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The running gait analysis technology: A comprehensive systematic literature review

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ABSTRACT

Background: Running is practiced worldwide, but more than 50 % of runners suffer some form of musculoskeletal injury each year. Biomechanics of running is an important aspect of sports medicine and gait analysis is central in the study of running mechanics for prevention of injuries and enhancing performance.
Objectives: The purpose of this systematic literature review is to Saragiotto et al. (2014 Apr 4) 1 assess the methods employed in conducting gait analysis studies from 2020 to 2024, 2 discuss spatiotemporal characteristics, bilateral asymmetry, and RRI, (Lenhart et al., 2014 Mar) 3 present wearable technology, and (Willson et al., 2014) 4 provide recommendations for future research and application based on the findings.
Methods: The study was conducted following the PRISMA guidelines and was registered in the PROSPERO database under the number CRD42024572642. The systematic search of articles was performed in the Scopus database, considering the articles written in English and published in journals between 2004 and 2024, which are focused on the analysis of running gait. Data were collected, pre-processed, and processed according to certain inclusion and exclusion criteria.
Results: Of 2175 articles, only 43 studies were included. The studies were mainly concerned with spatiotemporal features (Patino and Ferreira, 2018) ,16 gait asymmetry and injuries (Crowther et al., 2007 Jun 1) ,9 biomechanics (Mason et al., 2023 Sep 1) ,8 and gait measurement tools (Schubert et al., 2014 May 1) .10 IMUs, accelerometers, and pressure sensors were established as wearable technologies that can be used to monitor gait in the sports setting.
Conclusion: In this review, we discuss the latest developments in wearable technology for gait analysis, which can be considered a viable alternative to laboratory-based methods. However, the need to use standard methods and validation procedures has not lost its importance as it is crucial for the practical application of these technologies.
Protocol: Registration number CRD42024572642.

1. Introduction

Running is a widely popular recreational activity globally; however, despite its widespread appeal, nearly 50 % of runners suffer from musculoskeletal injuries related to running each year.[1] Human gait reflects an individual's unique style and quality of life. Accurately understanding gait characteristics over time, along with continuous monitoring and precise evaluation, has proven essential not only in clinical and medical contexts but also in sports, rehabilitation, training, and robotics research.[2] Running gait analysis benefits those with persistent injuries, such as patellofemoral pain, by supporting effective gait retraining.[3] While its impact on injury prevention and performance is still under study, comfortable adjustments can enhance outcomes without reducing running efficiency.[4] Analyzing more advanced measures, such as spatiotemporal (e.g., stride length, stride time, step frequency, speed), kinematic (e.g., angular velocity, joint angles), and kinetic (e.g., ground reaction forces) measures, requires more cumbersome and costly traditional gait laboratory methods like three-dimensional motion capture and force plates.[5]

Gait analysis is crucial in sports for improving performance and

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preventing injuries. However, traditional gait analysis methods, such as three-dimensional motion capture and force plates, are expensive, require specialized training, and are confined to controlled laboratory settings. These limitations hinder their accessibility and practicality for widespread use in real-world sports environments.[6]

Several studies have explored running gait analysis and technology for running gait analysis. This similar study demonstrated that running gait analysis, like walking gait analysis, employs various techniques, from real-time observations to advanced technologies. Key measurement systems include motion analysis, dynamic electromyography, force plate recordings, energy cost measurements, and stride characteristic assessments.[7] A review of 61 studies showed that wearable devices improve gait analysis for walking and running, offering unique real-world insights. More research is needed for long-term monitoring and diverse populations. Similar studies using wireless accelerometers reliably measured gait parameters. Future work should validate wearable metrics and establish guidelines.[9] Another studies highlight the importance of accurate gait analysis for understanding and addressing gait impairments.[9] This study found that in adolescent distance athletes, as running speed increased, contact time decreased, while step frequency, step length, and stride angle increased[10] This study highlights a minimal sensor setup that provides accurate and unobtrusive kinematic gait analysis, crucial for detecting gait abnormalities and preventing running injuries.[11]

This systematic literature review and meta-analysis aim to provide a comprehensive overview of studies on running gait analysis in sports from 2020 to 2024. The review specifically aims to[1]: evaluate the methodologies used in gait analysis research[2]; explore the spatiotemporal, and gait symmetry, running-related injuries[3]; identify wearable technology; and[4] offer evidence-based recommendations for future research and practical applications.[12]

2. Methods

The protocol of the current research study was registered in advance on the PROSPERO International Prospective Register for Systematic Reviews website (registration number CRD42024572642) in June 2024. The design and reporting of this review and bibliometric analysis follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines.[13,14]

2.1. Search strategy

A systematic search was undertaken to find relevant papers within the Scopus database. The review specifically targeted journal articles published in English that focused on running gait analysis. The search strategy and terms used are detailed in Table 1. Articles up to May 31, 2024, were included. Following the PRISMA guidelines (Fig. 1), the selection process involved[1]: initial title screening by independent authors (RK, PB) after merging search results and removing duplicates[2]; review of titles and abstracts by RK and PB, followed by a full-text review to confirm if studies met the criteria[3]; RK and PB assessed full texts based on inclusion/exclusion criteria. References of included studies were also checked for additional relevant publications. Throughout the process, RK and PB made inclusion or exclusion decisions, with VS consulted to resolve any disagreements (Table 1 of the Electronic Supplementary Material [ESM]).[8,15] (see Table 2)

Table 1
Literature search and keywords.

Database	Search Terms	Results	Format
Scopus	TITLE-ABS-KEY (gait AND analysis AND running) AND PUBYEAR >2003 AND PUBYEAR <2025	2175	CSV

* TITLE-ABS-KEY signifies that the search will encompass the title, abstract, and keywords. ** CSV: Stands for Comma-Separated Values file.

Table 2
Type of wearable sensor used within reviewed studies.

Gait Analysis Methods	n	References
• IMU (a combination of sensors in one unit; accelerometer, gyroscope, magnetometer)	26	[28], [29], [17], [18], 5, [37], [31], [42], [23], [32], [33], [49], [25], [26], [35], [45], [27], [46], [39], [40], [36], [53], [47], [50], [51], [58].
• Accelerometer only	12	[41], [30], [21], [22], [20], [38], [43], [34], [44], [54], [48], [57].
• Pressure sensor/insole	8	[30], [21], [42], [49], [26], [27], [40], [56].
• Pressure sensor and accelerometer	3	[22], [25], [57].
• Pressure sensor and IMU	4	[18], [33], [53], [59].
• IMU and separate accelerometer	1	[31].
• Gyroscope only	1	[26].

* IMUs were the most frequently used technology, followed by accelerometers and pressure sensors. Some studies combined different sensor types to enhance data accuracy.

2.2. Eligibility criteria for review

2.2.1. Inclusion criteria

This review focused on articles exploring spatial, temporal, and kinematic gait parameters, including running velocity, step metrics, and joint movements across the sagittal, coronal, and transverse planes. It also considered kinetic outcomes like ground reaction force and peak tibial acceleration. The scope extended to studies on gait symmetry, gait analysis technologies, and running-related injuries. Relevant literature from 2004 to 2024, including journal articles and conference contributions, was sourced exclusively from the Scopus database and was restricted to English-language publications.

2.2.2. Exclusion criteria

Articles that did not focus on the spatial, temporal, and kinematic parameters of gait, gait methods and technology, and running-related injuries were excluded from this review. Studies without full-text availability were also excluded. Non-English publications, articles published before 2004 and after 2024, and non-peer-reviewed literature such as conference abstracts, letters, and short communications were not considered. Additionally, studies involving participants under the age of 18, research focusing on activities other than natural running gait, studies evaluating only physiological measures such as metabolic equivalents, and research involving non-human subjects were excluded.[16]

2.3. Data extraction

Data were extracted by the author (RK) using a customized form to ensure standardized data collection (Table 1). The extracted data were then compiled into a table format by the author (RK) and verified by a second author (PB) for accuracy. The studies were categorized based on the review's objectives: those addressing spatial, temporal, and kinematic parameters, running-related injuries, and those focusing on running gait analysis methods. For each article, the extracted information included details about the participants, the sensor(s) utilized, the study protocol, any reference or additional measures, the analysis methods employed, the outcome measures, and the key findings.

2.4. Data cleaning and preparation

To ensure the integrity and consistency of the dataset, MS Excel was employed to identify and remove duplicate records. The data exported from the Scopus database was meticulously cleaned and standardized. This process involved harmonizing author names, publication years, titles, sources, volume and issue numbers, citations, and other essential bibliometric information. The cleaned and standardized data were then used for further analysis to ensure accuracy and reliability in the review findings.

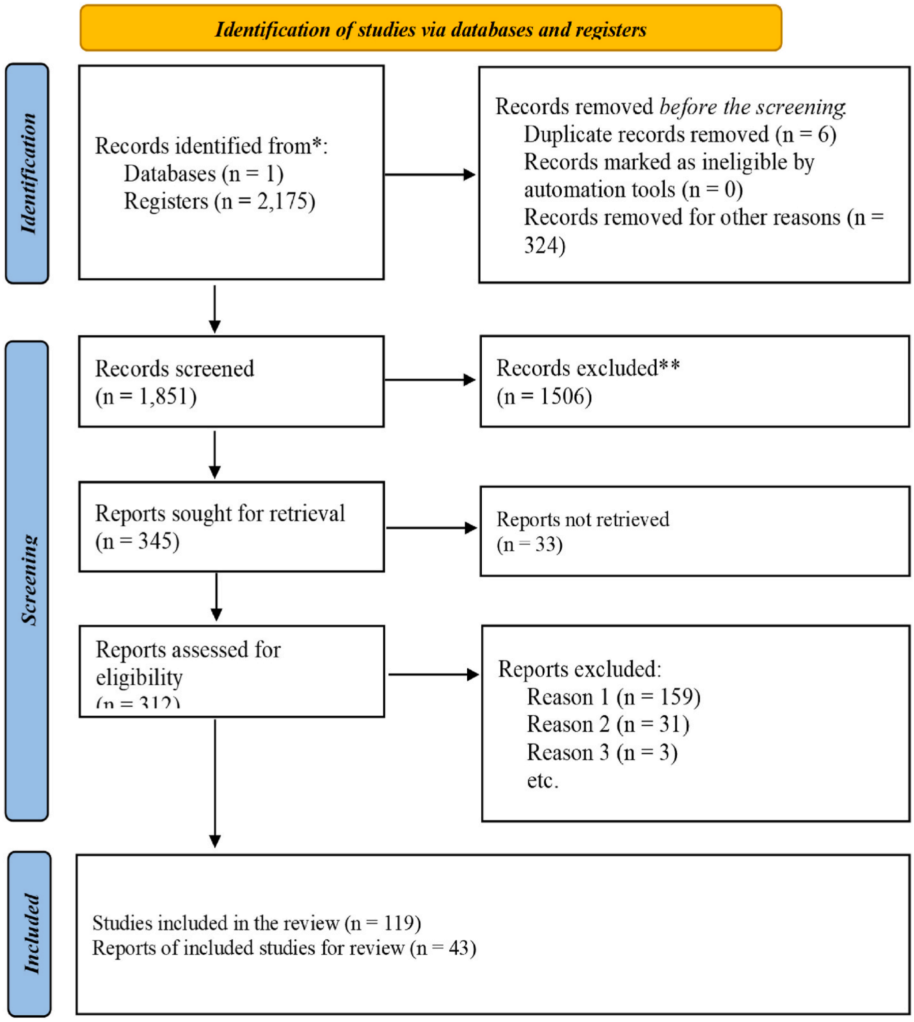

Fig. 1. Preferred Reporting Items for Systematic Reviews and Bibliometric Exploration of Running Gait Analysis (PRISMA) 2020 Flow diagram.

3. Results

3.1. Overview of search results

Out of 2175 articles identified, 43 papers were included in the review on running gait analysis employing wearable technology. A flow diagram in Fig. 1 shows the screening process. The selected studies covered overlapping topics: 16 focused on spatiotemporal characteristics, 9 on gait asymmetry and injuries, 8 on kinematic and kinetic aspects, and 10 on methods for gait assessment. The present study was conducted using specific inclusion criteria that offered a broad perspective of the existing literature in this area.

3.2. Characteristics of the study participants

The studies ranged from 10 to 100 participants, averaging 45 with a mean age of 30.5 years. Age details were missing in four studies,[17,18] 5,[20]), with only ranges provided in two.[21,22] Seven studies focused on participants over 50,[23,24,25,26,27] but none compared different age groups. The majority of studies[26] included both genders, with nine investigating[28,29,30,31,32,33,34,35,36] and five finding significant gender differences.[30,37,38,39,40] Eleven studies exclusively involved male participants,[28,41,31,42,32,43,44,45,46,47,48] and three focused on females.[23,26,27] Six studies did not specify gender,[20,49,25,50,51,52] and three lacked detailed gender data.[19,23,26] Most research targeted healthy, active young adults, though six examined injured runners.[41,42,23,26]

3.3. Gait analysis tools

3.3.1. Inertial Measurement Units (IMU)

Among the 43 reviewed articles, 26 stated that they used IMUs for gait analysis. Of these, 12 studies utilized only the accelerometer capabilities within the IMU,[28,35,46,39,36] while 14 studies used both the accelerometer and gyroscope components for data analysis,[29,17,18] 5,[21,31,42,32,33,25,26,27,53,50] The remaining studies either did not comment on the specific components used[21,22,38,44,45,54] or implied the use of all three components: Applications include accelerometer, gyro, and magnetometer.[40,47,48,55,56,51] Another study incorporated an IMU together with a different one-dimensional accelerometer.[31] Another study solely used the gyroscope of the IMU, at a sampling rate of 100Hz and an unknown range of the gyroscope.[26]

The common sampling frequency across these studies was 100 Hz (n = 10),[28,17,37,42,49,39,53,50,55,51], with additional frequencies including 50 Hz,[41] 200 Hz,[29] and 500 Hz.[27] The range of the accelerometers varied from ±2.0 g[21,22,38] to ±16 g, with ±16 g being the most frequently used (n = 6).[29,23,33,25,53,50] The gyroscope ranges used were 250°/s (n = 3),[17,37,50] 500°/s (n = 4),[30,32,35,53] and 2000°/s (n = 5).[42,49,27,40,55] A variety of sampling frequencies (10–1000 Hz), accelerometer ranges (2, 4, 8, 16 g), and gyroscope ranges (250, 500, 1000, 2000°/s) were employed in one comprehensive study.[51] Eighteen studies reported the weight and/or size of the IMU used, with a range of sizes from 5.0 × 1.5

× 0.5 cm up to 8.0 × 5.0 × 2.0 cm,[39] and the weight of the IMUs ranged from 5 g to 500 g.[46]

3.3.2. Accelerometry

Out of 43 studies using single accelerometer configurations, 12 did not specify the dimensions of the accelerometers.[21,22,38,43,26,44,45,40,36,54,48,57] Five studies used exclusively one-dimensional accelerometers,[28,20,42,33,35] one employed a two-dimensional accelerometer,[30] and three utilized both one-dimensional and 3D accelerometers.[17,37,48] Twenty-one studies exclusively used 3D accelerometers,[41] 5, .[31,23,32,49,34,25,27,46,39,53,47,55,56,51,58,52,59,60] The sampling frequency varied from 50 Hz to 1000 Hz, with 100 Hz being the most common.[28,17,37,42,49,39,53,50,55,51] The accelerometer range varied from ±2.0 g[18,21,48] to ±16 g, with the most common being ±16 g.[29,23,33,25,53,50] Sizes ranged from 5.0 × 1.5 × 0.5 cm[17] to 8.0 × 5.0 × 2.0 cm,[39] and weights from 5 g[37] to 500 g.[46]

The reviewed studies are mainly carried out on runners, with 19 of the studies targeting runners. Among these, 13 studies included recreational runners only.[28,18,37,38,34,45,36,47,55,56,58,52,29,59] Six investigations were performed on the runners with experience,[29,30,31,32,25,27] and seven studies were carried out with physically active individuals.[17,19,20,43,46,54,57] Most of the studies employed a cross-sectional design 10 studies,[61,62,23,24,35,40], which cross-sectional data, that is, is collected simultaneously. Further, four studies employed a quasi-experimental research design[21,42,33,44] which provides an estimate of the intervention's effect without randomization. These participant types and study designs emphasize the applied nature of gait analysis, which seeks to enhance basic and sports-related gait in various populations (see Fig. 2).

3.3.3. Sensors

This current review study found that 18 focused on pressure or force-sensitive insoles. Among these, four studies investigated the use of a combined pressure insole and an IMU,[18] 17,[33,53,59] while another three studies utilized a pressure insole alongside accelerometers,[62] The sampling frequency for pressure insoles varied, with the lowest being 50 Hz[61,21,23] and the highest being 1000 Hz[27]; the most common sampling frequency was 100 Hz (n = 8). Six studies provided details on the dimensions of the insoles/sensors,[30] 22, [42,49,27,56] with dimensions ranging from 0.5 × 0.3 × 0.1 cm[30] to 2.5 cm[24] (Table 3).

3.3.4. Gyroscope only

One study exclusively utilized a gyroscope (not encompassed in an IMU), with a sampling frequency of 102.4 Hz and a gyroscope range of ±2000°/s.[26] This study focused on capturing detailed rotational movements and angular velocities of the lower limbs during running. The high sampling rate and the wide range of the gyroscope were greatly useful in measuring fast rotational changes which were useful in understanding the kinetic profiles of joint movements. The information collected helped in improving the understanding of dynamic stability and coordination in runners particularly in relation to rotatory movements and the role of gait analysis.

3.3.5. Number of sensors

In our analysis of the 43 reviewed studies that utilized IMUs, accelerometers, or gyroscopes, the majority employed one (n = 18) or two (n = 12) sensors. A few studies used more than two sensors, with some employing three,[29,38,43] four,[30,26,45,54] five 24, seven,[19,31] or eight sensors.[28,37,32] It is noteworthy that when multiple sensors were used, they were not always the same type; for instance, a study might use both an IMU and an accelerometer. Additionally, three studies compared the effectiveness of multiple versus single sensor units.[18,35,48] Among the studies that utilized multiple sensors, seven specifically examined how sensor placement affected outcome measures.[30,37,23,33,25,36,58]

3.3.6. Location

The most frequently reported wearable locations in the reviewed studies were shin (10 studies), which was located on the medial or anterior-medial aspect in most cases; foot (9 studies) at the dorsal aspect, heel, or fifth metatarsal; and lower back (11 studies) at the sacral area. An instrumented insole was used in three studies,[38,27,56] while five studies placed the wearable on the chest, often in conjunction with lower body sensors,[18,22] 24,.[35,36] The wearables used in six studies on the upper back were typically integrated into a harness or vest.[30,31,43,44,54] Three studies placed accelerometers on the wrist, commonly found in sports watches,[29,34,57] and two studies placed multiple sensors on a garment worn by participants.[25,53] This distribution emphasizes lower limb sensor placement for detailed motion analysis.

3.3.7. Outcomes

Table 3 presents the summary of the outcome measures in the 43 reviewed studies for the following categories: spatiotemporal, kinematics, and kinetics. Stride length (SL) was provided in 18 of the studies[19,28,29,37,61,42,25,33,38,35,36,39,40,45,46,56] while vertical oscillation was noted in 10,[18,20,21] Ground contact time (GCT)/stance time appeared in 14 studies,[23,27,28,30,33,34,36,39,44,45,48,59] stride frequency (SF) in 12 41,[19,25,31,35,38,43,44,46,53,55,63] and stride or step time in 10[18,20,26,29,32,40,47,58] 22, 24. Peak or average tibial acceleration was measured in 11 studies.[19,26–28,33–35,37,40,63] Pressure insole outcomes included plantar pressure in 11 studies,[17,18,20,21,25,38,43,45–47,56] contact area in 22, 24,[23,30,36,44] and pressure or force-time integral in 9.[26,29,32,37,39,40,48,51,54] This variety of parameters illustrates the comprehensive approach to gait analysis in the reviewed studies.

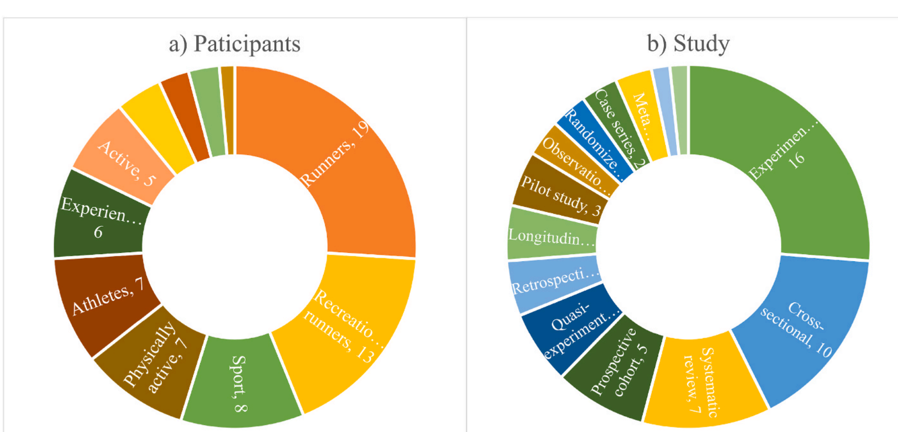

Fig. 2. Description of a) types of participants, and (b) studies included in the review.

Table 3
Outcomes measures, and definitions of selected reviewed studies.

Outcome	Definition	References
• **Spatiotemporal**		
Ground contact time/stance time (N = 14)	The time between initial foot contact and toe – off for the same foot.	[17,22,27,28,30,33,34,36,44,45,48,59].
Cadence, step/stance frequency/rate (N = 12)	The number of steps or strides taken during a given time.	[19,25,31,35,38,44,46,53,55,63].
Step/stride length (N = 18)	The distance between successive points of initial contact of the same foot (stride) or opposite foot (step).	[19,25,28,29,33,35–40,45,46,50,56,63].
Step/stride length (N = 10)	The time between two consecutive heel strikes of the same foot (stride) or opposite foot (step)	[20,26,29,32,38,40,47,58].
Vertical oscillation (N = 10)	The vertical movement of the body during running, measured from the lowest to the highest point.	[20,21,26,32,34,36,38,43,51,54].
Flight time (N = 8)	The time between toe-off from one foot to initial contact of the other foot.	[20,21,26,32,38,39,43,64].
Swing time (N = 8)	The period during which the foot is not in contact with the ground.	20,21,26,32,38,43,51,54.
Cycle time (N = 6)	The time taken to complete a single gait cycle.	[22–24,48,53].
• **Gait Analysis Methods**		
Pressure insole (N = 11)	Use of insole equipped with pressure sensors to measure plantar pressure.	[17,18,20,21,25,38,43,45–47].
IMUs (N = 10)	Inertial Measurement Units used to capture movement data.	[19,27,28,33–35,37,40,63].
Optical Systems (N = 7)	Use cameras and markers to track movements.	[22–24,30,48,54].
• **Gait Symmetry**		
Symmetry (N = 6)	Measures of imbalance between the right and left leg.	[22,24,30,40,45,50].
• **Running-Related Injuries**		
Injury risk factors (N = 9)	Identification of factors contributing to running-related injuries.	[22,23,25,29,30,36,43,47,56].
Rehabilitation outcomes (N = 8)	Measures of recovery and improvement post-injury.	[18,20,21,28,38,45,55,58].
• **Kinematics**		
Ankle/foot kinematics (N = 10)	Description of ankle or foot movement in any of the three cardinal planes.	[19,28,33–35,40,54,63].
Knee kinematics (N = 9)	Description of knee movement in any of the three cardinal planes.	[18,20,27,29,36,38,47,51].
Hip/pelvis kinematics (N = 9)	Description of hip or pelvis movement in any of three cardinal planes.	[17,23,30,45,50,56,64].
• **Kinetics**		
Planter Pressure (N = 11)	The pressure exerted by the foot on the ground, typically measured using pressure insoles.	17,18,20,21,25,38,43,45–47,56).
Ground reaction forces (N = 9)	The force exerted by the ground on the body during movement.	[19,23,26,29,40,48].
Joints movements (N = 9)	The rotational forces acting on joints during movement.	19,27,28,35,37,54,58,63).

Note: Some studies are referenced more than once as they reported on multiple outcome measures.

3.4. Spatiotemporal parameters

3.4.1. Overview of spatiotemporal parameters

The reviewed studies extensively investigated various spatiotemporal parameters to understand running gait mechanics. Ground contact time (GCT)/stance time was one of the most commonly reported measures, mentioned in 14 of the identified studies.[17,23,27,28,30,33,34,36,39,44,45,48,59] Cadence or step/stride frequency was reported in 12 studies, providing information about the number of steps or strides taken in a given time.[19,25,31,35,38,43,44,46,53,55,63] Stride/step length, which refers to the distance between successive points of initial contact, was measured in 18 studies.[19,25,28,29,35–40,45,46,50,56,63] Of these, step/stride time was observed in 10 studies, vertical oscillation in 10 studies,[18,20,21,26,32,34,36,43,51,54] and flight time in 8 studies.[18,20,21,26,32,39,43,64] Cycle time, the time taken to complete a single gait cycle was reported in 6 studies.[23,30,48,53]

3.4.2. Gait symmetry and running-related injuries

Gait symmetry and running-related injuries were prominent topics within the reviewed studies. Understanding these aspects is crucial for identifying potential injury risks and optimizing rehabilitation strategies. Six studies specifically focused on gait symmetry, examining the balance between the right and left legs to detect any asymmetries that could lead to injuries or affect performance.[30,40,45,50] Additionally, nine studies investigated running-related injuries, identifying factors contributing to injury risks and evaluating rehabilitation outcomes to enhance recovery and prevent future injuries.[23,26,29,30,36,43,47,56] These studies underscore the importance of addressing both gait symmetry and injury prevention in the context of running and rehabilitation.

3.4.3. Gait symmetry

Gait symmetry, which measures the balance between the right and left legs, was assessed in 6 studies.[30,40,45,50] These studies highlighted the importance of symmetry in preventing injuries and improving overall running efficiency. Imbalances in gait can lead to increased stress on specific body parts, potentially causing injuries. Addressing these asymmetries through targeted interventions can play a crucial role in injury prevention and enhancing performance in runners.

3.4.4. Running-related injuries

Some of the most relevant subjects of the discussed research were gait symmetry and running-related injuries. Knowledge of such aspects is important in finding possible sources of injuries as well as enhancing rehabilitation measures. Six of the studies were particularly concerned with gait symmetry, which is the ability of the right and left legs to balance each other in terms of force production in order to avoid injury or to optimize performance.[30,45,50] Also, nine of the studies focused on running-related injuries, determining factors that affect the risk of injury, and assessing the outcomes of the rehabilitation to improve recovery and avoid further injuries.[23,26,29,30,36,43,47,56] These studies suggest that gait symmetry should be considered and injury prevention should also be taken into consideration while running and rehabilitation.

3.5. Application studies

3.5.1. Footwear and clothing

Some of the reviewed papers focused on the effects of shoes and clothing on running gait patterns. Such factors as the type of shoes used can influence gait parameters as revealed in 11 of the identified studies that used pressure insole to determine plantar pressure.[17,18,20,21,25,38,43,45–47,56] Based on these conclusions, it can be stated that the proper choice of shoes is crucial for the improvement of the results and the decrease of the risks of injuries.

3.5.2. Intrinsic factors

Factors that were considered intrinsic include biomechanics and physiological aspects of the runner in a bid to determine how they influenced running gait. Research employing IMUs also shed light on kinematics of movement and found evidence of the part played by individual properties in regulating the dynamics of gait. These factors were further investigated in 10 of the reviewed studies[19,27,28,33–35,37,40,63] explaining how individual biomechanics and physiologic characteristics influence walking ability and susceptibility to injury.

3.5.3. Performance

Several studies were conducted to compare gait parameters with the running performance of the athletes. Other variables like step length and cadence were identified to be closely related to running economy and speed, thereby providing an understanding of how athletes can modify their gait patterns to enhance their performance. In 18 studies,[19,25,28,29,33,35–40,45,46,50,56,63] the relationship was further examined concerning how biomechanics of gait could be used to improve performance and minimize injury risk.

3.5.4. Fatigue

Fatigue and its consequence on running gait were studied and it was found out that there were changes in gait mechanics due to fatigue. These studies showed that fatigue causes changes in ground contact time, stride length, and other factors that may raise the probability of injury. Out of 10 studies,[20,26,29,32,37,40,47,58] this relationship was investigated to explain how fatigue affects the running form and increases the risk of injury.

3.5.5. Detecting gait parameters

Advanced techniques for identifying gait parameters were used in the examined papers, including pressure insoles, IMUs, and optical systems. These technologies allowed quantification of gait parameters, thus aiding in the understanding of running mechanics. Pressure insoles were used in 11 of the studies[17,18,20,21,25,38,43,45–47,56] IMUs in 10 studies[19,27,28,33–35,37,40,63] and optical systems in 7 These tools allowed researchers to gather detailed information on several parameters of gait mechanics which helped in improving the knowledge of running biomechanics and eventually helped in better training and prevention of injuries.

3.6. Usability

The practicality of using wearable technology in running gait analysis was evaluated in the examined papers. The use of wearable sensors including IMUs and pressure insoles was also found to offer real-time feedback and biomechanical information. These technologies have real-world uses in both clinical and athletic arenas, improving the efficiency of tracking and improving running performance as well as avoiding the occurrence of injuries. This was done in 26 of the studies.[17–21,25–28,30,33–37,39,40,43,44,46,56,63,65]

4. Discussion

4.1. Summary of key findings

The current systematic literature review and bibliometric analysis therefore provided an extensive review of running gait analysis using wearable technology. In total, 43 papers were included in the review, and the papers were grouped according to their relevance to spatiotemporal parameters, bilateral asymmetry, running injuries, kinematics and kinetics, and gait analysis. In this discussion, the major findings of the analyzed studies, the practical implications, the limitations, and the future research directions will be presented.

4.2. Advancements in wearable technology

The review highlights the following developments in wearable technology for gait analysis, as a more affordable and feasible solution to the current techniques such as three-dimensional motion capture equipment and force plates which are expensive and require a lab environment.[17,23,28,30,48,54] IMU, accelerometers, and pressure sensors, as worn on the body in IMU, accelerometers, and pressure sensors in the studies,[17–21,23,25–30,32,33,35–40,43–48,50–56,58–61,63,64] facilitate real sports environment analysis. Of these, 26 studies highlight the IMUs' ability to capture a wide range of motion data [19,27,28,33–35,37,40,63] as both accelerometers and gyroscopes to provide an exhaustive evaluation of the running gait mechanics. Accelerometers were used in 26 studies and they range from one-dimensional to three-dimensional sensors, proving that it can be applied to a variety of research environments.[19,27,28,33–35,37,40,63] In 11 studies, pressure sensors are employed for identifying plantar pressure distribution, which is critical for assessing the effects of shoes and for detecting abnormal gait.[17,18,20,21,25,38,43,45–47,56]

4.3. Gait parameters and performance

The spatiotemporal characteristics including stride length, ground contact time and cadence as presented in the reviewed studies have been presented to emphasize the significance of spatiotemporal parameters in running mechanics[19,25,28,29,33,35–40,45,46,49,61,63] These parameters are and are considered to be essential indexes of running efficiency and performance. For example, GT (ground contact time) and Cad (cadence) are known to be positively related to running economy and negatively with the risk of injury.[17,23,27,28,30,33,34,36,39,44,45,48,59] Also, kinematic and kinetic measures offer more information about joint kinematics and forces on the body during running.[19,27,28,33–35,37,40,54,58,63] These measures are crucial in establishing interventions that will help in improving running form and consequently performance. The studies reviewed show that these complex parameters can be measured using wearable technology with reasonable accuracy, which makes it possible to use it for real-time gait analysis.[17,18,21,25,38,43,45–47,56]

4.4. Gait symmetry and injury prevention

The knowledge of gait symmetry is important for avoiding injuries and enhancing the running economy. The review also established that asymmetry in movements can result in pressure on some parts of the body and may result in injuries.[30,40,45,50] Wearable sensors can be used to measure gait symmetry and give feedback to the athlete as well as clinicians for remedial action. In addition, running-related injuries and their predisposing factors were also described in detail. Some of the causes of injuries included poor biomechanics, ill-fitting shoes, and training errors.[23,26,29,30,36,43,47,56] Concerning rehabilitation, its results were evaluated, and the use of wearable devices for the assessment of the further recovery process as well as for the definition of the further rehabilitation schedule was noted.[18,20,21,28,38,45,55,58]

4.5. Practical applications

The applications of wearable technology in the analysis of running gait patterns are numerous. In runners, the determination of gait parameters in real time can assist in the improvement of running biomechanics, prevention of injuries, and increase in performance.[19,25,28,29,33,35–40,45,46,50,56,63] The data generated by wearable sensors can be used by coaches to design training regimens and to track progress made and clinicians can use such sensors to diagnose and manage running-related injuries. Moreover, pressure measurement using pressure insole to determine plantar pressure distribution is one of the highlights of the study. This application can be used to select the right footwear for an athlete or to design the right footwear for athletes hence avoiding injuries.[17,18,20,21,25,38,43,45–47,56] Moreover, the possibility of controlling fatigue and its impact on gait characteristics is useful for further training load regulation and overuse injuries prevention.[18,20,26,29,40,58,66]

4.6. Limitations and future research

The present review was supposed to provide a review of running gait analysis using wearable technology. However, the process and technique of developing the wearable devices were considered to be beyond the scope of this review and therefore the study does not provide much details on the process of developing and fine tuning of these devices. However, the focus of the technologies is in the hardware and algorithms, though, in this review, more emphasis has been placed on the application of wearable technology for gait analysis and the implications of the same. A limitation is that the search was done up to May 2024. Since the technological development of wearable devices and gait analysis methods is extensive and constantly evolving, it could be claimed that this review was performed at the end of and thus may miss some of the most recent data. Future reviews should include the latest developments especially in the area of sensors and real-time data processing in order to provide a more up-to-date review of wearable technology in running gait analysis.

For further investigation of the effectiveness of the wearable technology in analyzing the running gait, future studies should incorporate long-term cross-sectional studies as well as the use of advanced biomechanical model to determine the impact of these devices on running performance and injury prevention. Techniques like Computational Biomechanics and Multi-Body Dynamic Modeling might be helpful in predicting how changes to gait characteristics affect musculoskeletal wellbeing in the long term. Moreover, the integration of the developed Machine Learning algorithms to the Big Data collected by wearable devices might help to discover further patterns to personalize the gait training and/or predict the risk of injuries. The creation of standardized procedures and validation criteria for wearable devices in gait assessment is also suggested as necessary because, at the present time, they are absent. Setting up of these standards will assist in developing coherent and dependable data across the various devices and investigations. Last of all, incorporating advanced technologies such as AI based real time feedback systems to wearable devices improving their use in training and retraining by providing quicker and individualized feedback to both athletes and clinicians.

5. Conclusion

This systematic literature review provides a comprehensive overview of running gait analysis research, highlighting the advancements in wearable technology and their practical applications. The findings emphasize the importance of developing standardized methodologies and validation protocols for wearable devices to ensure their reliability and effectiveness in real-world sports environments. By leveraging wearable technology, athletes, coaches, and clinicians can enhance running performance and prevent injuries, contributing to the overall well-being of runners.

CRediT authorship contribution statement

Ravinder Kumar: a Doctoral Candidate in the Department of Physical Education at Banaras Hindu University, Varanasi, India, was responsible for the, Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Ravinder also served as the corresponding author for this review study. **Priyanka Bogia:** a Doctoral Candidate in the Department of Electrical Engineering at the Indian Institute of Technology, Jammu, India, contributed significantly to the, Investigation, Validation, Writing – review & editing. **Vikram Singh:** from the Department of Physical Education at Banaras Hindu University, Varanasi, India, provided, Supervision, Resources, and, critical revisions during the writing and, Writing – review & editing, Professor Dr. **T. Onima Reddy:** also from the Department of Physical Education at Banaras Hindu University, contributed to the.

Ethical statement

This study was conducted with strict adherence to the ethical principles of research. As a systematic literature review, it involved the collection and analysis of data from previously published studies, ensuring that no new data were collected from human participants. The review process was designed to minimize the risk of bias, with careful attention to the selection, evaluation, and synthesis of studies. The authors have taken all necessary steps to ensure that the findings presented are objective, accurate, and reflective of the existing literature.

Parental consent statement

This study is a systematic literature review and does not involve the collection of new data from human participants, including minors. As such, parental consent was not required or obtained. The study solely analyzed and synthesized data from previously published research where ethical approvals and consents were managed by the original investigators.

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Ravinder Kumar, Priyanka Bogia, Professor Dr. Vikram Singh, and Professor Dr. T. Onima Reddy have conducted this research without any external financial assistance. The study reflects the authors' commitment to advancing knowledge in the field of running gait analysis and wearable technology, supported solely by their academic institutions, which provided access to necessary research tools, software, and other resources.

The absence of external funding ensured that the research was conducted impartially and without any influence from commercial or other external entities. This allowed the authors to maintain complete control over the study's design, data interpretation, and reporting of findings, ensuring the integrity and objectivity of the research outcomes.

Declaration of competing interest

The authors hereby declare that there are no financial, personal, or professional conflicts of interest that could have influenced the research, findings, or interpretation of the results presented in this study.

Ravinder Kumar has no financial relationships or affiliations with any organizations or entities that could be perceived as influencing the research outcomes. His role as the corresponding author was conducted impartially, with no external pressures or biases impacting the review process.

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Professor Dr. Vikram Singh affirms that there are no competing interests, financial or otherwise, that could have biased the research. His involvement was purely academic, focusing on the supervision and integrity of the study.

Professor Dr. T. Onima Reddy confirms that there were no financial benefits, institutional affiliations, or personal relationships that could be seen as conflicts of interest in relation to the work presented in this manuscript. His participation was motivated purely by academic interest and the pursuit of knowledge in the field of physical education and gait analysis.

All authors have agreed to the content of the manuscript and have approved the final version for submission. They all adhere to ethical guidelines and have maintained the highest standards of integrity throughout the research process.

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