

3.2 | Area of research and study design

The most common area of study was the effect of previous injury history on performance or risk of reinjury ($k=19$), followed by injury risk assessment ($k=13$), and the effects of fatigue ($k=13$). Importantly, only 23 out of 51 [45%] included studies utilized a repeated-measures

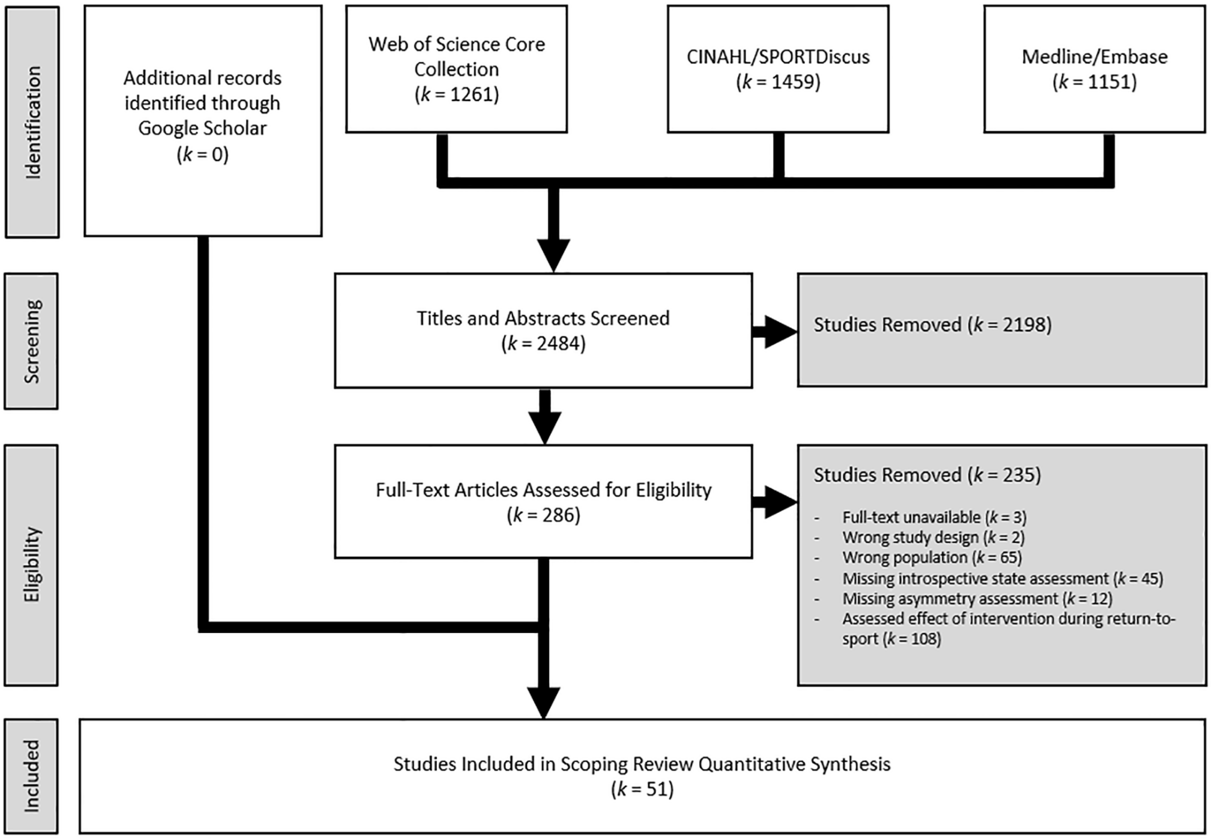

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram of the screening process.

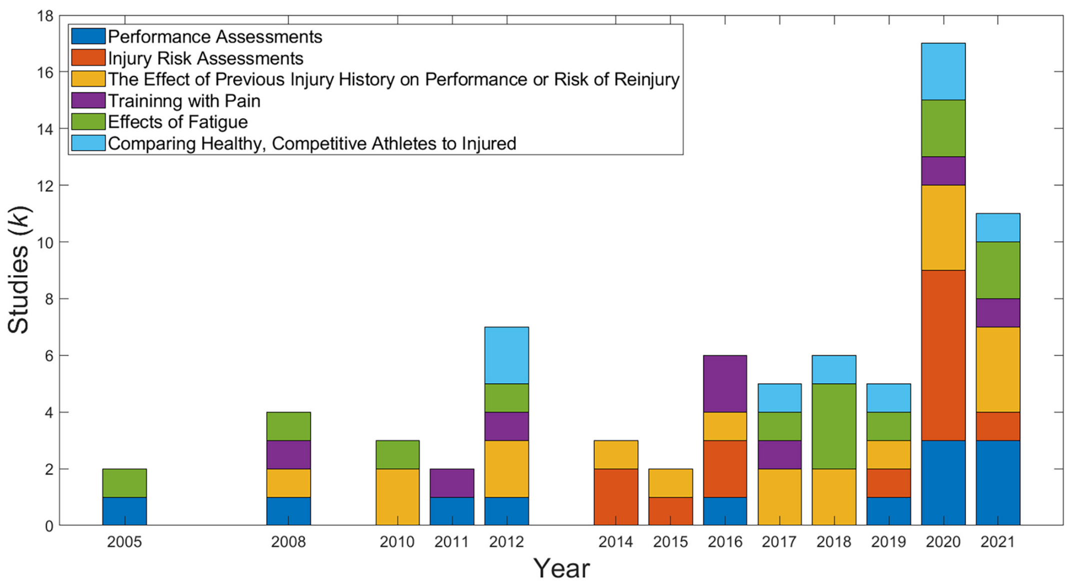

FIGURE 2 The number of studies published each year that measured biomechanical or performance-based asymmetry in conjunction with self-report introspective state in healthy, competitive athletic populations. The vertically stacked bar graph visualizes the total number of publications and the proportion of themes addressed in that year (i.e., a single study may span more than one theme).

study design to monitor biomechanics and introspective state across ≥2 collection sessions. Furthermore, only 4 [7.8%] of these studies[49,62,65,66] followed athletes prospectively throughout one or more competitive season(s). Figure 2 and Table 1 represent the overall distribution of included studies, their respective area of research, and whether an observational, quasi-, or true experimental study design was employed.

TABLE 1 Study design and demographics.

Study ID	Repeated measures design	Area of research	Sample size	Training experience (years)	Level of competition	Sport
Almeida 2012	No	Training with pain	42 (22 M and 20 F)	Back pain group: 8.9 ± 2.9; CON: 8.4 ± 3.1	Other competitive athletes	Judo
Arede 2020	Yes	Performance assessment	12 M	NA	National	Basketball
Belhaj 2016	No	Performance assessment; Training with pain	31 M	NA	Professional	Soccer
Birat 2021	Yes[QE]	Effect of fatigue	20 M	≥2	National	Endurance athletes
Bourne 2015	No	Injury risk assessment; Assessing effect of injury history on performance or risk of reinjury	178 M	NA	Professional; Other competitive athletes	Rugby
Bourne 2020	No	Injury risk assessment	152 M	NA	Professional	Soccer
Breen 2021	No	Performance assessment; Assessing effect of injury history on performance or risk of reinjury	58 M	NA	Professional	Rugby
Briem 2017	Yes[QE]	Effect of fatigue	116 (48 M and 68 F)	NA	Other competitive athletes	Handball; soccer
Cejudo 2020	No	Injury risk assessment; Assessing effect of injury history on performance or risk of reinjury	43 (15 M and 28 F)	M: 6.5 ± 2.3; F: 6.7 ± 2.9	Other competitive athletes	Equestrian
Chang 2020	Yes[QE]	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	30 F	NA	Other competitive athletes	Soccer; volleyball; basketball
Collings 2021	No	Assessing the effect of injury history on performance or risk of reinjury	369 F	NA	National; Professional	Australian football; soccer; rugby
Davenport 2016	No	Injury risk assessment	36 (2 M and 34 F)	12.8 ± 4.3	Collegiate	Dance
Delextrat 2005	Yes[QE]	Performance assessment; Effect of fatigue	8 M	≥3	National; other competitive athletes	Endurance athletes
Delextrat 2010	Yes[QE]	Effect of fatigue	8 M	8	Collegiate	Soccer
Della Corte 2021	Yes[QE]	Performance assessment; Effect of fatigue	12 M	>18 months	Collegiate	Handball
Gulgin 2008	No	Performance assessment	31 F	16.58 ± 6.48	Professional	Golf
Hanley 2018	Yes[QE]	Effect of fatigue	14 M	NA	Other competitive athletes	Endurance athletes
Hanna 2010	No	Assessing the effect of injury history on performance or risk of reinjury	120 M	8.8 ± 6.3 seasons	Professional	Soccer
Hides 2016	Yes	Training with pain; Assessing the effect of injury history on performance or risk of reinjury	25 M	6.4 ± 5.7	Professional	Soccer

(Continues)

TABLE 1 (Continued)

Study ID	Repeated measures design	Area of research	Sample size	Training experience (years)	Level of competition	Sport
Hung 2021	No	Injury risk assessment	21 (1 M and 20 F)	7.93 ± 2.29	Other competitive athletes	Dance
Ishøi 2016	Yes[E,L]	Injury risk assessment	20 M	NA	Other competitive athletes	Soccer
Kiesel 2014	No	Injury risk assessment	238 M	NA	Professional	American football
King 2018	No	Assessing the effect of injury history on performance or risk of reinjury	15 (11 M and 4 F)	NA	Other Competitive Athletes	Soccer
Kons 2020	Yes[QE]	Effect of fatigue	14 M	11.8 ± 5.1	National	Judo
Kuni 2008	Yes[QE]	Effect of fatigue	18 F	NA	National; Professional; other competitive athletes	Volleyball; handball
Lehnert 2018	Yes[QE]	Effect of fatigue	20 M	NA	Elite	Soccer
Lonergan 2018	Yes[QE]	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	14 M	NA	National; Professional	Rugby
Madić 2020	No	Injury risk assessment	136 M	5+	Other competitive athletes	Soccer
Manoel 2020	No	Injury risk assessment	89 M	2+	Professional	Soccer
Mentiplay 2019	No	Performance assessment	85 F	7.5 ± 5.4	Elite	Australian Football
Mertz 2012	No	Performance assessment	30 (7 M and 23 F)	12.8 ± 4.0	Collegiate	Dance
Moreno-Pérez 2019	Yes[E]	Injury risk assessment	26 M	12.04 ± 5.43	National; Professional	Tennis
Moreno-Pérez 2020	Yes[L]	Performance assessment	40 M	NA	Professional	Soccer
Myklebust 2017	No	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	858 F	NA	Elite	Handball; Soccer
Niederer 2020	Yes[E]	Effect of fatigue; Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	38 (18 M and 20 F)	NA	Other competitive athletes	Soccer; team sports
Niering 2021	Yes[QE,L]	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	35 M	NA	Other competitive athletes	Soccer

TABLE 1 (Continued)

Study ID	Repeated measures design	Area of research	Sample size	Training experience (years)	Level of competition	Sport
Rossi 2020	Yes[L]	Injury risk assessment	383 (M and F)	NA	Other competitive athletes	Basketball; Floorball
Sanders 2018	Yes	Effect of fatigue	13 F	NA	Collegiate	Volleyball
Schmitt 2012	No	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	90 (28 M and 62 F)	NA	Collegiate; Other competitive athletes	Cutting and pivoting sports
Shams 2019	No	Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	31 (11 M and 20 F)	NA	Other competitive athletes	Football; soccer; basketball; volleyball
Steinberg 2020	No	Injury risk assessment	132 F	NA	Other competitive athletes	Dance
Stuelcken 2008	No	Training with pain; Assessing the effect of injury history on performance or risk of reinjury	34 (8 M and 26 F)	M: 10.6 ± 4.0; F: 10.3 ± 5.0	National	Cricket
Tak 2020	No	Performance assessment; Training with pain	62 M	No LBP: 17.5 ± 6.0; LBP: 15.6 ± 6.1	Other competitive athletes	Judo
Tengman 2014	No	Assessing the effect of injury history on performance or risk of reinjury	103 (65 M and 38 F)	NA	Other competitive athletes	Soccer; Alpine Skiing
Thorborg 2011	No	Performance assessment	86 M	NA	Other competitive athletes	Soccer
Troester 2019	Yes	Effect of fatigue	27 M	46 ± 22 games	Professional	Rugby
Tsai 2010	No	Assessing the effect of injury history on performance or risk of reinjury	32 M	NA	Professional	Golf
Wang 2011	No	Training with pain	14 (10 M and 4 F)	9.6 ± 2.8	National	Tennis; Track and field; Badminton; Basketball
Webster 2012	Yes[QE]	Effect of fatigue; Comparing a healthy athletic control group to injured competitive athletes; Assessing the effect of injury history on performance or risk of reinjury	26 M	NA	Other competitive athletes	Australian rules football; basketball; soccer; volleyball
Whyte 2021	Yes[E]	Performance assessment	24 M	NA	Collegiate	Gaelic Football
Young 2014	No	Injury risk assessment	125 F	NA	Professional	Tennis

Note: Superscripted QE denotes quasi-experimental study designs; superscripted E denotes experimental study designs; superscripted L denotes longitudinal study designs conducted throughout one or more competitive season(s); values represent Mean ± SD, unless otherwise noted.

Abbreviations: CON, control group; F, female; LBP, lower back pain; M, male.

3.3 | Sample characteristics

Overall, a total of 4184 ($n=1773$ male, $n=2028$ female, and $n=383$ undeclared) athletes were assessed throughout the 51 included studies. The sample sizes used in these studies ranged from 8 to 858, with a median of only 32 participants. The majority of studies examined only male participants ($k=28$), with 14 studies using both male and female participants, and 9 as female only. The most frequently studied levels of competition were elite/professional ($k=24$) and other (i.e., semiprofessional/sub-elite or club-level athletes) ($k=33$), followed by national ($k=16$), and collegiate ($k=6$). Soccer ($k=22$ [43%]) was the most studied sport, followed by rugby ($k=8$), and volleyball ($k=7$) as visualized in Figure 3.

3.4 | Biomechanical, asymmetry and introspective assessments

The most utilized biomechanical lower limb asymmetry assessments were inter- and intra-limb differences in strength ($k=26$, and $k=17$, respectively), followed by kinetic or kinematic asymmetries from vertical jumps ($k=16$), and various assessments of range of motion asymmetry ($k=12$). Subsequently, the testing methodologies for these assessments were isokinetic/handheld dynamometers or load cells ($k=27$), followed by single- or dual force plates ($k=13$) utilized concurrently with optical 3D motion capture systems ($k=8$), and goniometers/inclinometers ($k=9$), respectively. The most measured introspective states were pain ($k=33$) and rating of perceived exertion (RPE) ($k=17$), which were most frequently collected using a visual analog scale (VAS) ($k=8$) and Borg Scale for RPE ($k=17$), respectively. Additional details regarding these assessments and testing methodologies can be found in Table 2.

3.5 | Lower limb biomechanics, including asymmetry and introspective state relationships

While all 51 of the included studies measured biomechanical and introspective state variables, not all of them directly examined the relationships between these two constructs. That said, 22 and 20 of the studies reported a statistically significant relationship between lower limb biomechanics and asymmetry with introspective state, respectively. Figure 4 visually summarizes the introspective state measures taken in conjunction with biomechanical measures in a network graph. In this figure, the diameter of the nodes depicts the total number of studies which collected each measure, while the width of the lines between nodes depicts the number of studies that collected both measures together. Additionally, where significant relationships were observed, lines were highlighted according to whether that relationship was identified for assessments of asymmetry or not.

The largest introspective node in Figure 4 was perceived pain, which was significantly related to strength ($k=6$), ROM ($k=5$), jumping ($k=1$), and proprioception ($k=1$). Further, this significant relationship to pain existed with measures of asymmetry in strength ($k=6$), ROM ($k=5$), balance ($k=2$), and jumping ($k=1$). There were also significant relationships identified between RPE and jumping ($k=3$), sport-specific tasks ($k=2$), ROM

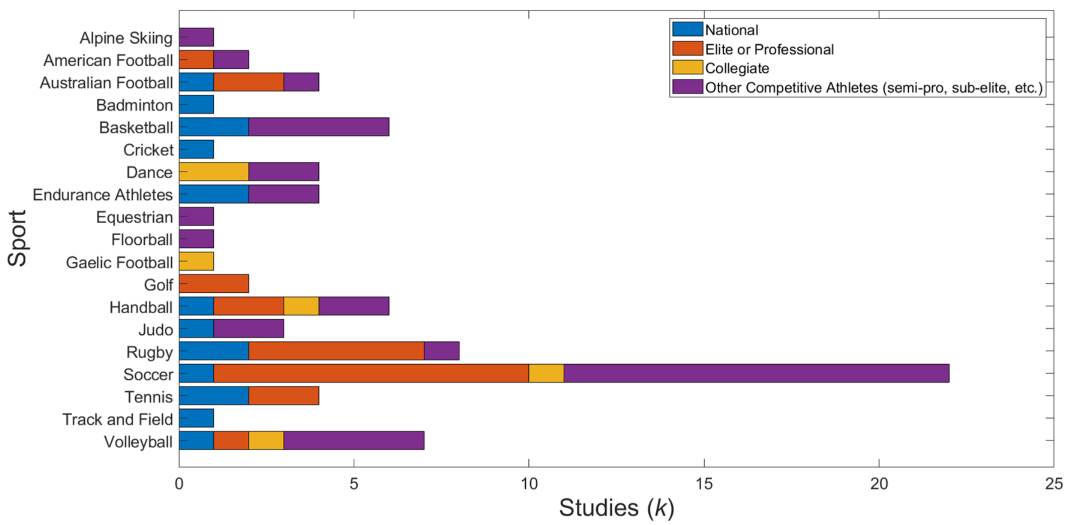

FIGURE 3 The proportion of studies published categorized by both sporting population and the level of competition. The horizontally stacked bar graph visualizes the total number of publications and the proportion of the level of competition addressed in that year by sporting population (i.e., a single study may span more than one sport and/or level of competition).

TABLE 2 Reporting of biomechanical asymmetry metrics and self-reported introspective measures.

Study ID	Biomechanical assessment	Testing methodology	Asymmetry assessment	Testing methodology	Introspective state	Questionnaire used
Almeida 2012	ROM	Digital picture with reflective markers	ROM	Digital picture with reflective markers	Pain; Functional capacity	VAS; RDQ
Arede 2020	Jumping; CODS; Gait; Sport specific	Motion Capture; Force plate[s]; Wearable sensors	Jumping	Force plate[S]	Exertion; Soreness	Borg RPE Scale 0–10; VAS
Belhaj 2016	Strength	Isokinetic Dynamometer	Strength (Intra- and Inter-Limb)	Isokinetic Dynamometer	Pain	NA
Birat 2021	Strength; Sport specific	Isokinetic Dynamometer; EMG; Heart Rate Monitor	Strength (Intra-Limb)	Isokinetic Dynamometer	Pain; Soreness	VAS
Bourne 2015	Strength	Uniaxial Load Cell	Strength (Inter-Limb)	Uniaxial Load Cell	Pain	NA
Bourne 2020	Strength	Uniaxial Load Cells	Strength (Inter-Limb)	Uniaxial Load Cells	Pain; Functional Capacity	HAGOS
Breen 2021	Strength	Handheld Dynamometer	Strength (intra- and inter-limb)	Handheld Dynamometer	Pain; Functional Capacity	HAGOS
Briem 2017	Jumping	Motion Capture; Force Plate[D]	Jumping	Motion Capture; Force Plate[D]	Fatigue	NRS 0–10
Cejudo 2020	ROM	Goniometer; Inclinometer	ROM	Goniometer; Inclinometer	Pain	NA
Chang 2020	Jumping; Gait; Strength	Motion Capture; Force Plate[D]; Isokinetic Dynamometer	Jumping; Strength (inter-limb)	Motion Capture; Force Plate[D]; Isokinetic Dynamometer	Exertion	Borg RPE Scale 6–20
Collings 2021	Jumping; Strength	Force Plate[D]; Uniaxial Load Cells	Jumping; Strength (inter-limb)	Force Plate[D]; Uniaxial Load Cells	Pain; Functional Capacity	KOOS; HAGOS
Davenport 2016	ROM; Strength; Sport specific	Goniometer; Handheld Dynamometer; Visual Observation	ROM; Strength (inter-limb); Sport specific	Goniometer; Handheld Dynamometer; Visual Observation	Pain, Anxiety, Fear	NA
Delextrat 2005	Strength; Sport specific	Cycle ergometer	Strength (inter-limb)	Cycle ergometer	Exertion	Borg RPE Scale 6–20
Delextrat 2010	Strength; Gait; Sport specific	Isokinetic Dynamometer; Distance; Heart rate monitor	Strength (intra- and inter-limb)	Isokinetic Dynamometer	Exertion	Borg RPE Scale 6–20
Della Corte 2021	Jumping; Strength	MyJump2 application; Leg extension machine	Strength (inter-limb)	Leg extension machine	Exertion	Borg RPE Scale 0–10
Gulgin 2008	ROM	Goniometer	ROM	Goniometer	Pain	NA
Hanley 2018	Gait	Force Plate[D]	Gait	Force Plate[D]	Exertion	Borg RPE Scale 6–20
Hanna 2010	Strength	Isokinetic Dynamometer	Strength (inter-limb)	Isokinetic Dynamometer	Pain	VAS
Hides 2016	Strength	Isokinetic Dynamometer	Strength (intra- and inter-limb)	Isokinetic Dynamometer	Pain	VAS
Hung 2021	Strength; Balance	Isokinetic Dynamometer; Handheld Dynamometer; YBT	Strength (intra-limb); Balance	Isokinetic Dynamometer; Handheld Dynamometer; YBT	Pain	CAIT

(Continues)

TABLE 2 (Continued)

Study ID	Biomechanical assessment	Testing methodology	Asymmetry assessment	Testing methodology	Introspective state	Questionnaire used
Ishøi 2016	Strength	Handheld Dynamometer	Strength (Inter-Limb)	Handheld Dynamometer	Exertion; Soreness	Borg RPE Scale 0–10; NRS 0–10
Kiesel 2014	ROM	FMS	ROM	FMS	Pain	FMS
King 2018	Jumping; Gait; Strength; ROM	Motion Capture; Force Plate^{D}; Handheld Dynamometer; Inclinometer; Goniometer	Jumping; Gait; Strength (intra- and inter-limb); ROM	Motion Capture; Force Plate^{D}; Handheld Dynamometer; Inclinometer; Goniometer	Pain	HAGOS
Kons 2020	Jumping	Force Plate^{S}	Jumping	Force Plate^{S}	Exertion; Soreness	VAS; Borg RPE Scale 0–10
Kuni 2008	Jumping	Force Plate^{S}	Jumping	Force Plate^{S}	Exertion	Borg RPE Scale 6–20
Lehnert 2018	Strength; Jumping	Isokinetic Dynamometer; Optojump Next System	Strength (intra-limb); Jumping	Isokinetic Dynamometer; Optojump Next System	Exertion; Fatigue	Borg RPE Scale 6–20
Lonergan 2018	Jumping; Sport specific	Force Plate^{D}; Camera with reflective markers; GPS	Jumping	Force Plate^{D}; Camera with reflective markers	Exertion	Borg RPE Scale 0–10
Madić 2020	Strength	Isokinetic Dynamometer	Strength (intra- and inter-limb)	Isokinetic Dynamometer	Pain	RDQ
Manoel 2020	Strength; Balance	Isokinetic Dynamometer; YBT	Strength (inter-limb)	Isokinetic Dynamometer	Pain	FAOS; Injury Incidence form
Mentiplay 2019	Strength; Balance; ROM	Isokinetic Dynamometer; SEBT; Weight-bearing lunge	Strength (intra- and inter-limb); Balance	Isokinetic Dynamometer; SEBT	Pain	NRS 0–10
Mertz 2012	Sport specific	Force Plate^{S}	Sport specific	Force Plate^{S}	Functional Capacity	Laterality Questionnaire
Moreno-Pérez 2019	Strength; ROM; Sport specific	Isokinetic Dynamometer; Inclinometer; Goniometer; GPS	Strength (intra- and inter-limb); ROM	Isokinetic Dynamometer; Inclinometer; Goniometer	Exertion	Borg RPE Scale 0–10
Moreno-Pérez 2020	ROM; Sport specific	LegMotion System; GPS	ROM	LegMotion System	Exertion	Borg RPE Scale 0–10
Myklebust 2017	Strength; Balance	Isokinetic Dynamometer; SEBT	Strength (intra- and inter-limb); Balance	Isokinetic Dynamometer; SEBT	Pain; Functional Capacity	KOOS
Niederer 2020	Strength	m^3 multi muscle machine	Strength (inter-limb)	m^3 multi muscle machine	Pain; Exertion; Fear	Borg RPE Scale 6–20; VAS; LKSS
Niering 2021	Jumping; CODS; Speed; Endurance	Optojump Next System; Laser timing gate (Smartspeed Lite)	CODS	Laser timing gate (Smartspeed Lite)	Pain; Anxiety; Fear; Hope	The Achievement Motives Scale; VAS
Rossi 2020	Jumping	Motion Capture; Force Plate^{D}	Jumping	Motion Capture; Force Plate^{D}	Pain	Standardized Nordic questionnaire of Musculo-skeletal symptoms (modified)
Sanders 2018	Jumping	Force Plate^{S}	Jumping; Muscle glycogen (physiological)	Force Plate^{S}; Ultrasound (physiological)	Exertion	Borg RPE Scale 0–10

TABLE 2 (Continued)

Study ID	Biomechanical assessment	Testing methodology	Asymmetry assessment	Testing methodology	Introspective state	Questionnaire used
Schmitt 2012	Strength; Jumping	Isokinetic Dynamometer; Distance	Strength (inter-limb); Jumping	Isokinetic Dynamometer; Distance	Pain; Functional Capacity	KOOS; IKDC
Shams 2019	Jumping; Strength	Motion Capture; Force Plate^{D}; Isokinetic Dynamometer	Jumping; Strength (intra- and inter-limb)	Motion Capture; Force Plate^{D}; Isokinetic Dynamometer	Pain; Fear; Functional Capacity	IKDC; KAKPS; TSK; Marx Activity Rating Scale.
Steinberg 2020	Strength; Balance; Proprioception	Handheld Dynamometer; YBT; Active Movement Extent Discrimination Apparatus	Strength (intra-limb); Balance; Proprioception	Handheld Dynamometer; YBT; Active Movement Extent Discrimination Apparatus	Pain	VAS
Stuelcken 2008	ROM; Muscular endurance	Inclinometer; Goniometer; Time until movement deviation	ROM	Inclinometer; Goniometer	Pain	NA
Tak 2020	ROM	Inclinometer	ROM	Inclinometer	Pain	VAS
Tengman 2014	Jumping	Motion Capture	Jumping	Motion Capture	Pain; Fear; Functional Capacity	LKSS; KOOS; TSK
Thorborg 2011	Strength	Handheld Dynamometer	Strength (intra- and inter-limb)	Handheld Dynamometer	Pain	VAS
Troester 2019	Jumping; Balance; Sport specific	Force Plate^{S}; Wearable sensors	Jumping; Balance	Force Plate^{S}	Exertion	Borg RPE Scale 0–10
Tsai 2010	Strength; Balance; ROM; Flexibility; Sport specific	Isokinetic Dynamometer; FABER test; Goniometer; Motion Capture; Force Plate^{D,S}	Strength (inter-limb); ROM	Isokinetic Dynamometer; Goniometer	Pain	ODQ
Wang 2011	Strength; Electrical activity	Load Cell; EMG	Strength (intra- and inter-limb); Electrical activity	Load Cell; EMG	Pain	VAS; VISA-A
Webster 2012	Jumping	Motion Capture; Force Plate^{S}; Vertical Measurement Device (Swift Performance)	Jumping	Motion Capture; Force Plate^{S}; Vertical Measurement Device (Swift Performance)	Pain; Fatigue	IKDC; Borg RPE scale 0–10
Whyte 2021	Strength	Isokinetic Dynamometer	Strength (intra- and inter-limb)	Isokinetic Dynamometer	Soreness	VAS
Young 2014	ROM	Digital Inclinometer	ROM	Digital Inclinometer	Pain	NA

Abbreviations: CAIT, Cumberland Ankle Instability Tool; CODS, change of direction speed; D, dual force plate; EMG, electromyography; FAOS, The Foot and Ankle Outcome Score Questionnaire; FMS, functional movement screening; HAGOS, Copenhagen Hip and Groin Outcome Score; IKDC, International Knee Documentation Committee; KAKPS, Kujala Anterior Knee Pain Scale; KOOS, Knee Injury and Osteoarthritis Outcome Score; LKSS, Lysholm Knee Scoring Scale; NRS, Numeric Rating Scale; ODQ, Oswestry Low Back Pain Disability Questionnaire; RDQ, The Roland-Morris Low Back Pain and Disability Questionnaire; ROM, range of motion; RPE, Borg Scale for Rating of Perceived Exertion; S, single force plate; SEBT, Star Excursion Balance Test; TSK, Tampa Scale for Kinesiophobia; VAS, Visual Analog Scale; VISA-A, Victorian Institute of Sports Assessment-Achilles; YBT, Y-balance test.

($k=1$), and balance ($k=1$), which further translated to asymmetries in strength ($k=3$), jumping ($k=1$), and ROM ($k=1$) metrics.

There were three other domains where significant relationships were found. First, there were significant relationships for fear with strength ($k=1$), balance ($k=1$), and between-limb differences in jumping ($k=1$). Second, significant relationships were found for perceived soreness with strength ($k=1$) and sport-specific measures ($k=1$). Finally, there were two significant relationships found for perceived functional capacity with strength ($k=1$) and sport-specific measures ($k=1$), while also demonstrating an association to jumping asymmetry ($k=1$), and strength asymmetry ($k=1$).

4 | DISCUSSION

This is the first review to investigate the relationship between an athlete's introspective or psychological state and their biomechanical state, with a focus on lower limb asymmetry. While much of the previous literature examining these associations have focused on injured athletes as seen by the primary rationale for exclusion in Figure 1, the current review aimed to summarize work examining these relationships in healthy athletes. In doing so, we identified 51 studies that met our criteria for collecting biomechanical asymmetry with introspective data in healthy, competitive athletes. Pain and RPE were the two most collected introspective variables, though a variety of additional introspective variables were measured with unique linkages to biomechanical outcomes, as visualized in Figure 4. Overall, these findings highlight the potential impact of the athlete's self-reported, introspective state across a variety of biomechanical variables, specifically those assessing lower limb asymmetries. This scoping review highlights the importance of collecting these multidisciplinary data to provide a more holistic understanding of factors affecting sport performance and risk of injury or reinjury.

4.1 | Pain and biomechanical asymmetries

Although this scoping review examined healthy, competitive athletes, the most assessed self-reported measure of introspective state was pain. This finding speaks to the fact that not only do many seemingly healthy athletes train and play with some level of perceived pain,[28] but that this pain can be associated with lower limb biomechanics and asymmetry.[86–88] With respect to general biomechanical associations, it was found that higher ratings of pain correlated with reduced ROM,[36,71,72,85] reduced muscle

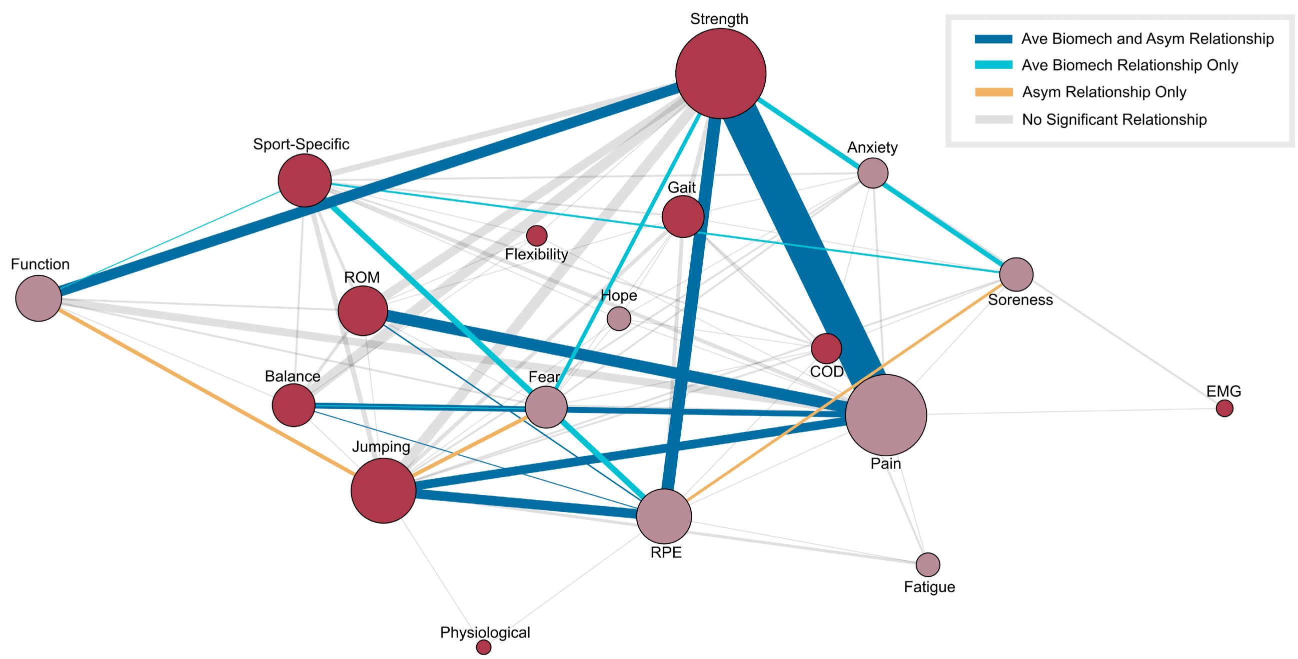

FIGURE 4 Network graph depicting lower limb biomechanical and introspective state measures collected together in healthy, competitive athletes. The dark maroon nodes show biomechanical assessments and the light maroon nodes show introspective assessments. Further, the size of the node and the width of the lines connecting them represent the number of times they were reported and the number of times they were reported together in a study, respectively. Lastly, the lines are colored to highlight where significant relationships were found, with gray lines indicating no statistically significant relationships found.

strength/torque output,[14,56] poor ankle proprioception ($\eta_p^2 = 0.08$, $p < 0.05$),[70] and altered vertical jump kinematics (hazard ratio = 2.2 [1.1–4.3] when femur-pelvic angle <80°).[66] However, with respect to the focus of our scoping review, higher pain ratings were also associated with greater asymmetries in lower limb ROM,[36,39,43,72] strength,[14,46,56,58,74,82] and balance ($\eta_p^2 = 0.08$, $p < 0.01$; $\eta_p^2 = 0.06$, $p < 0.05$, anterior and posterior-medial directions, respectively).[70] These observed relationships may not be surprising based on what we know about how pain alters biomechanics,[86–88] but most prior observations are generated from cross-sectional studies. If we aim to draw stronger conclusions regarding the relationship between pain and biomechanics, including the application of a more holistic prognostic tracking model for athletes, then future longitudinal, prospective studies are needed.

Only two studies were identified that measured introspective pain with lower limb biomechanical asymmetry variables in a prospective manner.[65,66] While Niering and colleagues[65] conducted a longitudinal study over the course of a competitive season in a cohort of adolescent sub-elite male soccer players, the authors did not examine individual differences in the relationships between physical and psychological variables, but rather quantified the group differences between those who had returned from an injury and those who had not sustained any injury. Nevertheless, while there were differences between these groups in performance outcomes throughout the season (i.e., worse CODS (left side: $1.37 \leq$ Cohen's $d \leq 1.51$, $p < 0.001$; right side: $1.24 \leq$ Cohen's $d \leq 1.53$, $p < 0.001$) and sprint performance ($0.48 \leq$ Cohen's $d \leq 1.26$, $p < 0.01$) in those who had RTS compared to those without any injury history) and introspective states at both the start of the season and 6 weeks into the competitive season (i.e., hope for success: $d = 0.65$, $p < 0.05$, and $d = 0.50$, $p = 0.076$; fear of failure: $d = 0.68$, $p < 0.05$, and $d = 0.80$, $p < 0.05$), which highlighted potential associations between these domains, lower limb asymmetries did not show any significant differences between these cohorts. Similarly, Rossi and colleagues[66] looked at back pain and lower limb jumping biomechanics (i.e., frontal plane pelvic kinematics, and vertical ground reaction force) prospectively over the course of multiple competitive seasons (e.g., once per year over 3 years). The authors found that frontal plane hip kinematics were related to injuries (i.e., pain and time loss; hazard ratio = 2.2 [1.1–4.3], $p < 0.05$), but strangely, this relationship was only observed on the right limb, potentially relating to some aspect of limb dominance. Nevertheless, these studies demonstrate that when looking prospectively, the relationship between lower limb biomechanical asymmetry and perceived pain is much less clear due to the scarcity of longitudinal studies investigating these relationships. Further, it is important to note that the way in which pain was assessed in these studies was simplified to describe injuries.

As reviewed by Hainline and colleagues,[28] pain is a highly complex and personalized experience that depends on a variety of biopsychosocial factors. Critically, the occurrence of pain is not synonymous with injury; that is, pain may persist even after the athlete has overcome their injury. Therefore, while several studies included in this scoping review reported on the relationships between pain and lower limb biomechanical or asymmetry measures in healthy, competitive athletes, the way that pain was often summarized limits our ability to understand precisely how it relates to biomechanical asymmetries. Specifically, the cross-sectional evaluation and/or the binary oversimplification (i.e., grouping as with or without pain) fails to encapsulate individual differences in the experience of pain over time, and therefore, the current summary may underestimate or overestimate the true relationships between pain and lower limb biomechanics or asymmetry. For example, we know that elite athletes often display a high tolerance for pain and/or coping mechanisms that help them modulate their pain so they can continue to train and compete.[28,29] Therefore, grouping competitive athletes based on the presence versus absence of pain, especially from a single-time point, is inherently confounded by individual differences in the threshold of pain that they will report and how much effort is required to cope with the pain they feel. Moreover, contextualizing pain based on its' variable impact on performance, mood, and function,[28] as well as an athlete's pain perception and coping strategies,[89] will be important to better understand this complex relationship between pain perceptions and biomechanical asymmetry.

4.2 | Rate of perceived exertion and biomechanical asymmetries

RPE was another frequently used measure of introspective state identified in this review. In contrast to our results on pain, we found that RPE with lower limb asymmetry was often monitored in repeated-measures and even longitudinal contexts. Typically, RPE assessments were taken before and after a fatiguing protocol or training session, and in relation to sport performance rather than injury. In this context and in accordance with previous findings,[90] a higher RPE, which often implies greater fatigue in athletes, was found to relate to reduced jump performance as quantified by kinetic and kinematic variables,[52,55,78,84] and impaired postural control (Cohen's $d \pm 90\%$ confidence limit $= 0.68 \pm 0.66$; $6.9 \pm 6.7\%$).[75] Specific to our focus on asymmetry however, we found that increased RPE was associated with reduced musculoskeletal strength of the nondominant limb compared to the dominant limb (i.e., increased between-limb differences) ($r=0.70$, and $r=0.63$–0.70, $p<0.05$; and Cohen's $d=0.27$–0.51, $p<0.05$, respectively),[40,42] and greater kinetic or kinematic between-limb differences during vertical jump tasks ($\eta_p^2=0.24$–0.53, $p<0.05$; no effect size reported in Webster et al., 2012).[52,78] However, contradicting findings remain,[64] and the heterogeneous findings related to fatigue and lower limb asymmetry are often reported[91–94] due to the many nuances that exist in study designs, protocols, metrics assessed, and the calculation of asymmetries. Nevertheless, the majority of findings presented on the relationship between RPE and biomechanics and/or asymmetry, here and previously,[90–94] pertain to either vertical jumping or gait asymmetries, and did not directly highlight the association between RPE and asymmetry in a more prospective, longitudinal context that considers data points across multiple sessions or a complete competitive season.

Only five included studies concurrently monitored RPE and lower limb biomechanics and asymmetry at multiple timepoints during training camps or a competitive season. Two studies used sessional-RPE (e.g., value of perceived session difficulty obtained by multiplying the duration of the session by the RPE)[95] to track internal load (perceived effort) of sport practices, training sessions, or games alongside measures of biomechanical asymmetry or performance measures.[62,67] Unfortunately, neither of these studies attempted to examine the statistical relationship of RPE with lower limb biomechanics and asymmetry. The remaining three studies tracked introspective state measures including RPE and perceived muscle soreness[47,49,79] at multiple timepoints in a training season to monitor changes across time. However, only Arede and colleagues[47] directly examined this relationship between the psychological and biomechanical domains. Unfortunately, in this work, asymmetry was only assessed once (at the onset of the study) and was not assessed in relation to other biomechanical (e.g., on-court training load and accelerations) and introspective (e.g., RPE, soreness) measures taken throughout training and competition over the year. Therefore, while these studies have numerous strengths related to monitoring athletes over time, our ability to draw strong inferences related to the interconnectivity of biomechanical asymmetry and RPE in competitive athletic populations is limited.

To fill the gap in the current literature, greater use of concepts such as sessional-RPE and "internal load" are recommended. Measuring internal load with sessional-RPE has been found to have high reliability and internal consistency across many sports and levels of competition.[96] Not only do these concepts quantify a rating of both internal (introspective RPE rating), and external (duration) variables, these values can be compared to additional biomechanical (external) measures to examine if the perception of the workload is correlated to the mechanical output of the task.[90] Specifically, we have seen, with some heterogeneity, that RPE from a single session can be related to lower limb asymmetry,[52,55,78,84,91–94] but the more important, cumulative effect of this relationship over multiple sessions or an entire season remains unknown. Therefore, future research may look to examine this association experimentally over multiple training sessions longitudinally, or perhaps more practically by integrating longitudinal asymmetry assessments alongside RPE in real-world, sport-specific settings prospectively. In doing so, we may begin to better uncover this relationship and its' potential application to sport performance, injury risk, and risk of reinjury.

4.3 | Other introspective state assessments and biomechanical asymmetries

While self-reported pain and RPE were the most used measures of introspective state by far, a small number of studies ($k=6$) also reported relationships between other introspective measures and lower limb biomechanics. Specifically, lower self-reported function was associated with reduced lower limb strength and greater lower limb strength asymmetry ($p=0.52$ and $p<0.001$ for high vs. low symmetry RTS cohorts, and healthy athletic controls vs. athletes who had RTS, respectively),[14] as well as increased side hop test performance asymmetry,[73] but was also reported to be uncorrelated with vertical jump kinetics and sport-specific performance in ballet ($\eta_p^2=0.01$–0.30, $p>0.05$).[60] This increased side hop test performance asymmetry was also related to a greater fear of movement or fear of reinjury ($r=-0.30$, $p<0.05$).[73] However, fear of reinjury was also reported to not be related to overall torque production or asymmetry ($p>0.05$).[64] As for soreness, higher delayed onset muscle soreness post-training was associated with decreased strength/toque output during subsequent training sessions,[69] but was also found to be associated with improved sport-specific performance as assessed via the agility t-test and game-related statistics ($r=0.59$, [0.06; 0.86], $p=0.09$, and $p<0.01$, respectively).[47] Unfortunately, the limited and inconsistent use of introspective measures outside of pain and RPE appear to preclude the ability to draw strong conclusions regarding the relationships that may exist between lower limb biomechanical asymmetry and self-reported function, fear, or soreness, in addition to a potential variety of other introspective measures not observed here.

As demonstrated by research in rehabilitative settings, the introspective psychological state, such as fear, hope, and athlete psychological readiness or perceived function, closely align with lower limb biomechanical asymmetries during RTS progression.[23–26] Additionally, the literature on athletes who have RTS suggests that biomechanical asymmetries[18–22] and psychological dysfunction (e.g., fear or kinesiophobia),[97] which are independent of pain and RPE, may persist well after RTS despite a seemingly successful rehabilitation, and may be prognostic factors for reinjury risk.[15] Furthermore, while some findings indicate that poor mental health and associated executive dysfunction may be related to biomechanical asymmetries during gait,[98–100] these findings have been limited to clinical or aging populations, and there is no known research investigating the relationship between general mental health and biomechanical asymmetry in healthy, competitive athletes. Therefore, while clinicians and researchers have no problem concurrently monitoring psychological and biomechanical domains during rehabilitation and RTS progression, they must now be encouraged to investigate how the relationship between introspective psychological factors and biomechanical asymmetry change in healthy, competitive athletes and those who have successfully RTS. If we are to truly understand contributory factors to sport performance and injury and delineate prognostic factors for reinjury, we must include a more fulsome characterization of the athlete's psychological state by including factors that are known to affect athletic performance, wellness, and injury risk such as but not limited to sleep[101,102] and general mental health[103,104] in prospective, longitudinal studies. Additionally, mental health literacy should be emphasized for coaching staff, athletes, and the associated healthcare team, as well as careful consideration and contextualization of biopsychosocial and environmental factors that contribute to general mental health, and ultimately, athletic performance, wellness, and risk of [re]injury.[103,104]

4.4 | Practical applications and future directions

As seen in Figure 4, this review highlighted a wide variety of potential connections between biomechanical asymmetry metrics and introspective state assessments in healthy competitive athletes. The studies which reported connections between introspective state and biomechanical asymmetry measures primarily reported trends between assessments of strength, ROM, or vertical jump kinetics and kinematics with assessments of pain and RPE, among a handful of others. Surprisingly, many introspective metrics known to impact athletic performance, such as sleep and general mental health[101–104] were not identified in this scoping review. While hope, anxiety, and fear were identified in some articles,[39,64,65,68,73] these were often more associated with athletics or reinjury, rather than aspects of general mental health and well-being, which is especially concerning following the COVID-19 pandemic whereby nationwide surveys have indicated up to a two times increase in mental health disorders.[105] In addition to the lack of incorporation of relevant introspective factors such as sleep and general mental health in sports medicine research that concurrently assesses biomechanical asymmetry, the sporadic and single-domain monitoring of competitive athletes' psychological state was further demonstrated in recent work by Neupert and colleagues.[106] The study conducted by Neupert and colleagues[106] highlighted that while many elite sporting organizations cite the use of athlete self-report measures that are purported to be backed by research, most of which appear to be single items questionnaires that were not necessarily validated. Furthermore, Neupert and colleagues[106] noted that there was often a divide between researchers/clinicians and elite sporting organizations, whereby feedback processes are felt to be insufficient and ineffective. Therefore, if introspective psychological states are to continue being incorporated in assessments of sport performance, injury risk, and risk of reinjury, novel streamlined self-report questionnaires that can be easily completed by athletes and used to gather and monitor information on the many domains of introspective state (e.g., pain, fatigue, exertion, sleep quality and quantity, anxiety, etc.) should be developed, with the results of these multidomain questionnaires being regularly communicated to and discussed with competitive athletes, coaching staff, and the associated healthcare team. However, while validation is important, practicality must be kept in mind when developing novel multidomain questionnaires so that the overall breadth of questions involved and the frequency by which these questionnaires are administered are not deterrents to compliance rates and utility in prospective, longitudinal contexts. Collecting all measures longitudinally is not possible, but determining a minimal set of criteria in a validated questionnaire is. As such, we urge researchers and clinicians to work with end-users in developing projects and questionnaires that are not only meaningful to the researcher and stakeholders, but practical for the athletes as well. Furthermore, the data that are obtained from these multidomain questionnaires should be contextualized on a subject-level basis with biomechanical data, such as asymmetry, for patient-centered preventive and prognostic purposes.

Additionally, given that lower limb asymmetry has been demonstrated to be a task-specific measure, and varies between muscle groups, motor task, and outcome measure of interest,[107,108] the seldom collection of sport-specific biomechanics and asymmetry (i.e., on-field or on-court) which would be most telling of sport performance and risk of [re]injury is concerning. The majority of research focuses on biomechanical asymmetries present during musculoskeletal strength, ROM, and jumping assessments; however, due to task-specificity,[107,108] these asymmetries may be vastly different than those seen in sport-specific settings.[109] Moreover, while a 10%–15% threshold is often cited for meaningful within- and between-limb differences,[11,110] there may be large between and within athlete variability[10,11,111–113] that can make these metrics challenging to interpret with any level of consistency and at the group level, especially without complementary information on the introspective psychological state of the athlete. Therefore, given the recent development and availability of wearable technology that permits clinicians, practitioners, and researchers to bridge the gap between traditional in-lab and real-world or sport-specific assessments,[6,109] it will be important to also gain context of movement patterns and asymmetries existing within their daily training and competition, and to contextualize changes in lower limb asymmetry with changes in psycho-social factors for preventive and prognostic purposes.

Next, while 23 studies used a repeated-measures study design, only four of which monitored athletes longitudinally throughout one or more competitive season(s). Across a sporting season, both the biomechanical load and asymmetry,[112,113] and psychological stress[103] incurred by an athlete can change dramatically, often largely increasing during competition periods, and thus contributing to potential changes in performance level or injury risk. As such, prospective, longitudinal studies aimed at determining how periods of accumulated or abrupt external (objective work performed) and internal (compounded physiological and psychological stress) workload intensification during various stages of competition coupled with changes in lower-limb biomechanics and asymmetry affect sport performance and risk of [re]injury should be included in future research. This can be accomplished with the use of innovative and accessible wearable technology that permits clinicians and researchers to monitor competitive athletes outside of traditional lab- and field-based assessments in real-world, sport-specific settings, which may be more indicative of biomechanical asymmetry that is relevant to sport-performance and injury susceptibility.

Lastly, there was a lack of diversity in both sport and level of competition identified, such that soccer and professional or semiprofessional athletes were overrepresented in the literature. Additionally, while the inclusion of male and female athletes in this review appears to be evenly distributed, 73% of the included female athletes in this scoping review have come from four recent (i.e., 2014–2021) female-only studies[38,63,70,81] in an effort to increase the inclusion of female athletes in this research landscape. This highlights a potential barrier in equity, diversity, and inclusion in sports medicine research, whereby there is an underrepresentation of female athletes, and in which sports and level of competition with access to funding are disproportionately favored, which has been highlighted in a similar scoping review conducted by Benson and colleagues.[6]

4.5 | Limitations

There are some noteworthy limitations to the present investigation. First, pain is discussed throughout this review, which includes both the overarching construct and intensity of this perceived pain. Additionally, the location, methodology used to report, and cueing used to contextualize such pain are heterogeneous throughout the included literature, and this review might under- or overestimate the associations that exist with biomechanical asymmetry due to these generalizations. Next, this review included healthy, actively participating competitive athletes, and excluded studies that have concurrently collected biomechanical asymmetry and introspective psychological state in injured competitive athletic populations. While relationships have been identified between these constructs in RTS settings,[23–27] the importance of the connection between biomechanics and psychology has been largely neglected in healthy competitive athletes, and this review provides an important, foundational step toward understanding how these domains of health are related and their potential implications to sports performance and injury risk. Last, studies included in the present scoping review were required to collect biomechanical asymmetry. Therefore, there is the possibility that relevant literature where other relationships have been identified between biomechanics and psychology without stratifying biomechanical measures into unilateral terms for between-limb comparison may have been missed.

5 | CONCLUSION AND PERSPECTIVE

The present scoping review highlights the existing but limited research relating measures of lower limb biomechanics and asymmetry with introspective psychological state in healthy, competitive athletes. While informative relationships exist between these domains, they are limited in their scope, as many introspective psychological factors known to affect sport performance and injury were largely neglected, and biomechanical asymmetry assessments in sport-specific settings (i.e., on-court or on-field) were limited. Furthermore, the majority of relationships identified pertained to cross-sectional investigations, with minimal research assessing the relationship between biomechanical asymmetry and introspective state in prospective, longitudinal contexts throughout one or more competitive season(s). Therefore, longitudinal, and concurrent analyses examining the relationships between biomechanical asymmetry and introspective states are needed to provide a more complete understanding of the contributory factors that may affect sport performance, injury risk, and risk of reinjury from a biopsychosocial and holistic perspective. In doing so, this framework of biopsychosocial preventive and prognostic patient-centered practices may provide an actionable means of optimizing health, well-being, and sport performance in competitive athletes.

AUTHOR CONTRIBUTIONS

JAJK, ZM, and DK participated in the design of the study; JAJK, EEW, ZM, SM, ACP, MCR, SK, and DK contributed to data collection; JAJK, EEW, ZM, SM, ACP, MCR, SK, and DK contributed to data reduction/analysis; JAJK, EEW, CB, MJJ, JJH, and DK contributed to the interpretation of the results; JAJK, EEW, CB, MJJ, JJH, and DK contributed to the manuscript writing. All authors have read and approved the final version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

DATA AVAILABILITY STATEMENT

Given this a review, all data is gathered from publicly available sources (i.e., published studies). Further, any meaningful data extracted from these sources is included in the manuscript or its tables. As such, there is no utility in having a separate repository for data.

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APPENDIX A

TABLE A1 Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) checklist.

Section	Item	Prisma-ScR checklist item	Reported on page #
Title			
Title	1	Identify the report as a scoping review.	Title page/1
Abstract			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
Introduction			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	3 and 4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	3 and 4
Methods			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	N/A
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	4
Information sources[a]	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	4
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Appendix A
Selection of sources of evidence[b]	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	4
Data charting process[c]	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	5
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	5
Critical appraisal of individual sources of evidence[d]	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	5

TABLE A1 (Continued)

Section	Item	Prisma-ScR checklist item	Reported on page #
Results			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	5 and Figure 1
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Tables 1 & 2, and Figures 2 & 3
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Tables 1 & 2, and Figure 4
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Pages 5–7
Discussion			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	7, 12–14
Limitations	20	Discuss the limitations of the scoping review process.	N/A
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	14
Funding			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Title page/1

Note: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al.[32]

Abbreviations: JBI, Joanna Briggs Institute; PRISMA-ScR, Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

[a] Where sources of evidence (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

[b] A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

[c] The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

[d] The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

APPENDIX B

B.1 | Complete search strategy

Search strategy individually optimized for each database based on the five broad topics of asymmetry, lower limb, movement/mechanics, athlete, and self-report joined using the AND search command/function.

B.2 | Web of Science core collection:

Asymmetry: TS=(asymmetr* OR symmetr* OR limb-dominance* OR lateralit* OR inter-limb OR intra-limb OR side adj5 difference OR imbalance OR side-to-side difference OR side difference OR lateral difference OR dominant adj5 non-dominant)

Lower Limb: TS=(lower-extremit* OR lower-limb* OR lower extremit* OR lower limb* OR lower body OR leg OR hip OR knee OR ankle OR foot OR Lower Extremity/).

Movement/Mechanics: TS=(ground reaction force OR GRF OR strength OR power OR range of motion OR flexibility OR landing OR kinematic* OR kin* OR run* OR jump* OR biomechanic* OR mechanic*)

Athlete: TS=(athlete* OR athletic* OR team* OR sport* OR player* OR Athletes/ OR Sports/ OR Team Sports/)

Self-Report: TS=(fatig* OR exhaust* OR weari* OR tired* OR exert* OR stress OR load OR strain OR effort OR pain* OR rpe OR mental OR questionn* OR surve*).

B.3 | Medline/Embase:

Asymmetry: (asymmetr* OR symmetr* OR limb-dominance* OR lateralit* OR inter-limb OR intra-limb OR side-to-side difference OR side difference OR lateral difference).mp OR (side adj5 difference OR imbalance).mp OR (dominant adj5 non-dominant).mp

Lower Limb: (lower-extremit* OR lower-limb* OR lower extremit* OR lower limb* OR lower body OR leg OR hip OR knee OR ankle OR foot).mp OR Lower Extremity/.

Movement/Mechanics: (ground reaction force OR GRF OR strength OR power OR range of motion OR flexibility OR landing OR kinematic* OR kin* OR run* OR jump* OR biomechanic* OR mechanic*).mp

Athlete: (athlete* OR athletic* OR team* OR sport* OR player*).mp OR Athletes/ OR Sports/ OR Team Sports/

Self-Report: (fatig* OR exhaust* OR weari* OR tired* OR exert* OR stress OR load OR strain OR effort OR pain* OR rpe OR mental OR questionn* OR surve*).mp.

B.4 | Cinahl/SPORTDiscus:

Asymmetry: TX=(asymmetr* OR symmetr* OR limb-dominance* OR lateralit* OR inter-limb OR intra-limb OR side adj5 difference OR imbalance OR side-to-side difference OR side difference OR lateral difference OR dominant adj5 non-dominant)

Lower Limb: TX=(lower-extremit* OR lower-limb* OR lower extremit* OR lower limb* OR lower body OR leg OR hip OR knee OR ankle OR foot OR Lower Extremity/).

Movement/Mechanics: TX=(ground reaction force OR GRF OR strength OR power OR range of motion OR flexibility OR landing OR kinematic* OR kin* OR run* OR jump* OR biomechanic* OR mechanic*)

Athlete: TX=(athlete* OR athletic* OR team* OR sport* OR player* OR Athletes/ OR Sports/ OR Team Sports/)

Self-Report: TX=(fatig* OR exhaust* OR weari* OR tired* OR exert* OR stress OR load OR strain OR effort OR pain* OR rpe OR mental OR questionn* OR surve*).