

Sacroiliac Joint Dysfunction in Endurance Runners Using Wearable Technology as a Clinical Monitoring Tool: Systematic Review.

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Abstract

Background: In recent years, researchers have investigated the relationship between the anatomy and biomechanics of sacroiliac joint (SIJ) pain and dysfunction in endurance runners in order to understand the relationship between lower back pain and the SIJ. However, the majority of SIJ pain and dysfunction is diagnosed and managed via a traditional athlete-clinician arrangement whereby the athlete is required to attend regular in-person appointments. Wearable sensors are increasingly being utilized as clinical diagnostic tools to monitor an athlete's day-to-day activities. Yet the occurrence of wearables being utilized in a remote setting to manage SIJ dysfunction in endurance runners is unknown.

Objective: This paper presents a systematic literature review (SLR) concerning wearable technologies and systems with scenarios for handling SIJ dysfunction in endurance runners in a remote setting.

Methods: Literature on SIJ movement and dysfunction and usage with wearables was reviewed by searching through the publication databases.

Results: An initial 45 papers were analyzed which was subsequently reduced to 21 after further review. Of the 21 studies over half were literature reviews, four were case reports and none could be classified as fully experimental.

Conclusions: SIJ dysfunction is an underdiagnosed and undertreated in endurance runners. In addition, there is no clear diagnostic or treatment pathway using wearables remotely despite the technology being readily validated and available.

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Original Paper

Sacroiliac Joint Dysfunction in Endurance Runners Using Wearable Technology as a Clinical Monitoring Tool: Systematic Review.

Abstract

Background: In recent years, researchers have investigated the relationship between the anatomy and biomechanics of sacroiliac joint (SIJ) pain and dysfunction in endurance runners in order to understand the relationship between lower back pain and the SIJ. However, the majority of SIJ pain and dysfunction is diagnosed and managed via a traditional athlete-clinician arrangement whereby the athlete is required to attend regular in-person clinical appointments with a range of allied health professionals. Wearable sensors (wearables) are increasingly being utilized as a clinical diagnostic tool to monitor an athlete's day-to-day activities in a remote setting, negating the need for in-person appointments. Yet the occurrence of wearables being utilized in a remote setting to manage SIJ dysfunction in endurance runners is unknown.

Objective: The purpose of this study was to systematically review the literature and gain a better understanding of the use of wearables in both in-person and remote settings for the purpose of biomechanical-based rehabilitation in SIJ dysfunction in endurance runners. Addressing this issue, the overall goal was to investigate how wearables can contribute to the *pre*, *at* or *post* clinical diagnosis of SIJ dysfunction.

Methods: Three online databases including PubMed, Scopus and Google Scholar were searched according to different combination of keywords. A total of 4097 article were initially identified, and ultimately 45 articles were analyzed which was subsequently reduced to 21 which were then included in this study after removal of duplicate and articles screening according to inclusion and exclusion criteria.

The quality of the investigation was assessed by the using the PRISMA evidence-based minimum set of items for reporting in systematic reviews.

Results: Of the 21 studies included in this review, over half of the investigations were literature reviews of wearable sensors in the diagnosis and treatment of SIJ pain, or wearable movement sensors for rehabilitation or a combination of the above for SIJ gait analysis in an intelligent healthcare setting. Four (52.2%) were case reports and only one could be classified as fully experimental. One paper was classified as being at the pre stage of SIJ dysfunction while six (42%) were identified as being at the at stage of classification. Considerably fewer attempted to capture or classify actual SIJ injuries, and no study directly addressed the injury recovery stage.

Conclusions: SIJ dysfunction is an underdiagnosed and undertreated in endurance runners. In addition, there is no clear diagnostic or treatment pathway using wearables remotely despite the technology being readily validated and available. Further research with higher quality is recommended to conduct and more investigations on SIJ disfunction in endurance runners and rehabilitation usage with wearables in remote settings.

Keywords: sacroiliac; sacroiliac dysfunction; sacroiliac wearables; sensors; injury management.

Introduction

Physical activity, exercise and sport are increasingly promoted as part of a healthy lifestyle. However, increased participation in physical activity and sport specialization may raise the risk of injury [1]. Running remains one of the most prevalent forms of physical activity, attracting individuals of all capability and ability levels to engage in this form of cardiovascular exercise. However, the burden of running related injuries and their potential impact on quality of life and societal costs call for research and effective interventions in all the areas associated with sports injury, namely prevention, assessment, and recovery [2-3]. One of the most overlooked sources of low back pain (LBP) in endurance runners is injury to the sacroiliac joints (SIJs) [4].

The SIJs are the largest axial joints in the body and sit between the sacrum and pelvic bones on either side. The SIJs connect the spine to the pelvis and facilitate load transfer from the lumbar spine to the lower extremities. Specifically, the SIJs sit between the iliac's articular surface and the sacral auricular surface. Therefore, the SIJ supports the torso and upper body muscular to dampen the impact of ambulation as the SIJ joint can experience forces of shearing, torsion, rotation, and tension when running. To improve and promote the efficiency in running whilst focusing on injury prevention, allied health professionals are exploring different preventative, monitoring and rehabilitative methods.

Different investigations have occurred to determine the factors can aid in the management and underlying biomechanics that cause SIJ dysfunction and pain [3-4]. One consideration is using wearable sensor technology for the purpose of clinical monitoring. In this regard, wearable sensors (wearables) incorporate a broad range of advances in microelectromechanical (MEMS) [5], electrocardiogram (ECG) [6] electromyogram (EMG) [7] and electroencephalogram (EEG)-based neural sensing platforms [8]. Since injuries such as SIJ dysfunction can require frequent monitoring, the continuousness of patient/athlete monitoring for timely intervention and rehabilitation seems essential. Wearables present an opportunity to measure the biomechanical parameters of SIJ dysfunction in a continuous, real-time, and nonintrusive manner by leveraging electronics packaging technology. It has been conveyed that by leveraging this technology, more time for engagement, continuity of experience, and dynamic data for decision-making for both athlete and clinicians will endure [9]. While remote and ambulatory monitoring are growing needs in the healthcare environment [10], the efficacy surrounding wearables in remote monitoring relative to SIJ dysfunction are largely unknown. This is despite acknowledgement that remote monitoring provides increased data volume and can promote improved athlete performance [11] and can accelerate the patient/athlete rehabilitation processes [12]. Furthermore, an apparent limitation of existing research is that there has been a focus on the effectiveness of wearables on running performance metrics that generally do not consider the ongoing rehabilitative considerations. Strategies for the prevention of [14] and recovery from SIJ injury have been proposed [3], alongside models of injury causation [15] and injury factors (e.g., intrinsic vs. extrinsic; modifiable vs. not modifiable) [16] has been offered. In turn, this has potential to help monitor compliance, quality, and progress of movement performance when an injury-prevention or return-to-activity program is implemented [17]. Clinicians and allied health professionals will explore different training methods of preventive and rehabilitative measures but rarely evaluate together with biomechanics parameters and its effect on SIJ dysfunction. Thus, there is a need for evidence-based information on how wearables could be used for rehabilitation purposes in a remote setting when SIJ dysfunction is considered.

To maintain pace with the rapidly evolving field of wearables in endurance runners, this review

provides an update on the state of the literature with a particular focus on literature published in the past ten years. Case studies illustrate the use of wearable data in development or monitoring of running programs. For the purposes of this review, “wearable device” was operationally defined as a device that can be attached to the runner, shoe, or garment — or is a smartphone application. Thus, the purpose of this study was to systematically review the literature and gain a better understanding of the use of wearables in both in-person and remote settings for the purpose of rehabilitation in SIJ dysfunction in endurance runners. Addressing this issue, the overall goal was to investigate how wearables can contribute to the pre, at or post clinical diagnosis of SIJ dysfunction.

Methods

Design and reporting of this review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [18]. The general search strategy and search terms are described in Table 1. Articles published up to 1 October 2022 were reviewed.

Table 1. Systematic search strategy and key terms used.

Wearable technology	"Wearable Biomechanics" OR "Wearable Technology" OR "Wearable Devices" OR "Wearable Sensors Biomechanics" OR "IMU" OR "Inertial Sensor" OR "Inertial Measurement Unit" OR "Gyroscope" OR "Magnetometer" OR Accelerometer* OR "Pressure insoles" OR "Remote Wearables" TITLE-ABS-KEY.
Running gait	"Running Biomechanics" OR "Endurance Running" OR "Run" OR "Jog" OR "Running over 5 km" OR "Endurance Runners" OR "Long Distance Runners" OR "Athletics" TITLE-ABS-KEY
Sacroiliac joint	"SIJ pain" OR "SIJ rehabilitation" OR "SIJ dysfunction" OR "SIJ injury prevention" or "SIJ management". TITLE-ABS-KEY

Thereafter, the selection process consisted of the following steps using the PRISMA guidelines (Figure. 1): (1) an initial title screen for relevant articles was performed once the searched database results had been combined and duplicates had been removed; (2) both the titles and abstracts of the selected articles were then reviewed (a review of the full text was completed if it was not clear from the title or abstract whether the study met the review criteria); and (3) the full texts and selected articles were read based on the inclusion/exclusion criteria.

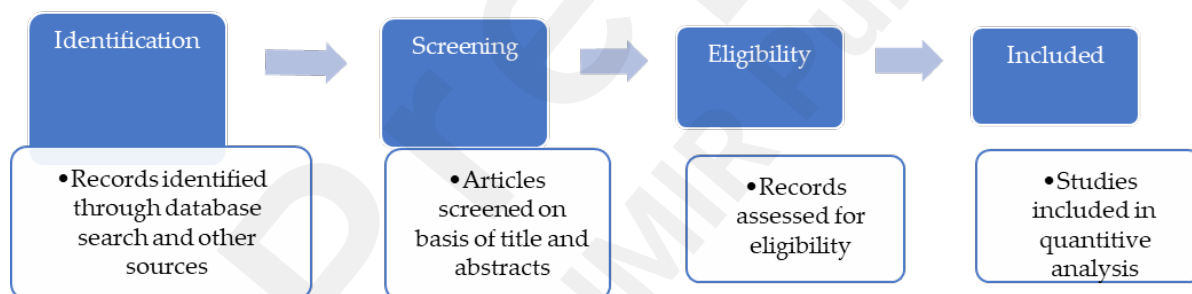


Figure 1. Flow diagram for PRISMA guidelines used.

A systematic search was conducted to identify potentially relevant papers in the following scientific databases: PubMed, Scopus, and Google Scholar. The focus of this review was on journal articles published in English that described the use of wearable technology to analyze, quantify, and emphasize wearables for remote monitoring in SIJ dysfunction and rehabilitation in endurance runners. This extends to endurance runners undergoing rehabilitation in SIJ dysfunction (i.e., had been diagnosed) or the ongoing management of SIJ dysfunction in previously diagnosed endurance runners (i.e., rehabilitation). For the purpose of this search strategy an endurance runner was considered as someone partaking in regular running related events (recreational, fun runs) or competitive based event (competition, professional, elite). An endurance runner was classified as athletes running more than 5 km in one protocol either during repeated trials or studies that classified participants as endurance runners. In line with the main objective, inclusion and exclusion criteria was established to help eliminate studies that were not aligned with the research questions. An

independent coder reviewed subsequent abstracts yielded from the search strategy and then the full articles for study selection. The review screened for information inclusive of health record, research systems including design, functionality, implementation, applications (remote and in-person settings) outcomes, and benefits. The search included articles published between 2000 and 2022. A manual review of the reference section of selected articles was then performed to identify relevant studies missed in the electronic search. Only English language articles were reviewed (Table 2).



Inclusion and Exclusion criteria

Table 2. Summary of Inclusion and Exclusion Criteria

Study Characteristic	Inclusion Criteria	Exclusion Criteria
Communication type	Journal, conference proceedings	Letters, short communications, technical notes, and other non-peer-reviewed literature. Non-evidence-based guidelines, letters to the editor, and expert opinion papers.
Injury classification	Pre, at or post the clinical diagnosis of SIJ dysfunction which included and/or incorporated the use of wearables as a viable method of evaluating SIJ motion.	Articles reporting exclusively on activity monitoring from global navigation satellite systems, injury surveillance without biomechanical measurements.
Classification of wearable	Accelerometer, gyroscope, magnetometer, or a combination of those (IMU), foot/shoe insoles (pressure mapping),	Temperature sensors, pulse oximeters, pressure sensors, correlated glycemic measurement sensors, bio-sensitivity techniques, smartphone applications and related sensors, rehabilitation, and monitoring ambulator based sensors
Defined running gait outcome measure	Spatiotemporal (global outcomes of the running gait cycle); running velocity, acceleration of the centre of mass (CoM), distance, displacement, ground contact time, step length, step frequency (cadence), stance time and flight time was included. Kinematics (description of segmental or joint movement, generally in the three cardinal planes: sagittal, coronal (frontal), transverse planes, without consideration for forces). Kinetic (the action of forces in producing or changing motion): for example, ground reaction force, peak pressure, centre of pressure, braking, impulse, time to peak pressure, pressure time integral, loads, force time integral, and contact area,	Studies aiming to determine running power or economy were excluded likewise were studies investigating walking gait variability or regularity. Studies evaluating robotic systems, exoskeletons, prosthetics, and virtual reality environments were excluded. Studies investigating the use of biofeedback or gait retraining (i.e., non-natural running gait) and studies involving use of altered weight conditions (e.g., wearable resistance, anti-gravity treadmills or water-based protocols). Computer algorithms, machine learning or statistical approaches and those using robotic systems, exoskeletons, prosthetics, and virtual reality environments.

Participant	> 18 years, male and female. Endurance running classified to runners regularly completing over 5 km in training and/or competitive situations.	< 18 years. Endurance runners not regularly completing over 5 km in training and/or competitive situations. Studies done on animals and cadavers.
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Although no restriction was imposed on the types of wearable technology used in SIJ dysfunction, the search terms were primarily focused on wearable inertial sensors and IMU devices (Table 3).

Table 3 Comparative overview of wearable sensor modalities utilized in running today.

Category	Technology	Capabilities	Pros	Cons
Soft tissue injury prevention	Surface EMG	Identifies muscle recruitment and potential weaknesses	Small; wireless, provides live data	Low sign to noise ratio
Workload management and athletic performance	GPS, IMU, accelerometers	Distance, velocity, acceleration, deceleration, medio-lateral movement, work, power, dehydration, fatigue, athletic performance, detecting gait parameters.	Good range of data points	No biometric data; GPS can be pricey.
Cardiac health	ECG/PPG sensors	Heart rate, sleep rate, HRV, respiration, muscle oxygen saturation, atrial fibrillation, stress levels, respiration rates, blood volume, body temperature.	Accurate, cost effective.	Price point.

Note: Table refers to comparative overview of common wearable sensors currently available rather than the components used for analysis (i.e. some studies used an IMU, but only analyzed data from one element of the unit)

Study classification and assessment

Multiple feature domains of the studies selected were reported including (1) strength of evidence, time setting, and primary scope; (2) study characterization in terms of experimental conditions and setting (running field-based, running laboratory based using treadmills), age of endurance runners tested; and (3) characteristics of the technologies and types of wearable device and measures used relative to SIJ dysfunction. We also defined and assessed (4) the injury-research readiness level (IrRL) relative to SIJ dysfunction.

Selection process: strength of evidence, time setting, and scope

The strength of evidence of each article was assessed to three main categories in decreasing order of strength, based on the experimental design used: experimental, i.e., meeting the requirements of endurance running and SIJ dysfunction *at* or *post* clinical diagnosis and injury; randomized controlled trials; quasi-experimental, i.e., including a manipulation of the experimental conditions under which participants performed endurance running, but lacking random assignment or group comparison; and observational, i.e., without assessing the effects of an intervention, and only describing participant behaviour [19]. A separate class was used for studies looking exclusively at the validation of new equipment or methods. Literature reviews in wearables combined with synergies in remote settings and/or in endurance running related SIJ injuries were included and assessed by the primary author.

Classification and characterization of SIJ dysfunction

Studies must have classified and characterised the diagnosis of SIJ dysfunction. Therefore, akin to Preatoni et al. [20] an *at/post* classification was used to express the chronological relationship between the experimental data collected and the SIJ dysfunction in endurance runners. Thus, studies were classified as the *at* category if studies were identifying and classifying SIJ injury factors, diagnosis, or underlying mechanisms, and therefore attempted to capture or track SIJ injury occurrences in endurance running (e.g., cohort studies with biomechanical screening and in-field injury events that referenced use of wearable technology). Studies were classified as *post* if the data collection was performed after the SIJ injurious event, that is - during the SIJ recovery phase with the aim focused on rehabilitation techniques in both field based and laboratory environments where the endurance runner had received a clinical diagnosis of SIJ dysfunction. The *post* classification was also used for studies that assessed the likelihood of SIJ injury or a greater magnitude of dysfunction. For clarity, studies that examined endurance runners who had returned to full running activity (e.g., comparisons between healthy individuals and those with a history of a specific or existing SIJ injury) were classified as *pre*, because they were not centered on the recovery process that goes from injury occurrence (or medical intervention, if relevant) to being able to return to full running activity.

The characterization of studies was based on the following categories: (1) studies analyzing pre-existing running-related SIJ dysfunction using wearable technology and to monitor running biomechanics in both a field-based and laboratory setting for the purpose of clinical management and clinical management in a remote setting (*pre*); (2) studies assessing endurance running related SIJ dysfunction and/or injury factors or injury risk using wearable technology to monitor running biomechanics after SIJ dysfunction has been formally diagnosed and classified as in the acute stage of injury in both a field-based and laboratory setting for the purpose of clinical management (*at*); (3) studies assessing ongoing running related SIJ injury factors or injury risk using wearable technology to monitor running biomechanics after SIJ dysfunction has formally diagnosed and classified as in the chronic stage of injury in both a field-based and laboratory setting for the purpose of clinical management and/or management in a remote setting (*post*); and (4) studies attempting to establish injury threshold criteria from a biomechanical perspective; studies characterizing protective wearable devices; and studies focusing on *post* SIJ injury monitoring or return-to-run assessment using wearables. Validation and literature review studies were classified according to the primary aim for which the method or tool tested had been devised, as stated by the authors.

To describe the experimental conditions, information was extracted about the settings in which data were collected (i.e., laboratory- vs. field-based). Specifically, studies were labelled as field-based if wearable obtained data were acquired during a scheduled running training event; a simulated running training event, or a running competition in a specific setting. Conversely, investigations carried out within a laboratory, or in the field but using wearable technology were labelled accordingly. The stage of SIJ dysfunction addressed by the study was then classified as caused by overuse (chronic) or acute events further to Bahr et al. [15]. Furthermore, annotated classification of the endurance runner was addressed by each study (i.e., recreationally active, trained/developmental, highly trained/national level, elite/international, world-class, or not specified/insufficient data to be classified) [21]. The risk of bias was assessed by the primary author.

Injury-research readiness level

Building on the system readiness level (SRL) framework by Sauser et al (22), an Injury-research Readiness Level (IrRL) was modelled to capture the maturity, functionality, and readiness of the studies aiming to contribute to preventing, assessing, or recovering from SIJ dysfunction. According to the SRL model, technology and system development follow similar maturation paths, whereby technology is inserted into a system and interacts via a proposed architecture. Knowing about the

system components and their integration is important, and this knowledge allows a classification of the system as being in its research, development, or deployment stage [23]. In the context of SIJ dysfunction and endurance running-related injuries, for the purpose of this review a method is deemed mature for deployment only when it relies on measuring wearable tools that are characterised by high ecological validity (i.e., fully wearable and unobtrusive or markerless); can be applied directly in the field; is supported by validation studies against an established gold standard or, when validation is not practicable but adheres to standardised experimental procedures. Specifically, the biomechanical quantities pertaining to the SIJ should demonstrate evidence of a causal relationship with SIJ dysfunction and management in endurance running, and their interpretation should be driven by specific guidelines (e.g., individual- or population-based normative boundaries, thresholds, or trends) (Table 4).

Table 4. The injury-research readiness level classification model, where different classes of research maturity (IrRL1-3, in columns) are mapped against the following feature domains (rows): knowledge of causal relationship, experimental settings, testing technology, and normative guidelines.

IrRL1: Research	IrRL2: Development	IrRL3: Deployment
Exploring causal relationship	Building on established causal relationship	
Laboratory or in field setting		In field setting
Mixed instruments		No lab-based technology
Developing research perspectives		Using set guidelines

Data extraction and collection

After the data search was complete, data were obtained and extracted from eligible studies in a custom form that was created in Microsoft Excel. The form included, (1) Author, title, journal, publication year; (2) Research design; (3) Sample size, (4) Participant characteristics (age, gender, etc.); (5) Intervention features (type, length, and frequency); (6) Measures and settings (laboratory, field-based, the type of wearable technology used (sensor(s) (7) Analysis, (8) key findings relative to the *pre*, *at* and *post* for clinical SIJ dysfunction management using wearables in a remote and/or clinical setting, and (9) Research outcomes, the metrics used and conclusive statements. Data were then synthesised into a table format in Microsoft Excel and confirmed for data entry by the principal author. No automation tools were used in the process.

Results

From the 4097 articles identified through the database search (Google Scholar = 2263; Scopus = 1624; PubMed = 210), and after removing duplicate items, 2245 publications were excluded based on title, abstract and inappropriateness of topics (e.g., knee arthroplasty in endurance runners). A further search was then performed in the databases with exclusion criteria (“without the words”) “knee” AND “lower back” AND “hip”. A search “with the words” was then refined to include “remote”. An additional 551 articles were removed due to “knee” appearing in the article while 2 papers were removed due to not being written in English. A further 4 were removed due to the topic being limited to physiological assessments only. A total of 1295 articles remained. A further 585 articles were then discarded (most frequent reasons: not including wearables; not mentioning SIJ injury or SIJ dysfunction or running-related activities; and not describing the relationship between biomechanical quantities from wearables and SIJ, or not defining the injury-research readiness level

classification model relative to SIJ and wearable usage in endurance runners), yielding a total of 45 studies to be considered for review.

A total of 151 participants were identified as being runners or endurance runners from the 45 papers analysed. Sixty-five percent of the included studies either presented a review of wearable sensors in the diagnosis and treatment of SIJ dysfunction, or wearable movement sensors for rehabilitation or a combination of the above for SIJ gait analysis in an intelligent healthcare setting. Ten percent of the review papers analysed specifically mentioned wearable technology and the COVID-19 pandemic. However, only one of the review papers specifically mentioned measuring biomechanical loads and asymmetries in elite long-distance runners through inertial sensors. Ten percent of the reviewed papers were original research papers that reported on measuring biomechanical loads and contralateral pelvic drop in SIJ pain or examined the biomechanical effect spine-relief orthosis for treatment of SIJ pain in endurance runners. The remaining research papers specifically mentioned iliac stress fractures in endurance runners linked to the SIJ, hip pain or SIJ dysfunction. The remaining studies did not openly discuss the link between wearables and remote settings and SIJ dysfunction but mentioned such relationships as being possible or hypothetical. Thus, a total of 21 manuscripts remained, with overlapping reports on topics relative to SIJ dysfunction. No immediate forms of information bias (measurement bias) were detected in the final 21 studies.

Records identified through
database screening.
(n = 4097)

Additional record identified
through other sources.
(n = 0)

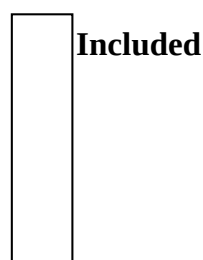


Figure 2. Final PRISMA flow diagram for articles selected for review.

Journals and years

The 21 original manuscripts included in the review appeared in over 11 different journals, with 11 journals publishing nearly half of the total, and at least 5 relevant articles published in orthopaedic, traumatology or physical therapy journals. One paper was published in a rehabilitation journal while three papers were published in technology and engineering journals. The number of articles in the area under scrutiny appears to increase over time, as seven papers were published since the onset of the COVID-19 pandemic in telehealth (remote), sensors, and machine learning in endurance running injury management. The use of wearables in field-based and self-reliant monitoring seems to be increasing in popularity, as also demonstrated by the seven review papers published between 2020 and November 2022.

More than half of the 21 studies scrutinised were literature reviews, four (52.2%) were case reports and one was classified as fully experimental. Five (37.5%) attempted to develop a predictive model or a machine learning approach to identify risk factors for running related SIJ dysfunction. One study was classified as being at the *pre* stage of SIJ dysfunction while six (42%) were identified as being at

the *at* stage of classification. Considerably fewer attempted to capture or classify actual SIJ injuries, and no study directly addressed the injury recovery (Table 5).



Table 5. Validity and reliability and application. Information extracted from each article included the classification of the study. Where N/A = not applicable. An at/post classification = if scope was to identify and characterize SIJ injury factors, diagnosis or underlying mechanisms, or track SIJ injury occurrences in endurance runners. Pre = pre SIJ dysfunction (before SIJ injurious event).

Author	Year	Location	Injury-research Readiness Level (IrRL)	Classification	Number and gender	Age	Metric(s)
Alcantara et al. [24]	2021	Force-measuring treadmill (laboratory)	IrRL1: Research (exploring causal relationship)	Validity (<i>at</i>)	37	20 ± 2	Quantified accuracy of applying quantile regression forest (QRF) and linear regression (LR) models to sacral-mounted accelerometer data to predict peak vGRF, vertical impulse, and ground contact time across a range of running speeds.
Whitney et al. [25]	2022	Treadmill (laboratory)	IrRL2: Development (building on established causal relationship)	Case control (<i>at</i>)	81 runners with SI pain (runners without SI pain (n=63); Runners with SI pain (N=18)	27.3 ± 12.9 23.8 ± 10.5	In midstance, runners with SI pain had greater contralateral pelvic drop compared to controls. For unilateral SI joint pain cases (N=15), greater contralateral pelvic drop was observed when loading their affected side compared to the unaffected side. Female runners with SI joint pain demonstrated greater contralateral pelvic drop during midstance phase; along with less knee flexion, greater “tibial overstride”, and greater ankle dorsiflexion at initial contact compared to controls.
Höfer & Siemsen [26]	2008	Treadmill (laboratory)	IrRL1: Research (exploring causal relationship)	Application (<i>at</i>) (proof of concept)	3 male participants	-	Computations showed the pressure between the sensor contact area and the lumbar region was measured with FSR sensors.
Amorosa et al [27]	2014	N/A	IrRL1: Research (exploring causal relationship)	Review	1 female	24	Report on a second case of an isolated stress fracture of the iliac wing in a female marathon runner and the associated diagnosis of the female athlete triad.
Ueberschär et al. [28]	2019	Treadmill (laboratory)	IrRL2: Development	Experimental (<i>pre</i>)	45 healthy junior-elite	-	Mean peak tibial accelerations in junior elite long-distance runners ranged between 14 ± 3 and 16 ± 3 g (g ≈ 9.81 m s ⁻¹)

			(building on established causal relationship)		long-distance runners		for running speeds of 14–16 km h ⁻¹ . Corresponding mean peak sacral and scapular accelerations amounted to 4 ± 1 g to 5 ± 1 g (32 ± 8% of tibial load) and 4 ± 1 g (27 ± 6%), respectively.
Liu et al. [29]	2021	N/A	IrRL1: Research (exploring causal relationship)	Review	N/A	N/A	Daily monitoring of basic health data by wearable devices supports physicians to detect the health problem. However, most current wearable sensors are not accurate enough for clinical evidence
Banos et al. [30]	2015	Laboratory	IrRL1: Research (exploring causal relationship)	Application (proof of concept/case report)	1 male	Not stated	A novel mobile health system to support trunk endurance assessment. The system employs a wearable inertial sensor to track the patient trunk posture, while portable electromyography sensors are used to seamlessly measure the electrical activity produced by the trunk muscle
Falowski et al. [31]	2020	N/A	IrRL1: Research (exploring causal relationship)	Review	N/A	N/A	A review and algorithm in the diagnosis and treatment of sacroiliac joint pain
Zadeh et al. [32]	2021	Laboratory	IrRL2: Development (building on established causal relationship)	Application (at) (proof of concept)	55 (39 male, 16 female)	21.1 ± 3.84 (male), 20.1 ± 1.18 (female)	Proof-of-concept that wearable technology has the potential to predict injury in sports.
Porciuncula et al. [33]	2018	N/A	IrRL1: Research (exploring causal relationship)	Review	N/A	N/A	Wearable movement sensors for rehabilitation: a focused review of technological and clinical advances
Lorussi et al. [34]	2018	Field-based	IrRL3: Deployment	Application (at) (proof of	N/A	N/A	A wearable system for remote monitoring of the treatments of musculoskeletal disorder

				concept)			
Shen et al. [35]	2021	N/A	IrRL1: Research (exploring causal relationship	Review	N/A	N/A	Digital technology-based telemedicine for the COVID-19 pandemic
Nascimento et al. [36]	2020	N/A	IrRL1: Research (exploring causal relationship	Review	N/A	N/A	Sensors and systems for physical rehabilitation and health monitoring
Charna et al. [37]	2021	N/A	IrRL1: Research (exploring causal relationship	Review	N/A	N/A	The rise of wearable devices during the COVID-19 pandemic: a systematic review
Rahlf et al. [38]	2022	N/A	IrRL1: Research (exploring causal relationship	Application (at) (proof of concept)	N/A	N/A	Proof of concept using runners who run at least 20 km. Prospective longitudinal cohort study using statistical analysis of the data is performed using machine learning (ML) methods.

Experimental setting

In the two field-based studies that analysed endurance runners during either the *at* or *post* SIJ dysfunction, investigations were either case-study based or were classified as proof-of-concept. No studies included this review were deemed to be experimental or classified as an observational study design pertaining to the use of wearables in a self-monitoring and/or a remote rehabilitation capacity. This was despite most of the studies being literature or systematic reviews that focused on wearables for the purpose of self-monitoring, self-monitoring in a remote setting or a combination of both.

Participant characteristics

Overall, the studies included between one participant [27] and 81 participants [28], with the mean number of participants $21 (\pm 32)$. The mean age of participants was $22.2 (\pm 3.7)$ years. None of the selected studies performed a comparison of SIJ dysfunction and related gait patterns across the selected age groups nor did they compare SIJ dysfunction using a validity approach in wearables. Many of the studies included both male and female participants, however, none of the selected studies examined differences between male and females in SIJ dysfunction using wearables. One study [28] focused on female runners with SIJ or sacral stress fractures while another [26] used male only participants using pressure sensors in the lumbar region. Given the discrepancy in participant characteristics, a source of inequity, that is gender bias – was prevalent in some studies analyzed.

Clarification of SIJ pathomechanics

Overall, the SIJ appears to function as a stabilizer of the pelvis, absorbing ground reaction forces during gait and shear forces during movement [6]. The SIJ has also been described as a multidirectional force [39]. Activities that involve a one-leg stance such as running would presumably increase the force in each SIJ, yet this was not specifically mentioned in the studies. Similarly, this would influence the vertical ground reaction force that occurs with each step. Another significant influence is the centre of mass (CoM, which is in slightly different positions for men and women). One study noted the importance of the CoM, particularly in women as the CoM commonly passes in front of or through the SIJ [40]. Some of this can be explained due to sexual dimorphism being apparent in the pelvis with the female sacrum being wider and with a more backward tilt. This would also account for the higher loads and stronger SIJs that are commonly seen in men [41]. This characteristic also may explain why men have more restricted mobility, as the average movement for men is approximately 40% less than that of women [42]. In this regard, the mechanism of SIJ dysfunction is primarily due to a combination of axial loading and abrupt rotation [43]. De Rosa and Porterfield [44] describe the main influences as the force of gravity acting downwards through the spine creating the flexion moment of the sacrum on the ilium, and the ground reaction force traversing upwards through the lower extremity from heel strike creating a posterior rotational (termed "torsional") moment of the ilium on the sacrum; they termed these motions sacroiliac and

iliosacral respectively. Falowsj et al. [31] presented an algorithm in the diagnosis and treatment of sacroiliac joint pain. In this case, the authors believed that SIJ pain is an underdiagnosed and undertreated element of lower back pain. Citing an emerging disconnect between the growing incidence of diagnosed SI pathology and underwhelming treatment efficacy of medical treatment, they created a diagnostic and treatment pathway to establish an algorithm for patients that can include conservative measures and interventional techniques once the diagnosis is identified.

Classification of wearables

Eight studies used wearables in some form, however, only one study used a sensor (a triaxial accelerometer) to measure biomechanical loads in endurance runners [28], although this study did not specifically review SIJ dysfunction. In the 8 studies that mentioned wearables, accelerometers and gyroscopes featured but the authors did not provide enough information to establish the type, range, and technical specification of the devices. There was a large range in reported usage of temperature sensors, pulse oximeters, BioHarness wearable technology, pressure sensors, correlated glycemic measurements, bio-sensitivity techniques, electrodes, environmental monitoring, smartphone accelerometers, and next-generation wearable movement sensors despite these studies not specifically mentioning SIJ in endurance runners (Table 6).

Table 6. Breakdown of various approaches used for wearables.

Referred to sensors' validation within the cited article	Compared to gold standards (e.g., stereophotogrammetry, force platforms, high-speed video, or photocells) [32-37].
	Comparing classification results against human\ validated software classification [33-38]
Pilot or proof studies	Biomechanical effect of a lumbar spine-relief orthosis for treatment of sacroiliac pain [26].
Referred to ad hoc procedures for the performed measures	Describing procedures for SIJ monitoring or pain management measures using machine learning or similar approaches [46, 47].

In the reviewed studies that used proof of concept designs [32, 38], these studies included generic descriptions of wearables relating to self-monitoring usage and remote rehabilitation monitoring despite inadequate information provided pertaining to SIJ or SIJ for the purpose of rehabilitation in endurance runners. Furthermore, while describing the technical features of the wearable is key to the accurate clarification of data quality and of the implication of the changes that a remote intervention may encourage, many studies did not report this information in sufficient detail. Notably, and as highlighted by recent systematic reviews on wearables and inertial sensors for sport performance evaluation

[48], and on accelerometry of impact loading in runners [27], reporting the features of the wearable device used—as well as information on the attachment location and fixing methods—is essential.

Discussion

This review examined 21 studies that examined the effects of wearable usage in remote settings in SIJ dysfunction in endurance runners. A secondary purpose of this review was to evaluate the effectiveness of wearables in possible or probable SIJ rehabilitation programs for endurance runners. Explicitly, this review reported on the: (1) strength of evidence, time setting, and primary scope of studies relating to SIJ dysfunction in endurance runners; (2) characterization of SIJ dysfunction in terms of experimental conditions and setting (running field-based, running laboratory based using treadmills), age of endurance runners tested; and (3) characteristics of the technologies and types of wearables and measures used relative to SIJ dysfunction in endurance runners. We also defined and assessed (4) the injury-research readiness level (IrRL) relative to SIJ dysfunction. This review has demonstrated that the use of wearable technology for SIJ dysfunction monitoring in endurance running either from a laboratory or from a remote (telehealth) perspective is emerging, but further work is required to establish a standardized methodology and the validity or reliability of instrumentation.

We have provided a comprehensive overview of wearable technology used for a SIJ dysfunction in endurance runners, and here we provide recommendations for future work.

Injury type and classification

The quality of the included studies varied with one of the most challenging aspects of diagnosing and treating SIJ dysfunction in the endurance running population appearing to be the inconsistent judgement and, in some instances, concerning the presentation of the injury. The main difficulty faced by authors appears to be the diagnostic challenges given that the pathomechanics and diagnostical classification of SIJ dysfunction is inconsistent in the literature. This was mainly observed in studies that referred to SIJ dysfunction as either a potential source of lower back pain or symbolic of hip related issues. Moreover, lumbopelvic rhythm was used as a definitive term by some authors. This, then, makes any possible deployment of wearables for rehabilitation purposes challenging if the diagnosis is either missed or misdiagnosed. Because specific characteristics of SIJ dysfunction in endurance runners were required for investigations, the number of eligible participants was limited given that acute injuries were investigated primarily in one study [27] and chronic SIJ dysfunction in another [25], both of which occurred in control settings. No study was found to monitor acute or chronic SIJ dysfunction using wearables in a remote setting.

There were additional variations amongst the reviewed studies. While two studies examined the usability of wearables through active engagement with endurance runners, many studies lacked considerations for the wearer's physical, psychological, and social preferences regarding the technology. Although one study looked at the *pre* stage of SIJ

dysfunction, many studies (42%) were found to be at the *at* stage of injury classification. However, it is important to consider the practicality of using wearables to classify SIJ dysfunction at the *pre* during running. Further research exploring the feasibility and necessity of utilizing wearables is required, or whether this is feasible given the apparent difficulty in diagnosing SIJ dysfunction. Further research will enhance understanding at how wearables could be used at the onset of possible SIJ dysfunction to deliver the most pertinent data while enabling a clinical diagnosis.

A major issue in the approach to wearable instrument application is that more than half of the 21 studies analyzed were literature reviews, four (52.2%), and one was classified as fully experimental relative to classification of SIJ dysfunction. The results showed that while different wearables have been used for the analysis of biomechanical parameters in running gait analysis, and some relevant SIJ parameters pertaining to diagnostic or predictive stages of SIJ dysfunction, a paucity of research exists in the rehabilitation and remote monitoring of SIJ dysfunction. Indeed, our findings show that different descriptions related to possible or probable SIJ diagnosis exist in that injury classification is also referenced in relation to lower back pain and lumbopelvic rhythm. This, then, makes it difficult to draw firm conclusions regarding how wearables could be deployed remotely for rehabilitation purposes. Therefore, we are beginning to understand that the *at* stages of SIJ dysfunction requires more than a concentration on the risk factors associated with injury occurrence.

Evidence also suggests that SIJ rehabilitation using wearable technology, both in controlled and remote settings, are highly nuanced (i.e., varying across classification, injury stage, diagnosis, participant age and gender). This may extend to the confusion in terminology and diagnosis between lower back injury and SIJ dysfunction given that possible differences in running gait mechanics when running in a controlled (e.g., laboratory) and remote setting. For example, one study noted that the most common complaints include pain in the lower back, buttocks, leg, groin, and hip [49]. However, while some studies acknowledged that pain originating from the lower back region is likely more common than most endurance runners realize due to difficulty in localizing symptoms and referred pain patterns, our results suggest that reference to running-related SIJ issues was infrequent. This is not necessarily surprisingly as low back pain (LBP) is among the most common human health problems and accounts for a significant amount of disability worldwide [50]. Interestingly, the SIJ has been estimated to contribute to pain in as much as 38% of cases of LBP [51]. Although topographical classifications such as 'sacroiliac', 'pelvis' and 'spine' serve a crucial didactic purpose, they can impede understanding of normal and altered functional SIJ mechanisms. Because different classifications exist it remains somewhat unknown if greater SIJ dysfunction in endurance runners exists, thus making any reference to the possible role of wearables relative to injury classification and rehabilitation in remote monitoring challenging.

What is commonly stated amongst the papers reviewed was that clinical examination of an endurance runner with SIJ dysfunction commonly begins with an evaluation of gait. Our results suggest that this often commenced in a clinical setting with ongoing monitoring of the condition commonly requiring the patient to be in the same clinical and

controlled setting. It is at this juncture where wearables could be used in a remote and personalized setting whereby data is fed to the clinician to monitor and track gait related patterns or irregularities. Notwithstanding the literature reviews discussed in the current paper that highlight the obvious and practical gap in using this technology in an SIJ dysfunction setting, more research is needed to test the feasibility and validity of the different wearable devices currently available. This extends to the level of expertise needed to operate and interpret the data from an operator, athlete (runner) and clinician perspective. Additionally, our results point to lumbopelvic rhythm (LPR) being frequently referenced in the literature alongside LBP and SIJ dysfunction. The literature suggests that LPR is the relationship between the lumbar spine, hip and pelvis when the trunk is in flexion. The classification of LPR during torso forward bending and backward return has also been widely investigated and commonly related to low back disorders [52]. This defines LPR and LBP without necessarily drawing on the biomechanical differences and classification on how these injuries are managed in endurance runners. Furthermore, our results show considerable differences in the methods used to measure, and approaches used to characterize, LPR. Overall, it appears as though the timing aspect of LPR has been examined to obtain insights into the neuromuscular control of torso motion. The lack of consensus in LPR, LBP and SIJ dysfunction is further impacted by the fact that there are no 'gold-standard' algorithms for the detection of running gait outcomes from wearable sensor set-ups, which likely explains the large variation of outcomes and definitions reported in the reviewed studies.

Treatment of SIJ dysfunction

It appears that treatment and management of SIJ dysfunction is often non-surgical that involves packages of care that can include analgesics, physiotherapy, corticosteroid injections and radiofrequency ablation [53]. Non-face-to-face (remote) care models exist where the athlete is physically separated from the physician (or other healthcare workers), is empowered by communication-based technologies such as video conferencing and the use of continuous patient monitoring (wearable or "surface sensor") technologies that capture athlete metrics and deliver health data remotely to the physician. These technologies have existed for some time, however widespread implementation has been constrained by laws, regulations, and policies. The use of wearables in movement science and sport is widespread [54]; however, relative to SIJ dysfunction using wearables in either a laboratory and clinical setting or a remote setting, it could be argued that their application is still in an "exploratory phase". Therefore, we agree with Huges et al. [55] in that the technology and the associated methods still require further development and careful analysis.

The results concerning SIJ injury risk mitigation have been well addressed in the literature [56-57]. Notwithstanding injury mitigation factors, no exploratory research has occurred to systematically investigate the feasibility of wearables usage as a rehabilitation tool in SIJ injury assessment and/or dysfunction in endurance runners. This includes how wearables could potentially be used to characterize the severity of SIJ dysfunction as well as exploring the provision of acquired information to support either clinical preventive or rehabilitative interventions. That SI joint motion has been studied

empirically and analytically, dating back to the late nineteenth century yet has only recently been widely accepted to exist [58,59] may explain why SIJ dysfunction can be confused with LBP and LPR. Moreover, nowadays, the topography of SIJ motion should be measured to establish the conceivable axes of motion. From the study of Wilder et al. [60], translation must occur for any sagittal innominate rotation to be possible because of the irregular surfaces and taut ligament structure. Accordingly, clinical theories have been proposed regarding the details of these motions. Along this line, Lee et al. [6] stated that nutation seems to occur bilaterally when moving from supine to standing, and unilaterally with flexion of the hip joint. Moreover, this kind of information would be relevant to any treatment of SIJ dysfunction given that counternutation occurs bilaterally and sometimes near the end of trunk flexion and unilaterally during hip extension. Some authors [e.g., 61] suggested that individuals with SIJ dysfunction display symmetrical gait and a depressed synergy between muscles providing SIJ force closure. The disorder involves reduced coactivation of the gluteus maximus and contralateral activation of the latissimus dorsi, which together provide joint stability during running. The disorder would be enlarged in endurance runners given the requirement for maximum gluteus maximum activation and torso stability, both of which requires consideration when treating SIJ dysfunction. In spite of this, these results indicate that the information on SIJ dysfunction in endurance runners and the treatment options that exist using wearables is unrepresented. Despite these limitations, it is pertinent to consider whether such treatment methodologies are clinically and practically feasible within a given wearables context.

Information technology and health care

Outcomes obtained from this review posit that health services have experienced great changes, especially in remote monitoring [62]. Additional, clinical studies have shown that wearables are widely used to monitor functional and daily activity inclusive of walking and running gait. The wearables used commonly integrated with an IM U sensor and controlled with a smartphone application [63]. The increased use of wearable technologies, either in isolation or as part of integrated, preventative, or rehabilitative approaches, offers an opportunity to collect quantitative data “in the field”, less obtrusively, for extended periods of time, and with fewer spatial limitations than conventional motion-capture technologies [e.g., 47]. In this regard wearables are increasingly viewed as promising alternatives to expensive analytical instruments in health care when specificity and selectivity criteria are met. It could be that wearables are used to monitor for possible pain, therefore exploring the use of torso acceleration as a proxy using a triaxial accelerometer. As goals of SIJ dysfunction and treatment may include increasing suppleness, strengthening, and correcting of any asymmetries, opportunity remains to explore how wearables could be used as a viable treatment monitoring option. This, then, is an area for future research.

Wearables can help quantify spatiotemporal variables (stride, step length, cadence) and physiology (heart rate, recovery time) and are commonly employed for human activity detection and quantified self-assessment. Until recently, or specifically since the emergence of the novel coronavirus, COVID-19 in January 2020, evidence for the

effectiveness of remote usage and wearable monitoring, compared to traditional care models, has been scarce [64]. Along this line, the combination of telemedicine as an audio-visual communications platform, and wearables that transmit field-based kinematic metrics, provides numerous benefits to both health providers and runners alike. Similarly, machine learning approaches have been widely utilized in gait biomechanics studies in the past decade [65-67]. However, our results show that of the papers included in the review, only three [29, 30, 34] that focused on wearables and for the sole purpose of remote monitoring of treatment of musculoskeletal disorders, clinical advances, and rehabilitation. This ambiguity further complicates the usage and uptake of wearables for SIJ dysfunction, which need to accommodate such conditions.

While wearables can be used for home monitoring of activity and for the purposes of rehabilitation, little research has examined the potential of wearables when applied to acute or chronic SIJ dysfunction in endurance running. For example, when used remotely (i.e., at home), the wearer (runner) could be required to complete standardized functional, rehabilitative assessments whilst data are continually recorded from the wearable device and relayed directly to the doctor or medic. Therefore, rather than comprising only standardized functional test data, as would be the case in a clinical setting, the runner's ambulatory movement dataset would contain data corresponding to all movements whilst he/she is wearing the sensor, including recovery, and running activity. Indeed, common movements can be tracked using suitably wearable devices which are commonly integrated with an IMU sensor and controlled with a smartphone application [63]. Besides research into wearable usage in stride, step, stance, and spatiotemporal variables relative to both performance and injury mitigation, a greater understanding of the processes and predictors of SIJ rehabilitation has the potential to inform and strengthen public health. In this regard we agree with Regterschot et al. [68] in that important challenges and barriers in the deployment of wearables in clinical care remain. Similarly, Lang et al. [78] discussed the major barriers for the application of wearables in motor rehabilitation and proposed benchmarks for the implementation of wearables in clinical practice. These clinical barriers include the demanding clinical environments that often exist, and the lack of realization from some health professional of the value information that can be obtained from wearables. There are also technology-related barriers including: (1) wearables that are inaccurate for many athletic populations (i.e., inconsistent data output or lack of validity); (2) wearables that are not user-friendly for clinicians and/or athletes; (3) and the lack of published data regarding reliability and clinical validity of some wearables. This extends to the development and optimization of innovative wearable configurations and data analysis techniques (e.g., machine learning-based algorithms that enable detection of specific activities and movements in free-living conditions). While Regterschot et al. [77] state that the development of reliable and valid wearables in clinical populations and free-living environments exist, medical technology professionals could be encouraged to help allied health specialists develop the knowledge and skills required to effectively use wearables for remote rehabilitation purposes. Returning to our results, we agree with Regterschot et al. [68] in that barriers exist in the deployment of remote wearable usage that enable detection of specific activities and movements in free-living conditions. Our results suggest that clinical barriers extend to the busy medical environment and the lack of realization of the value of the information

that can be obtained with wearables. However, it appears as though technological barriers also exist, including: (1) a perception that wearables are inaccurate for many patient populations; (2) wearables that are not user-friendly for clinicians and/or patients; (3) a lack of published data regarding reliability and clinical validity of sensor systems. Relatedly, Lang et al. [69] discussed the clinical barriers for the application of wearables in motor rehabilitation and proposed benchmarks for the implementation of sensors in clinical practice. We therefore encourage researchers to investigate the usability, acceptance, feasibility, reliability, and clinical validity of wearable sensors in clinical populations to facilitate the application of wearable movement sensors in SIJ rehabilitation.

Limitations

Some caution should be exercised when considering these findings. It merits noting that this review was a single-author systematic review. The author performed manual searches of all databases stated in this review and then coded and analyzed all retrieved results. Despite this, being a single author review consequently ensured that the processes described are based on what the author believed are eligible articles notwithstanding the PRIMSA guidelines that were duly followed. While systematicity was adhered to as best as possible, a single-author review does incur a possible likelihood of unintentional bias and methodological limitations when compared to group reviews. However, the processes described by the author are based on data accumulation with clear links between the knowledge and content of the subject as well as providing evidence for future research. Additionally, it merits noting that this review is not meant to be exhaustive and includes only a cursory evaluation of the issues. The clinical applications discussed are limited to SIJ dysfunction in an endurance running population. As a potential limitation, endurance running was classified to runners regularly completing over 5 km in training and/or competitive situations. Therefore, papers that featured experimental trials involving runners below this distance were not included. This was motivated by the very high publication rate that made their inclusion infeasible. Nevertheless, this potential limitation did not alter the key points raised in the large number of papers included in this review and presented in the discussion section. While an effective SIJ is fundamental in one's ability to run with biomechanical efficiency and effectiveness, this systematic review was not intended to review sensor-based methods solely for applied real-time gait analysis. As gait analysis can include sensors located on the shank and foot, which are most often used for gait analysis in combination with threshold or peak identification methods for gait detection, for the purpose of SIJ assessment review papers on gait analysis were limited.

Recommendations

Despite these limitations, future studies should focus on the quality of the research, which aimed to reduce the discrepancy on result interpretation and increase reliability and validity, which promote study generalizability. Given these findings, the review agrees with Miller et al. [70] in that it is likely that SIJ pain and dysfunction in endurance runners is highly underdiagnosed and undertreated. In addition to SIJ dysfunction,

clinicians should be aware of broader differential diagnosis regarding other possible sources of posterior hip and lower back pain in endurance runners.

Based on our findings, wearables combined with smart devices, could enable real-time data could be sent to healthcare professionals and clinicians to simultaneously to track endurance runners, thereby monitoring the magnitude of SIJ dysfunction. This also challenges the engineering community to develop more intelligent, real-time, accurate information, making it user-friendly and offering athletes and clinicians actionable insights based on context-specific evaluation frameworks. As noted by Clermont et al. [71], personalized and effective wearable technology should be rooted in a thorough understanding of the user's experience, attitudes, and opinions which, if not properly considered, can severely hamper the potential of applications.

The selected articles, notably those from 2020 and the onset of the COVID-19 pandemic undoubtedly testify to the widespread interest in the area and an increasing trend in popularity. The analysis led to some key conclusions, which were reported, and main reflection points that led to some guidelines and good practices for future research and dissemination that include:

- (1) Articles should explicitly state the rationale for choosing and analyzing specific biomechanical quantities relating to the SIJ and include a justification of what relationship may exist with the SIJ and the diagnosed dysfunction. When previous literature and reviews are cited to support the choice made, the strength of evidence of previous studies should be discussed, together with the context from which that evidence emerged.
- (2) More effort should be spent to fully exploit the potential of wearable technologies to detect and manage SIJ dysfunction, particularly as part of an injury-management plan (*post*). This would allow the unobtrusive monitoring and quantification of the effects of prescribed interventions (preventive or rehabilitative) more regularly.
- (3) The continuous progress in wearables offer many opportunities to collect data on many athletes simultaneously, non-obtrusively, for long periods, and in field-based situations. However, the great “power” that even consumer-level technologies (e.g., smart phones, watches, pods) currently offer does not come free of problems, such as those associated with validity, user and clinician experience and interpretation of data.

Conclusions

A current “state of play” in SIJ dysfunction in endurance runners for rehabilitation considerations using wearables in a remote setting was presented. This study took a systematic review approach to exploring the existing literature in SIJ dysfunction in an endurance running population, using wearables as a rehabilitation tool. Viewed through the lens of wearable technology, the results, from this review shows that diagnosing, treating, and managing SIJ dysfunction in endurance runners varies considerably due to

the inconsistent definition of the condition. To identify optimal rehabilitation considerations and remote wearable usage to effectively monitor this condition, further investigations that better clarify the condition are recommended. Moreover, greater usage of wearables for measuring both bio and pathomechanics is suggested, to enhance the reliability and accuracy of using wearables remotely.

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Data Availability

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The author declares no conflict of interest.

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Abbreviations

CoM: Centre of mass
ECG: Electrocardiogram
EMG: Electromyogram
EEG: Electroencephalogram
IMU: Inertial measurement unit
IrRL: Injury-research readiness level
LBP: Low back pain
LPR: Lumbopelvic rhythm
MEMS: microelectromechanical
SIJ: Sacroiliac

References

1. McGuine TA, Post EG, Hetzel SJ, Brooks MA, Trigsted S, Bell DR. A prospective study on the effect of sport specialization on lower extremity injury rates in high school athletes. *Am J Sports Med* 2017 Oct;45:2706–2712. doi:10.1177/0363546517710213.
2. Emery CA, Pasanen K. Current trends in sport injury prevention. *Best Prac Res Clin Rheumatol* 2019 Feb;33:3–15. doi:10.1016/j.berh.2019.02.009.
3. Creighton DW, Shrier I, Shultz R, Meeuwisse WH, Matheson GO. Return-to-play ins sport: a decision-based model. *Clin J Sport Med* 2010 Sept;20:379–385. doi:10.1097/JSM.0b013e3181f3c0fe.
4. Dydyk AM, Forro SD, Hanna A. Sacroiliac joint injury. In: StatPearls Treasure Island. Florida, USA: StatPearls Publishing; 2022.
5. Grayson ACR, Shawgo RS, Johnson AM, Flynn NT, Yawen LI, Cima MJ, Langer R. A BioMEMS review: MEMS technology for physiologically integrated devices. *Proc IEEE* 2004 Feb; 92(1):6-21. doi:10.1109/JPROC.2003.820534.

6. Lee SP, Ha G, Wright DE, Ma Y, Ellora SG, Haubrich NR, Branche PC, Weihua Li, Gilbert L, Huppert MJ et al. Highly flexible, wearable, and disposable cardiac biosensors for remote and ambulatory monitoring. *npj Digit. Med* 2018 Jan; 1,2.
7. Taelman J, Adriaensen T, Horst C, van der Linz T, Spaepen A. Textile integrated contactless EMG sensing for stress analysis. *Proceedings of the 29th Annual International Conference of the IEEE Eng Med Biology Soc*; 2007 August 22-26; Lyon, France.
8. Park JL, Fairweather MM, Donaldson DI. Making the case for mobile cognition: EEG and sports performance. *Neurosci Biobehav Rev* 2015 May; 52:117–130. doi:10.1016/j.neubiorev.2015.02.014.
9. Hilty DM, Armstrong CM, Edwards-Stewart A. Sensor, wearable, and remote patient monitoring competencies for clinical care and training: scoping review. *J Technol Behav. Sci* 2021 Jan; 6:252–277. doi.org/10.1007/s41347-020-00190-3.
10. Tormene P, Bartolo M, De Nunzio AM, Recchia F, Quaglini S, Tassorelli C, Sandrini G. Estimation of human trunk movements by wearable strain sensors and improvement of sensor's placement on intelligent biomedical clothes. *Biomed Eng Online* 2012 Dec;11:95. doi:10.1186/1475-925X-11-95.
11. Seshadri DR, Drummond C, Craker J, Rowbottom JR, Voos JE. Wearable devices for sports: new integrated technologies allow coaches, physicians, and trainers to better understand the physical demands of athletes in real time. *IEEE Pulse* 2017 Jan-Feb; 8:38–43. doi: 10.1109/MPUL.2016.2627240.
12. Capecci M, Ceravolo MG, Ferracuti F, Iarlori S, Monteriu A, Romeo L, Verdini F. The KIMORE Dataset: kinematic assessment of movement and clinical scores for remote monitoring of physical rehabilitation. *IEEE Trans. Neural Syst Rehabil Eng* 2019 Dec;27:1436–1448. doi:10.1109/TNSRE.2019.2923060.
13. McIntosh AS. Risk compensation, motivation, injuries, and biomechanics in competitive sport. *Br J Sports Med* 2005 Jan;39:2–3. doi:10.1136/bjsm.2004.016188.
14. Finch C. A new framework for research leading to sports injury prevention. *J Sci Med Sport* 2006 May;9:3–9. doi:10.1016/j.jsams.2006.02.009.
15. Bahr R, Alfredson H, Järvinen M, Järvinen T, Khan K, Kjær M, Matheson G, Mæhlum S. *The IOC manual of sports injuries*. Hoboken, NJ. John Wiley & Sons, Ltd; 2012 Jun; ISBN:978-0-470-67416-1.
16. Jacobs JM, Cameron KL, Bojescul JA. Lower extremity stress fractures in the military. *Clin Sports Med* 2014 Oct;33:591–613. doi:10.1016/j.csm.2014.06.002.
17. Bennett H, Arnold J, Norton K, Davison K. Are we really “screening” movement? The role of assessing movement quality in exercise settings. *J Sport Health Sci* 2020 Dec;9:489–492. doi:10.1016/j.jshs.2020.08.002.
18. Page MJ, McKenzie JE, Bossuyt PM. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *PLoS Med* 2021 Mar;18(3):e1003583.
19. Portney LG, Watkins MP. In: *Foundations of Clinical Research: Applications to Practice*. 3rd edition. Saddle River, NJ: Pearson/Prentice Hall; 2015. ISBN:0131716409, 9780131716407.
20. Preatoni E, Bergamini E, Fantozzi S, Giraud LI, Orejel Bustos AS, Vannozzi G, Camomilla V. The use of wearable sensors for preventing, assessing, and

- informing recovery from sport-related musculoskeletal injuries: a systematic scoping review. *Sensors (Basel)* 2022 Apr;22(9): 3225. doi:10.3390/s22093225.
21. McKinney J, Velghe J, Fee J, Isserow S, Drezner JA. Defining athletes and exercisers. *Am J Cardiol* 2019 Feb;123:532–535. doi:10.1016/j.amjcard.2018.11.001.
 22. Sauser B, Verma D, Ramirez-Marquez J, Gove R. From TRL to SRL: The concept of systems readiness levels. *Conf Syst Eng Res* 2006 Feb;1–10.
 23. Henderson RM, Clark KB. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. *Source Adm Sci Q* 1990 Mar;35:9–30. doi:10.2307/2393549.
 24. Alcantara RS, Day EM, Hahn ME, Grabowski AM. Sacral acceleration can predict whole-body kinetics and stride kinematics across running speeds. *Peer J* 2021 Apr;12:9. doi:10.7717/peerj.11199.
 25. Whitney KE, Sugimoto D, d'Hemecourt CA, d'Hemecourt DA, d'Hemecourt PA. Running gait biomechanics in female runners with sacroiliac joint pain. *J Phys Ther Sci* 2022 Apr;34(4):327–334. doi:10.1589/jpts.34.327.
 26. Höfer S, Siemsen, CH. Proof of the biomechanical effect of a lumbar spine-relief orthosis for treatment of sacroiliac pain. *Z Orthop Unfall* 2008;146(4), 439–43. doi:10.1055/s-2008-1038612.
 27. Amorosa LF, Serota AC, Berman N, Lorch DG, Helfet DL. An isolated iliac wing stress fracture in a marathon runner. *Am J Orthop* 2014 Feb;43(2):74–7.
 28. Ueberschär O, Fleckenstein D, Warschun F, Kränzler S, Walter N, Hoppe M W. Measuring biomechanical loads and asymmetries in junior elite long-distance runners through triaxial inertial sensors. *Sport-Orthopädie Sport-Traumatologie* 2019 Oct;35(3):296–308.
 29. Liu X, Zhao C, Zheng B, Guo Q, Duan X, Wulamu A, Zhang D. Wearable devices for gait analysis in intelligent healthcare. *Front Comput. Sc* 2021 May;3:661–676. doi:10.3389/fcomp.2021.661676
 30. Banos O, Moral-Munoz JA, Diaz-Reyes I, Arroyo-Morales M, Damas M, Herrera-Viedma E, Hong CS, Lee S, Pomares H, Rojas I, Villalonga C. A novel mobile health system to support trunk endurance assessment. *Sensors* 2015 June;15:13159–13183. <https://doi.org/10.3390/s150613159> 45.
 31. Falowski S, Sayed D, Pope J, Patterson D, Fishman M, Gupta M, Mehta P. A review and algorithm in the diagnosis and treatment of sacroiliac joint pain. *J Pain Res* 2020 Dec;13:3337–3348.
 32. Zadeh A, Taylor D, Bertson M, Tillman T, Nosoudi N, Bruce, S. Predicting sports injuries with wearable technology and data analysis. *Inf Syst Front* 23 2021 Aug;1023–1037. <https://doi.org/10.1007/s10796-020-10018-3>
 33. Porciuncula F, Roto A, Kumar D, Davis I, Serge R, Walsh C, Awad L. Wearable Movement Sensors for Rehabilitation: A Focused Review of Technological and Clinical Advances. *PM&R*, 10. Doi:10.1016/j.pmrj.2018.06.013
 34. Lorussi F, Lucchese I, Tognetti A, Tognetti N, Carbonaro N. A wearable system for remote monitoring of the treatments of musculoskeletal disorder. *Proceedings of the IEEE International Conference on Smart Computing (SMARTCOMP)*; 2018 June 18–20; Sicily, Italy.
 35. Shen YT, Chen L, Yue WW, Xu HX. Digital technology-based telemedicine for

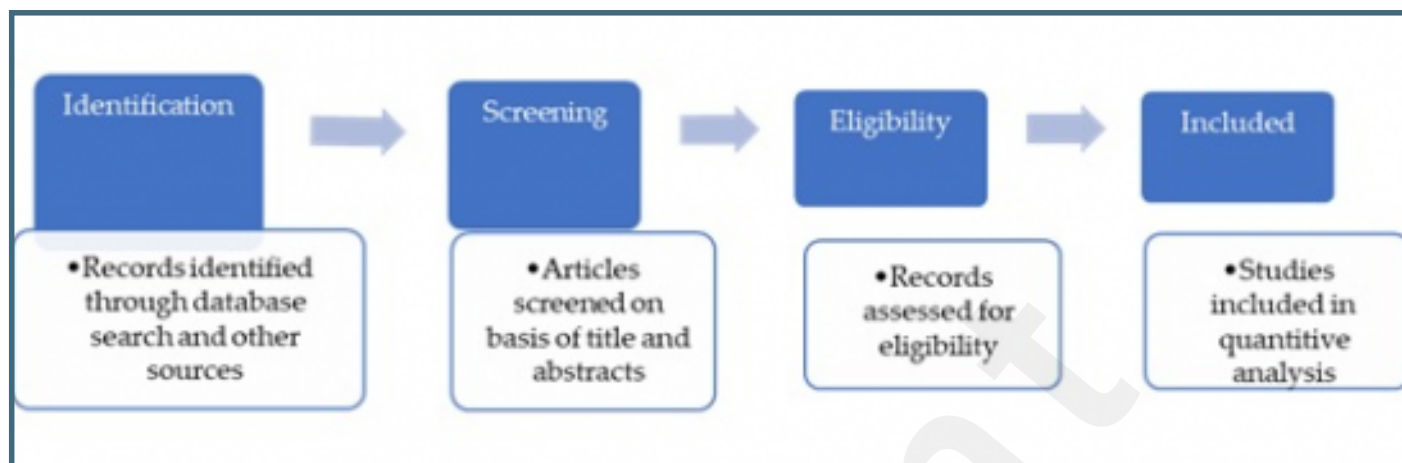
- the COVID-19 pandemic. *Front Med (Lausanne)* 2021 July;6(8):646-506. doi:10.3389/fmed.2021.646506.
36. Nascimento LMSd, Bonfati LV, Freitas MLB, Mendes Junior, JJA, Siqueira, HV, Stevan SL Jr. Sensors and systems for physical rehabilitation and health monitoring—a review. *Sensors* 2020 July;20:4063. <https://doi.org/10.3390/s20154063>.
37. Channa A, Popescu N, Skibinska J, Burget R. The rise of wearable devices during the COVID-19 pandemic: a systematic review. *Sensors (Basel)* 2021 Sept;28:21(17):5787. doi:10.3390/s21175787.
38. Rahlf AL, Hoenig T, Fohrmann D, Stürznickel J, Sanchez-Alvarado A, Rolvien T, Hollander KA. A machine learning approach to identify risk factors for running-related injuries: study protocol for a prospective longitudinal cohort trial. *BMC Sports Sci Med Rehabil* 2022 Apr;14:75
39. Snijders CJ, Vleeming A, Stoeckart R. Transfer of lumbosacral load to iliac bones and legs Part 1: Biomechanics of self-bracing of the sacroiliac joints and its significance for treatment and exercise. *Clin Biomech* 1993 Nov;8(6):285-94. doi:10.1016/0268-0033(93)90002-Y. PMID: 23916048.
40. Bellamy N, Park W, Rooney PJ. What do we know about the sacroiliac joint? *Semin Arthritis Rheum* 1983 Feb;12(3):282–313.
41. Vleeming A, Schuenke MD, Masi AT, Carreiro JE, Danneels L, Willard FH. The sacroiliac joint: an overview of its anatomy, function and potential clinical implications. *J Anat* 2012 Sept;221(6):537–567.
42. Stureson B, Uden A, Vleeming AA. Radiostereometric analysis of the movements of the sacroiliac joints in the reciprocal straddle position. *Spine* 2000 Jan;25(2): 214–217.
43. Dreyfuss PC, Cole AJ, Pauza K. Sacroiliac joint injection techniques. *Phys Med Rehabil Clin North Am* 1995 Jan;6(4):785–813.
44. DeRosa CP, Porterfield JA. A physical therapy model for the treatment of low back pain. *Phys Ther* 1992 Apr;72(4):261-9. doi:10.1093/ptj/72.4.261. PMID: 1533940.
45. Banos O, Moral-Munoz JA, Diaz-Reyes I, Arroyo-Morales M, Damas M, Herrera-Viedma E, Hong CS, Lee S, Pomares H, Rojas I, Villalonga C. A novel mobile health system to support trunk endurance assessment. *Sensors* 2015 June;15:13159-13183. <https://doi.org/10.3390/s150613159>
46. Rahal AL, Hoenig T, Stürznickel J, Cremans K, Fohrmann D, Sanchez-Alvarado A, Rolvien T, Hollander K. A machine learning approach to identify risk factors for running-related injuries: study protocol for a prospective longitudinal cohort trial. *BMC Sports Sci Med Rehabil* 2022 Apr;14(1):75: doi: 10.1186/s13102-022-00426-0.
47. Mündermann L, Corazza S, Andriacchi TP. The evolution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications. *J Neuro Eng Rehabil* 2006 Mar;3:1–11. doi:10.1186/1743-0003-3-6.
48. Camomilla V, Bergamini E, Fantozzi S, Vannozzi G. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: A systematic review. *Sensors* 2018 Mar;18:873. doi:10.3390/s18030873.

49. Schwarzer AC, April CN, Bogduk N. The sacroiliac joint in chronic low back pain. *Spine* 1995 Mar;20(1):31–7.
50. March L, Smith EUR, Hoy DG. Burden of disability due to musculoskeletal (MSK) disorders. *Best Pract Res Clin Rheumatol* 2014 Jun;28(3):353–366. doi: 10.1016/j.berh.2014.08.002.
51. Yoshihara, H. Sacroiliac joint pain after lumbar/lumbosacral fusion: current knowledge. *Eur Spine J* 2012 Sept;21(9):1788–1796. doi: 10.1007/s00586-012-2350-8.
52. Vazirian M, Van Dillen L, Bazrgari B. Lumbopelvic rhythm during trunk motion in the sagittal plane: A review of the kinematic measurement methods. *Phys Ther Rehabil* 2016;3:5: doi:10.7243/2055-2386-3-5.
53. Dale M, Evans J, Carter K, O'Connell S, Morgan H, Carolan-Rees G. iFuse implant system for treating chronic sacroiliac joint pain: A NICE medical technology guidance. *Appl Health Econ Health Policy* 2020 Jun;18(3):63-373. doi:10.1007/s40258-019-00539-7.
54. Adesida Y, Papi E, McGregor AH. Exploring the role of wearable technology in sport kinematics and kinetics: A systematic review. *Sensors* 2019 Apr;19:1597. doi:10.3390/s19071597.
55. Hughes G, Camomilla V, Vanwanseele B, Harrison A, Fong D, Bradshaw E. Novel technology in sports biomechanics: Some words of caution. *Sport Biomech* 2021 Apr;1–9. doi:10.1080/14763141.2020.1869453.
56. Van Hooren B, Goudsmit J, Restrepo J, Vos S. Real-time feedback by wearables in running: Current approaches, challenges and suggestions for improvements. *J Sports Sci* 2020 Oct;38:214–230. doi: 10.1080/02640414.2019.1690960.
57. Sheerin KR, Reid D, Besier TF. The measurement of tibial acceleration in runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. *Gait Posture* 2019 Jan;67: 12–24. doi:10.1016/j.gaitpost.2018.09.017.
58. Alderink, G.J. The sacroiliac joint: review of anatomy, mechanics, and function. *J Orthop Sports Phys Ther* 1991;13(2):71-84. doi:10.2519/jospt.1991.13.2.71. PMID: 18796854.
59. Kissling R, Brunner C, Jacob HAC. Mobility of the sacroiliac joint in vitro. *Z. Orthop* 1990 May-Jun;128(3):282–288
60. Wilder DG, Woodworth BB, Frymoyer JW. Pope MH. Vibration and the human spine. *Spine* 1982;7(3):243–254.
61. Feeney DF, Capobianco RA, Montgomery JR, Morreale J, Grabowski AM, Enoka RM. Individuals with sacroiliac joint dysfunction display asymmetrical gait and a depressed synergy between muscles providing sacroiliac joint force closure when walking. *J Electromyogr Kinesiol* 2018 Feb;43:95-103. doi:10.1016/j.jelekin.2018.09.009.
62. Li XL, Guo, LH, Sun LP, Yue WW. Teleultrasound for the COVID-19 pandemic: a statement from China. *Adv Ultrasound Diagn Ther* 2020;4:27–111. doi:10.37015/AUDT.2020.2000.
63. Iman K, Al-Azwani H. Integration of wearable technologies into patient's electronic medical records. *Qual Prim Care* 2016 Mar;24:151–155.
64. Yoong NKM, Perring J, Mobbs RJ. Commercial postural devices: a review.

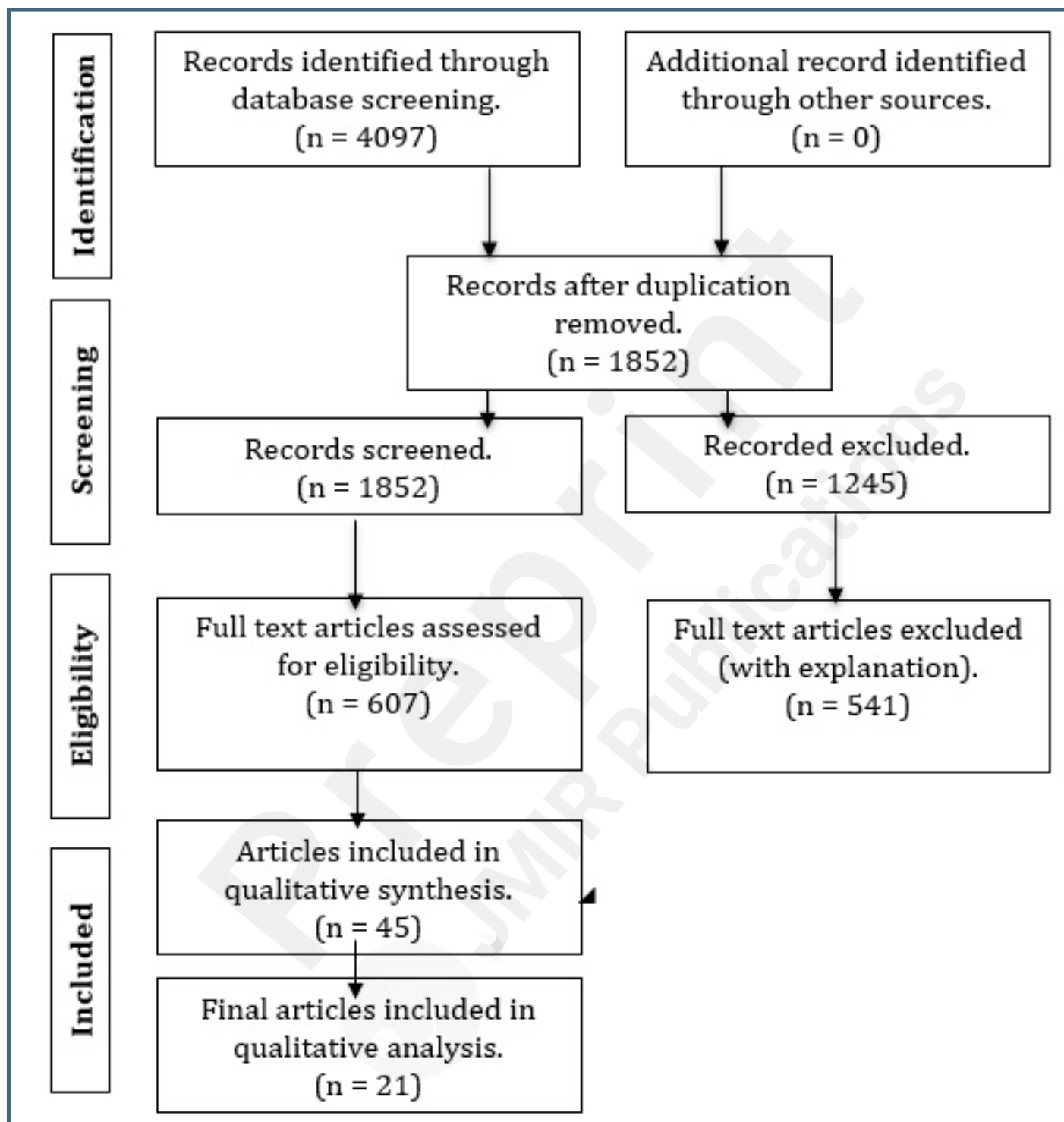
- Sensors (Basel) 2019;19: 5128. doi:10.3390/s19235128
65. Halilaj E, Rajagopal A, Fiterau M, Hicks JL, Hastie TJ, Delp SL. Machine learning in human movement biomechanics: best practices, common pitfalls, and new opportunities. *J. Biomech* 2018 Nov;81:1–11. doi:10.1016/j.jbiomech.2018.09.009
 66. Xiang L, Gu Y, Mei Q, Wang A, Shim V, Fernandez, J. Automatic classification of barefoot and shod populations based on the foot metrics and plantar pressure patterns. *Front Bioeng Biotechnol* 2022 Mar;10:843204. doi:10.3389/fbioe.2022.843204.
 67. Vijayan V, Connolly JP, Condell J, McKelvey N, Gardiner, P. Review of wearable devices and data collection considerations for connected health. *Sensors* 2021 Aug;21(16):5589. <https://doi.org/10.3390/s21165589>
 68. Regterschot GRH, Ribbers GM, Bussmann JBJ. Wearable movement sensors for rehabilitation: from technology to clinical practice. *Sensors* 2021 Jun;21: 4744. <https://doi.org/10.3390/s21144744>
 69. Lang CE, Barth J, Holleran CL, Konrad JD, Bland MD. Implementation of wearable sensing technology for movement: pushing forward into the routine physical rehabilitation care field. *Sensors* 2020 Oct;20:574.
 70. Miller L, Block JE. Minimally invasive arthrodesis for chronic sacroiliac joint dysfunction using the SImmetry SI joint fusion system. *Med Devices (Auckl)* 2014 May;7:125–130. doi:10.2147/MDER.S63575.
 71. Clermont CA, Duffett-Leger L, Hefting BA, Ferber R. Runners' perspectives on 'smart' wearable technology and its use for preventing injury. *Int J Hum Comput Interact* 2020;36:31–40. doi:10.1080/10447318.2019.1597575.

Supplementary Files

Untitled.



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Multimedia Appendixes

Untitled.

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