Methodological protocol of running on a treadmill using IMU in healthy people. Scoping review

Protocolo metodológico de la carrera en cinta mediante IMU en personas sanas. Revisión de alcance

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Abstract

Introduction: Running is a popular and accessible activity with well-established health benefits, although it carries a risk of musculoskeletal injuries. Biomechanical analysis helps identify risk factors and guide preventive strategies. Inertial measurement units (IMUs) have enhanced the assessment of running technique.

Objective: This study aimed to review the methodological protocols applied in the kinematic analysis of treadmill running among recreational runners using IMUs in healthy individuals.

Methodology: The review followed PRISMA-ScR guidelines. Searches were conducted in Medline/PubMed, Web of Science, SportDiscus, and SafeJournal. Eligible studies included descriptive, reliability, validity, and intervention designs using IMUs in healthy participants. Methodological quality was assessed with the modified Downs & Black Index, and inter-rater reliability with Cohen's Kappa coefficient.

Results: From 6,169 records, 30 studies met the eligibility criteria. A total of 31 devices were analyzed, with sampling frequencies ranging from 1600 Hz to 1 Hz. The tibia was the most common sensor location. Across studies, 553 men (66.2%) and 282 women (33.8%) participated. The most frequently assessed parameters were acceleration, angular velocity, and spatiotemporal variables such as cadence and contact time.

Conclusions: Treadmill-based IMUs are valid tools for measuring kinematic parameters and provide valuable insights into running technique and performance. Measurement accuracy depends on sensor placement. Key limitations included the low representation of women, the predominance of recreational runners, and the frequent use of reduced running speeds. Future studies should incorporate balanced sex representation and systematic comparisons of sensor locations to enhance reproducibility and support injury-prevention programs.

Keywords

Biomechanics; kinematics; running; treadmill test; wearable.

Resumen

Introducción: Correr es una actividad popular y accesible con beneficios para la salud, aunque con riesgo de lesiones musculoesqueléticas. El análisis biomecánico permite identificar factores de riesgo y orientar la prevención. Las unidades de medida inercial (IMU) han potenciado la evaluación de la técnica de carrera.

Objetivo: Este estudio tubo cómo objetivo revisar el protocolo metodológico empleado en el análisis cinemático de la carrera a pie de corredores recreacionales utilizando unidades de medición inercial en cinta rodante y en personas sanos

Metodología: Se siguieron las guías PRISMA-ScR. La búsqueda se realizó en Medline/PubMed, Web of Science, SportDiscus y SafeJournal. Se incluyeron estudios descriptivos, de fiabilidad, validez e intervención con IMU en personas sanas. La calidad metodológica se evaluó con el índice de Downs & Black modificado y con el coeficiente Kappa de Cohen.

Resultados: De 6.169 registros, 30 estudios cumplieron los criterios. Se analizaron 31 dispositivos con frecuencias entre 1600 Hz y 1 Hz. La tibia fue la localización más frecuente. La muestra total incluyó 553 hombres (66,2 %) y 282 mujeres (33,8 %). Los parámetros más estudiados fueron aceleración, velocidad angular y variables espaciotemporales como cadencia y tiempo de contacto.

Conclusiones: Las IMU en cinta rodante son válidas para medir parámetros cinemáticos y aportar información sobre técnica y rendimiento. La colocación de sensores condiciona la precisión. Las limitaciones fueron la baja representación femenina, el predominio de corredores recreativos y las velocidades reducidas. Futuras investigaciones deben equilibrar sexos y comparar localizaciones.

Palabras clave

Biomecánica, carrera, cinemática, dispositivo portátil, prueba en cinta rodante.

Introduction

Running is a popular and accessible activity practiced by various people for leisure and competition, which improves body composition, reduces fat, cholesterol, and triglycerides, and is associated with lower mortality (Oja et al., 2015). Furthermore, it strengthens the respiratory muscles, improves lung function, and is beneficial for long-term health (Akhade & Muniyappanavar, 2014), and longer workouts are associated with greater benefits (Oja et al., 2015). However, it entails risks of musculoskeletal injuries, with the most common being patellofemoral pain syndrome, iliotibial band syndrome, Achilles tendinopathy, tibial stress fractures, plantar fasciitis, and patellar tendinopathy (Bramah et al., 2018). These injuries can lead to a reduction or interruption of training by approximately 30 % to 90 % (Bramah et al., 2018). The accumulation of repetitive impacts below the acute injury threshold produces fatigue, contributing to mechanical overload injuries (Glauberman & Cavanagh, 2014).

Biomechanical analysis of running technique helps identify injury risk factors (Bramah et al., 2018). For example, a 7.5 % to 10 % reduction in stride length is associated with a reduction in vertical load and braking force (Lieberman et al., 2015). Increasing running speed reduces braking force and minimizes the hip flexion moment (Lieberman et al., 2015). Modifying running speed influences contact time and leg stiffness, improving elastic energy storage (Farley & Gonzalez, 1996).

An altered biomechanical pattern has been observed in injuries such as patellofemoral pain syndrome, where runners experience lower impulse force due to increased contact time (Bramah et al., 2018).

Previous studies have examined movement variability in individuals with neurological disorders, musculoskeletal injuries, and other pathological conditions. Research comparing injured and healthy runners has found that 62% of studies report significant differences in movement variability patterns (Iqbal & Chow, 2025).

Technological advances in IMUs have created new opportunities to investigate the biomechanics of human movement, thanks to their ability to perform a wide range of calculations and apply sophisticated algorithms. IMU sensors, which integrate gyroscopes, magnetometers, and accelerometers, are particularly suitable for the analysis of human motion in various environments (Echeverry et al., 2018). Their use is recommended outside the laboratory due to their low cost, portability, and accuracy in kinematic information (Hughes et al., 2021). However, they require calculations and algorithms to estimate their orientation (Zhang et al., 2017). They provide better estimates of sagittal joint angles compared to frontal or transverse angles (Poitras et al., 2019). The validity and reliability of IMU sensors for measuring kinematic parameters of running have been widely demonstrated (Echeverry et al., 2018). The sensor location does not affect its validity and reliability, but it does influence the mechanical parameters analyzed (Horsley et al., 2021). IMUs are useful for analyzing running techniques used by coaches, physical trainers, podiatrists, and physiotherapists. It is important to understand the types of devices that can be used in healthy individuals and the protocols applied to improve the transfer to training rhythms.

The objective of this scoping review was to evaluate the validity and reliability of biomechanical parameters during treadmill running, with a focus on comparing different calibration protocols and IMU sensor placements in healthy individuals.

Method

Data extraction and synthesis

In this scoping review, the results section summarizes the data extracted from the analyzed studies, as detailed in Table 2. The table includes information on authors, demographic characteristics of participants, study design, and applied protocols. It also specifies details related to the measurement devices and the biomechanical variables assessed. These data are essential to contextualize the findings of the review.

Eligibility criteria

Article identification, screening, and selection were performed independently by two reviewers, with disagreements resolved through a structured process involving a third reviewer, using the Rayyan tool (Ouzzani et al., 2016). To clarify the resolution process, the independent third reviewer assessed only the disputed studies in a blinded manner, applying both the Downs and Black Index and the predefined eligibility criteria. This reviewer provided independent scores with documented justification, and the final decision was reached by consensus among all three evaluators, ensuring objectivity and methodological rigor without altering the predefined eligibility criteria.

The eligibility criteria were as follows: (a) continuous running analysis; (b) treadmill and laboratory-based assessments; (c) use of IMU devices for biomechanical evaluation; (d) studies in healthy humans, both male and female, aged 16 to 70 years; (e) inclusion of validity, reliability, descriptive, and intervention studies, focused exclusively on methodology and protocols regardless of outcomes; (f) exclusion of review articles and conference proceedings; and (g) articles published between 2007 and 2025. The timeframe was selected to cover a sufficiently broad period to capture the evolution of wearable technologies in running biomechanics. Although wearable devices date back to 1982 with the introduction of the POLAR Sport Tester PE2000 (Willy, 2018), restricting the search to studies published since 2007 allowed for the inclusion of 18 years of contemporary literature on IMU use in running biomechanics. This timeframe ensured both sufficient breadth to capture technological advances and data manageability. We acknowledge that excluding literature prior to 2007 may have resulted in the omission of relevant foundational studies.

Search process and databases

This scoping review followed PRISMA-ScR guidelines (Tricco et al., 2018). Searches were conducted in Medline/PubMed, Web of Science (WOS), SportDiscus, and SafeJournal (MDPI) through January 2025, using keywords such as “Running,” “biomechanics,” “kinematics,” “prevention,” “wearable,” “treadmill,” and related terms (see Supplementary Material 1). The search strategy was limited to databases specific to sports science and biomechanics. Including additional databases such as Embase, Scopus, or CINAHL may have enriched the results, and this limitation should be considered in future systematic reviews.

Quality assessment and risk of bias

Methodological quality was assessed using the modified Downs and Black Index (Downs & Black, 1998), specifically adapted for reliability and descriptive studies (Schubert et al., 2014). This tool was selected for its versatility in assessing heterogeneous studies designs, a critical aspect given the diversity of studies included in this review. The index was originally developed to evaluate both randomized and non-randomized trials, with domains specific to study design.

The final scale included 15 items after systematically removing those not applicable to descriptive and reliability studies, consistent with previous systematic reviews (Ceyssens et al., 2019). Items were scored as “yes” = 1, “no” = 0, or “unable to determine (UD)” = 0, except item 5, which was scored up to two points (see Supplementary Material 2). Item 27, related to sample size calculation, was scored as 1 or 0 depending on whether it was reported (Korakakis et al., 2017). Studies scoring ≥11 points were classified as high quality, 6–10 as moderate, and ≤5 as low quality (Ceyssens et al., 2019).

Quality assessment was performed independently by two reviewers. In case of disagreement, a third independent reviewer re-evaluated only the disputed studies in a blinded manner, applying both the Downs and Black criteria and the eligibility criteria of the review. This reviewer provided independent scores with documented justification, and the final decision was based on consensus among the three evaluators. This process ensured objectivity and methodological rigor without altering predefined eligibility criteria. We acknowledge that applying a single tool to heterogeneous designs is a methodological limitation, and future reviews may benefit from design-specific instruments.

Inter-rater agreement

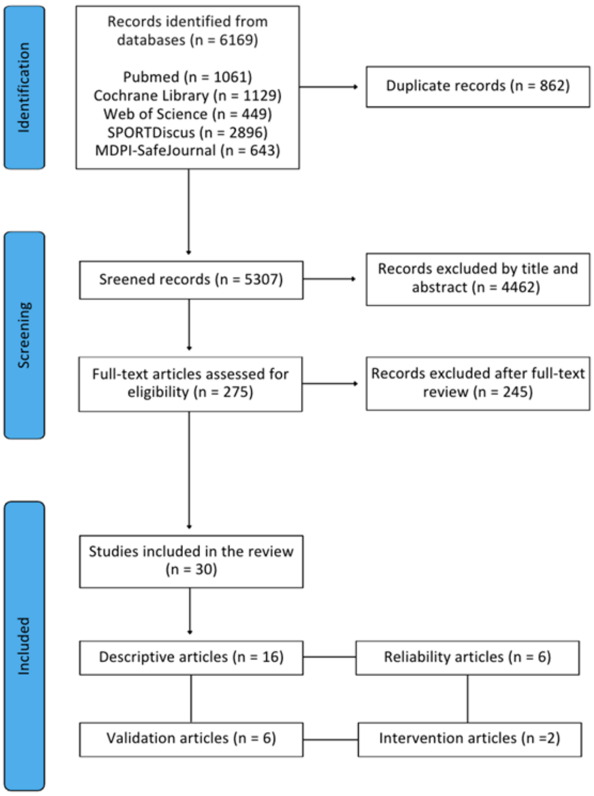
Inter-rater reliability was assessed using Cohen’s Kappa coefficient. Results indicated almost perfect agreement between the first and second reviewers (mean $\kappa = 0.94$) and perfect agreement between the first and third ($\kappa = 1.00$). In contrast, agreement between the second and third reviewers showed significant inconsistencies (mean $\kappa = -0.27$), particularly in specific criteria. These findings confirm that at least two reviewers maintained high consistency in their assessments, ensuring the reliability of the review process.

Results

Study selection

A total of 6,169 records were retrieved, and 862 duplicates removed. After screening titles and abstracts, 4,462 articles were excluded, leaving 275 for full-text review. Finally, 30 studies met the eligibility criteria: 16 descriptive, 6 reliability, 6 validation, and 2 intervention studies (see Figure 1).

Figure 1. Flow diagram of the inclusion and exclusion process (created by the authors using Microsoft PowerPoint and Canva).



Methodological quality and risk of bias

Scores on the modified Downs and Black quality index (Ceyssens et al., 2019) ranged from 10 to 16 points, with 16 being the maximum possible score. The scale was modified by removing items irrelevant to this specific study context, following validated methodology (Ceyssens et al., 2019). Cut-off points were defined as follows: high quality ≥12 (≥75% of the maximum score), moderate quality 8–11 (50–74%), and low quality <8 50%). These thresholds provide a solid and replicable methodological basis for quality classification in this specific context. Based on these criteria, 20 articles (66.7%) were classified as high quality (12–16 points), 10 (33.3%) as moderate quality (10–11 points), and none as low quality, suggesting an appropriate selection of studies with robust methodology (see Table 1).

Table 1. Downs and Black checklist (Downs & Black, 1998), risk of bias assessment for all included studies (N = 30).

	Items														
Author	1	2	3	5	6	7	9	10	11	12	13	16	18	20	27	Total
Abbasi et al., 2020	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	0	13
Chabot et al., 2024	1	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	12
Clermont et al., 2018	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	0	13
Darch et al., 2023	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	1	14
Dimmick et al., 2022	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	0	13
Doyle., et al 2024	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15
Fohrmann et al., 2022	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
García-Pérez et al., 2014	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
Gómez-Carmona et al., 2019	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
Hernandez et al., 2021	1	1	1	0	1	1	1	0	UD	UD	1	1	1	1	0	10
Jaén-Carrillo et al., 2024	1	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	12
Johnson et al., 2020a	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	0	13
Lee et al., 2015	0	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	11
Mason., et al 2023	1	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	12

Table 1 (Continuation). Downs and Black checklist (Downs & Black, 1998), risk of bias assessment for all included studies (N = 30).

	Items														
Autor	1	2	3	5	6	7	9	10	11	12	13	16	18	20	27	Total
Miqueleiz et al., 2024a	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	15
Miqueleiz et al., 2024b	1	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	12
Pareja-Cano et al., 2024	1	1	1	1	1	1	1	1	UD	UD	1	1	1	1	0	11
Patoz et al., 2022	1	1	1	2	1	1	1	1	1	1	1	1	1	1	0	15
Perpiñá-Martínez et al., 2023	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
Provot et al., 2019	1	1	1	1	1	1	1	0	UD	UD	1	1	1	1	0	11
Rantalainen et al., 2016	1	1	1	0	1	1	1	1	UD	UD	1	1	1	1	0	11
Reenalda et al., 2021	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
Riglet et al., 2024	1	1	1	1	1	1	1	0	UD	UD	1	1	1	1	0	11
Rowlands et al., 2007	1	1	1	2	1	1	1	1	UD	UD	1	1	1	1	0	13
Ruiz et al., 2023	1	1	1	2	1	1	1	0	UD	UD	1	1	1	1	0	12
Sheerin et al., 2020	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	16
Uno et al., 2023	1	1	1	0	1	1	1	UD	UD	UD	1	1	1	1	0	10
Yang et al., 2011	1	1	1	0	1	1	1	1	UD	UD	1	1	1	1	0	11
Yang et al., 2022	1	1	1	0	1	1	1	0	UD	UD	1	1	1	1	0	10
Zandbergen et al., 2022	1	1	1	0	1	1	1	0	UD	UD	1	1	1	1	0	10

Scoring: UD (Unable to determine), 0 (does not score), 1 point, 2 points. Attached items (see Supplementary Material 2).
The table presents a summary of the studies included in the scoping review. Key aspects related to the methodology used in each study are detailed, differentiating between the determination of pace and test speed, which is essential for the correct interpretation of the data obtained.

Inter-rater agreement

Inter-rater reliability, assessed with Cohen's Kappa coefficient (Cohen, 1960), revealed variable agreement among reviewers. Almost perfect agreement was observed between the first and second reviewers (κ = 0.94) and perfect agreement between the first and third reviewers (κ = 1.00). In contrast, agreement between the second and third reviewers showed significant inconsistencies (κ = −0.27). For most criteria, Kappa values ranged from moderate to almost perfect (κ > 0.60–0.80, and in several cases κ > 0.80), confirming that at least two of the three reviewers maintained high consistency in their evaluations.

Types of studies

Sixteen descriptive studies were identified, characterizing different methodologies (Abbasi et al., 2020; Clermont et al., 2018; Doyle et al., 2024; García-Pérez et al., 2014; Hernandez et al., 2021; Jaén-Carrillo et al., 2024; Johnson et al., 2020a; Lee et al., 2015; Miqueleiz et al., 2024a; Pareja-Cano et al., 2024; Patoz et al., 2022; Provot et al., 2019; Rantalainen et al., 2016; Rowlands et al., 2007; Yang et al., 2011; Yang et al., 2022). Six studies focused on reliability and validity, evaluating the accuracy and consistency of the employed methods (Dimmick et al., 2022; Fohrmann et al., 2022; Gómez-Carmona et al., 2019; Mason et al., 2023; Miqueleiz et al., 2024b; Perpiñá-Martínez et al., 2023; Riglet et al., 2024; Ruiz-Malagón et al., 2023; Uno et al., 2023; Zandbergen et al., 2022; Reenalda et al., 2021). Additionally, two intervention studies evaluated the effectiveness of different methodologies (Darch et al., 2023; Sheerin et al., 2020) (see Figure 1).

Sample characteristics

All included studies reported male participants, and 80% also included female participants. In total, 553 males (66.2%) and 282 females (33.8%) were included (see Figure 2). Among males, 427 (77%) were recreational runners, 92 (17%) competitive, and 34 (6%) unspecified. Among females, 230 (82%) were recreational, 29 (10%) competitive, and 23 (8%) unspecified.

Data collection instruments

Across 30 references, 31 IMU devices were identified. The most frequently used was the Blue Trident, IMeasureU Blue (Auckland, NZ) (19.4%), followed by the MVN Link, Xsens (16.1%). Other brands were used only once. Regarding sampling frequency, 8 IMUs operated between 1000 Hz and 1600 Hz, 11 devices between 200 Hz and 500 Hz, and 9 IMUs between 100 Hz and 128 Hz. The lowest sampling frequency reported was 1 Hz (see Figure 2). All IMUs incorporated a triaxial accelerometer, gyroscope, and magnetometer, except two devices that lacked a magnetometer.

Sensor placement protocols

IMUs were most often positioned on the tibia (31.3%), followed by the foot (28.4%), sacrum (23.7%), sternum (6%), thigh (4.5%), femur (3%), and knee (1.5%). Seventeen studies employed multiple anatomical placements, whereas 14 used a single location (see Figure 2).

Running protocols

The most common running speeds ranged between 9.5 and 10.5 km/h (Clermont et al., 2018; Darch et al., 2023; Hernandez et al., 2021; Mason et al., 2023; Perpiñá-Martínez et al., 2023; Provot et al., 2019; Rowlands et al., 2007; Ruiz-Malagón et al., 2023; Sheerin et al., 2020), followed by speeds between 11.5 and 12.5 km/h (Chabot et al., 2024; Dimmick et al., 2022; Hernandez et al., 2021; Jaén-Carrillo et al., 2024; Miqueleiz et al., 2024a; Miqueleiz et al., 2024b; Mason et al., 2023; Pareja-Cano et al., 2024; Perpiñá-Martínez et al., 2023; Provot et al., 2019; Riglet et al., 2024; Rowlands et al., 2007; Sheerin et al., 2020; Uno et al., 2023; Yang et al., 2011). The maximum running speed recorded was 26 km/h (Rowlands et al., 2007), while the minimum was 5 km/h (Rantalainen et al., 2016) (see Table 2).

Inter-rater agreement:

Table 2. Results and characteristics of the selected studies (N = 30).

Author (year)	Sex, physical characteristics, and type of study	Methodological protocol (Determination of pace; running speed; treadmill used)	IMU characteristics (Type, frequency)	IMU location; Number of IMUs	Kinematic parameters
Abbasi et al. (2020)	7 M / 13 W M: 21.28 ± 3.86 yr 175.14 ± 4.74 cm 70.14 ± 4.41 kg W: 21.76 ± 2.04 yr 163.84 ± 4.86 cm 56.84 ± 5.44 kg RR. DS.	The SPD was determined across 10 m (asphalt) at its PS x3 series. SPD PS was calculated: 30.49 km/h. Races were performed at 20% + slow and 20% + fast than the PS, both on treadmill RUN 30'', 5' D between tests. Doesn't mention treadmill.	myoMOTION. 200 Hz. Accel 3D; Gir; Mag.	Foot, tibia, femur and sacrum. (N: 4)	Flx/Ext de hip, Flx/Ext KNEE, DF ANK and plantar Flx.
Chabot et al., (2024)	16 M / 11 W 22.8 ± 2.9 yr 1.8 ± 0.1 cm 68.1 ± 9.3 kg RR. IS.	10' one SPD PS, 10' one SPD usual, 6' one SPD PS 9, 10, 12, 13,63, 17, 79, 20 and 21 km/h IS and PS. Bertec Corporation, Columbus.	Xsens MTw Awinda 100. Hz. Accel 3D; Gir; Mag.	Tibial tuberosity. (N: 2)	GRF, LR, ACC TIB and AVTAP.
Clermont et al. (2018)	25 M / 16 W M RR: 30.8 ± 12.37 yr / 177.5 ± 7.11 cm / 74.21 ± 8.40 kg M CR: 35.0 ± 12.5 yr / 180.73 ± 5.62 cm / 75.85 ± 3.87 kg W RR: 30.67 ± 11.70 yr / 163.33 ± 4.18 cm / 63.48 ± 9.18 kg W CR: 34.71 ± 14.86 yr / 165.34 ± 4.16 cm /59.9 ± 4.23 kg RR y CR. DS.	RUN on treadmill 5' to ps, the first and last 15'' were eliminated, resulting in 4'30'' of analysis. M RR / CR: 11.08 ± 0.82 km/h / 9.64 ± 0.82 km/h W RR / RC: 10.22 ± 1.08 km/h / 8.89 ± 0.79 km/h PS. Bertec, Columbus, OH.	Shimmer3. 201.03 Hz. Accel 3D; Gir; Mag.	Sacrum. (N: 1)	Regularity of step and stride symmetry, ACC, stability and DR efficiency.
Darch et al. (2023)	15 M / 13 w M: 38.8 ± 5.3 yr 180 ± 0.1 cm 78.4 ± 9.0 kg	6' between 8 and 10 km/h with a fixed INT until exhaustion at 85% of VO2max (between 20 and 60') with an INC of 1 %	Blue Trident IMU. 1125 Hz. Accel 3D; Gir; Mag.	Antero-medial distal tibia L and R. (N: 2)	Axial TIB ACC MAX.

	w: 38.0 ± 6.0 yr 170 ± 0.1 cm 62.5 ± 8.2 kg CR. IS.	IS. Woodway, Waukesha.			
Dimmick et al. (2022)	9 M / 7 W 30.1 ± 4.2 yr mean 174.3 ± 9.1 cm medium 70.5 ± 10.5 kg RR and CR. RS.	45' until exhaustion between 12.06 ± 1.44 km/h, with 5' before 6.9 km/h. IS. Doesn't mention treadmill.	Blue Trident IMU. 1125 Hz. Accel 3D; Gir; Mag.	Sacrum. (N: 1)	ML and AP ACC.

Table 2 (Continuation). Results and characteristics of the selected studies (N = 30).

Author (year)	Sex, physical characteristics, and type of study	Methodological protocol (Determination of pace; running speed; treadmill used)	IMU characteristics (Type, frequency)	IMU location; Number of IMUs	Kinematic parameters
Doyle et al. (2024)	17 M / 13 W M: 35.7 ± 7.0 yr 173.6 ± 8.5 cm 68.4 ± 9.3 kg F: 34.8 ± 9.5 yr 166 ± 6.9 cm 59.8 ± 8.4 kg RR. DS.	60'' at 9, 11, 13, 15 and 17 km/h. IS. AMTI Compact Tandem.	Blue Trident IMU. 1125 Hz. Accel 3D; Gir; Mag.	Distal, proximal tibia. Distal femur leg D and sacrum. (N: 4)	Strength, peak loading rate. IMP peak, VERT charge rate. Peak ACC, F and CTT.
Fohrmann et al. (2022)	13 M / 12 W Between 18 y 65 yr 174.8 ± 8 cm 69.4 ± 12.4 kg RR. RS.	5' to SPD self-selected. PS. Doesn't mention treadmill.	OPAL, Apdm. 128 Hz. Accel 3D; Gir; Mag.	In the foot, the tibial tuberosity, the sacrum and the xiphoid process of the sternum. (N: 4)	Angular SPD and stability of the RUN.
García-Pérez et al. (2014)	11 M / 9 F 34 ± 8 yr 172 ± 8 cm 63.6 ± 8.0 kg RR. DS.	400m at an SPD of between 13.72 ± 1.44 km/h. IS. Excite Run 700, TechnogymSpA.	MMA7261QT, Freescale Semiconductorq. 100Hz. Uniaxial ACC, only 1 direction, does not incorporate GIR or MAG.	Proximal tibia R and forehead. (N: 2)	ACC MAX, Tibial IR, ACC MAX, IMP attenuation (%).
Gómez-Carmona et al. (2019)	20 M / 0 W 27.32 ± 6.65 yr 174 ± 0.03 cm 68.96 ± 4.37 kg RR. RS.	5' at 65 % MHR, 8 km/h, every 12'' +0.1 km/h, until the athlete could not do the V. 5' at 55% MHR. IS. MASiprTM.	WIMU PRO. 1000 Hz. Accel 3D; Gir; Mag.	Scapula (VE and C6), sacrum (VE L3), knee and ankle. (N: 4)	Differences in joint IMPs: ankle-knee, knee-COM and COM-scapula.
Hernandez et al. (2021)	27 M / 0 W 26.5 ± 3.9 yr 175 ± 0.07 cm 68.3 ± 10 kg RR. DS.	8, 10, 12 and 14 km/h. IS. Doesn't mention treadmill.	Whoop - PUSH Design Solutions. 100 Hz. Accel 3D; Gir; Mag.	Sacrum, inner/eternal thigh, tibia L and R. (N: 5)	Sacrum: Flx, ADD, ROT / Knee: Flx / RA: DORF, INV / LH: Flx, ADD, ROT / LK: Flx / LA: DF and INV.
Jaén-Carrillo et al., 2024	15 M / 0 W 30.8 yr 176 cm 70.7 kg CR. DS.	10’ RUN INT low-moderate, 3' at 10 km/h and 3' at 12 km/h followed by 9' and 3' at maximum SPD reaching up to 21 km/h. IS and PS. WOODWAY Pro XL.	Stryd Power. 1 Hz per second.	Feet (metatarsus). (N: 2)	CT, LS, VO, CAD and SPD.
Johnson et al. (2020.a)	10 M / 8 W 33 ± 11 yr, it doesn’t mention cm or kg. RR. DS.	10.70 km/h ± 1.12 km/h 16''. PS. AMTI, Watertown.	IMeasureU Blue Trident. 1600 Hz. Accel 3D; Gir; Mag.	Distal-medial TIB R. (N: 1)	TIB ACC, stride variability, VK load and F IMP load.

Table 2 (Continuation). Results and characteristics of the selected studies (N = 30).

Author (year)	Sex, physical characteristics, and type of study	Methodological protocol (Determination of pace; running speed; treadmill used)	IMU characteristics (Type, frequency)	IMU location; Number of IMUs	Kinematic parameters
Lee et al. (2015)	15 M / 0 W 26.9 ± 3.1 yr 173.5 ± 5.4 cm 73.4 ± 9.0 kg RR. DS.	12.6 km/h. IS. AMG-7310, Magtonic.	ADXL345, Analog Devices. 200 Hz. Accel 3D; Gir; Mag.	Foot L. (N: 1)	ACC and ANS (antero-posterior, medio-lateral and superior-inferior).
Mason et al. (2023)	26 M / 15 W 36.4 ± 11.8 yr 173 ± 8.7 cm 72.6 ± 12.2 kg	60'' at 8, 10, 12 and 14 km/h. IS. Spirit fitness XT485.	DANU sports system. 250 Hz. Accel 3D; Gir; Mag.	Medial tibia. (N: 2)	Linear ACC. CT, SWT and ST.

	RR. RS.				
Miqueleiz et al., (2024.a)	16 M / 16 W 32.8 ± 9.3 yr 176 ± 3.8 cm 70.0 ± 7.5 kg CR. DS.	6' RUN, SPD INCR: 9.2, 15.1, 18.0 and 21.0 km/h. Same protocol repeated on the track. Record of first 30'', first 30 steps and first step of each SPD. 9, 15, 18 and 21 km/h IS. ERG-ELEK-EG4.	MTw, 3DOF 8 Human Orientation Tracker, Xsens Technologies BV Enschede. 120 Hz. Accel 3D; Gir; Mag.	Sacrum L4-L5. (N: 1)	FREQ STR, LEN STR, CT, FT, DISP VERT, DISP MLAT, ACC VERT/MEDLAT/ANT-POST
Miqueleiz et al., (2024.b)	15 M / 15 W 37.0 ± 9.7 yr 177 ± 4.5 cm 69.5 ± 6.6 kg RR. RS.	6' INCR test from 8 km/h with increments of 1 km/h per stage up to 21 km/h (30" V final). 20" at 9, 15 and 21 km/h. IS. ERG-ELEK-EG4.	MTw, 3DOF 8 Human Orientation Tracker, Xsens Technologies BV Enschede. 120 Hz. Accel 3D; Gir; Mag.	Sacrum L4-L5. (N: 1)	DES TRK VERT and MLAT. ACC TRK.
Pareja-Cano et al., (2024)	18 M / 4 W 29 ± 6 yr 176 ± 7 cm 77 ± 9 kg RR. DS.	6' RUN (10k pace): 5' adaptation + 1' registration. 10 and 12 km/h. PS. Salter PT 298-STR.	IMU Shimmer3. 512 Hz. Accel 3D; Gir; Mag.	Tibial tuberosity. (N:2) Sacrum L5-S1, T12-L1. (N: 2)	RF, PWR, TIB ACC, KNEE RDM, STR TIME, CAD, CT and SF.
Patoz et al. (2022)	73 M / 27 W M: 30 yr 180 ± 6 cm 71 ± 7 kg F: 29 ± 7 yr 169 ± 5 cm 61 ± 6 kg RR. DS.	1' at 9, 11 and 13 km/h. IS. Arsalis T150-FMT-MED.	Movesense. 208 Hz. Accel 3D; Gir; Mag.	Sacrum. (N: 1)	ACC and FMAX reaction VERT, CT and FT.
Perpiñá-Martínez et al. (2023)	51 M / 50 W between 18 and 53 yr average 170 cm 65.7 kg RR. RS.	SS 9.98 km/h and 8.75 km/h, MS was considered for values between 9.98 and 11.70 km/h and between 8.75 km/h and 10.11 km/h, and FS was considered for values greater than 11.71 km/h and 10.11 km/h for M / W respectively. IS. BH Fitness Columbia Pro.	BTS G-Sensor. 1000 Hz. Accel 3D; Gir; Mag.	Sacrum at the level of S1. (N: 1)	CAD, STR LONG and RC, the symmetry index of ACC VERT, the kinematic ranges of INC, OBL and ROT.

Table 2 (Continuation). Results and characteristics of the selected studies (N = 30).

Author (year)	Sex, physical characteristics, and type of study	Methodological protocol (Determination of pace; running speed; treadmill used)	IMU characteristics (Type, frequency)	IMU location; Number of IMUs	Kinematic parameters
Provot et al. (2019)	10 M / 8 W 31.4 ± 8.9 yr 172 ± 0.09 cm 69.9 ± 12.3 kg RR. DS.	1' at 8, 9, 10, 11, 12, 13, 14, 16, 18 km/h. IS. NordiTrack C300®.	IMU-Hikob. 1344 Hz. Accel 3D; Gir; Mag.	Foot R above the metatarsals. Tibia. Sacrum. (N: 3)	FREQ average stride and average CT duration, average flight duration, mechanical and stable leg stiffness and average FREQ stable contact.
Rantalainen et al. (2016)	28 M / 11 W 24.2 ± 2.5 yr 179 ± 0.09 cm 71.6 ± 12.0 kg RR. DS.	5.4 km/h, for a minimum of 60''. IS. Quinton Q65.	MinimaxX S4. 100 Hz. Accel 3D; Gir; Mag.	Shoulder blade. (N: 1)	Variability and duration of the step.
Riglet et al., (2024)	16 M / 14 W 28.2 ± 6.1 yr 180.3 ± 5.3 cm 74.4 ± 8.6 kg RR. RS.	5' RUN to PS 10 km/h, FS 10.4 km/h 3' to FS from 10 to 14.9 km/h from PS to FS on the ground. Tape, 5' CO to PS and 3' FS. IS and PS. Bertec Corporation, Columbus.	Plantillas DSPro ®. 104 Hz. Accel 3D; Gir; Mag.	Feet (plant). (N: 2)	SPD, CAD, FT, CT, LEN STR, AZ and FA.
Reenalda et al. (2021)	15 M / 5 W 30.1 ± 9.2 yr 184.3 ± 7.9 cm 68.7 ± 7.5 kg RR. VS.	2' at 11 km/h, 13 km/h, 15 km/h. IS. C-Mill, ForceLink.	MVN Link, Xsens. 240 Hz. Accel 3D; Gir; Mag.	Sternum, sacrum, mid-thigh, anterior medial of the tibia, mid-foot. (N: 5)	CTT of the foot at different SPD.
Rowlands et al. (2007)	10 M / 0 W 23.1 ± 3.4 yr 177.9 ± 5.6 cm 72.5 ± 8.1 kg CR. DS.	60'' at 8, 10, 12, 14, 16 and 18 km/h, 30'' at 20, 22, 24 and 26 km/h, with 1' to 5' rest between SPD. IS. Woodway Slat Belt ELG55 Weiss, Weil Am Rhein.	30Hz RT3. 30Hz ActiGraph. Yamax (pedometer). Accel 3D; Gir.	Sacrum (RT3, 2), Sacrum (ActiGraphs, 2). Foot (Yamax, 2). (N: 4)	ACC, trunk inclination, SPD, FREQ step and DR movement efficiency.
Ruiz et al. (2023)	16M / 0 W 22.7 ± 2.6 yr mean 172 ± 0.10 cm	10' SPD auto-selected, 3x1' at 5, 10 and 15 km/h. IS.	RunScribe. 500 Hz. Accel 3D; Gir;	Sacrum, foot L and R. (N: 3)	Pelvic kinematics of OSC VERT, INC, OBL, ROM ROT and AR MAX and foot

	69.1 ± 11.7 kg RR. VS.	WOODWAY Pro XL.	Mag.		impact patterns.
Sheerin et al. (2020)	11 M / 7 W M: 38.3 ± 8.2 yr 181 m ± 0.07 cm 82.5 ± 10.2 kg F: 30.4 ± 10.4 yr 167m ± 0.06 cm 58.7 ± 4.5 kg RR. IS.	5' SPD self-selected, followed 9.72, 10.8, 11.88, 13.32 km/h. IS. Bertec, Columbus.	IMeasureU. 1000 Hz. Accel 3D; Gir; Mag.	Antero-medial tibia. (N: 2)	ACC and IMP.

Table 2 (Continuation). Results and characteristics of the selected studies (N = 30).

Author (year)	Sex, physical characteristics, and type of study	Methodological protocol (Determination of pace; running speed; treadmill used)	IMU characteristics (Type, frequency)	IMU location; Number of IMUs	Kinematic parameters
Uno et al. (2023)	6 M / 3 W 25.4 ± 2.2 yr mean 166.6 ± 9.7 cm mean 60.3 ± 10.7 kg RR. VS.	6, 9 and 12 km/h. IS. MyRun, Technogym.	ORPHE Inc. 200 Hz. Accel 3D; Gir; Mag.	Feet (sole and instep). (N: 4)	Stride SPD, VERT height, stance phase TIME and swing TIME.
Yang et al. (2011)	4 M / 3 W 23 ± 2 yr 175 ± 10 cm Doesn't mention kg. CR. ED.	9 km/h / 12.6 km/h at five different Vs: 9, 9.9, 10.8, 11.7, 12.6 km/h. Each test 90''. IS. Optotrak 3020, Northern Digital Inc.	(Inertia-Link1, MicroStrain. 100 Hz. Accel 3D; Gir; Mag.	Medial tibia. (N: 1)	Linear ACC and SPD ANS DR.
Yang et al. (2022)	36 M / 0 W Doesn't mention years, cm, kg. RR and CR. DS.	30 m at different V, 10 m at 75%, 85% and 95% of MAX SPD. PS. Doesn't mention treadmill.	Blue Thunder, I Measure U. 500 Hz. Accel 3D; Gir; Mag.	Ankle L and R. (N: 2)	CT and FT DR.
Zandbergen et al. (2022)	2 M / 2 W 30.6 ± 9.2 yr 181 ± 4 cm 65.0 ± 5.4 kg RR. VS.	12.96 km/h. IS. Doesn't mention treadmill.	MVN Link, Xsens. 240 Hz. Accel 3D; Gir; Mag.	Tibial tuberosity. (N: 1)	3D orientation and displacement, the SPD and ACC.

Note: abbreviations used Table 2.

%: percentage; '': seconds; ': minute; 3D: three-dimensional; ACC: acceleration; ACCEL: accelerometer; ADD: adduction; AM: anteromedial; ANK: ankle; ANT: anterior; AP: anteroposterior; AR: angular rates; ANS: angular speed; AS: average speed; AVTAP: amplitude and variability of the tibial acceleration peak; BIL: bilaterally; CAD: cadence; COM: center of mass; CR: competitive runner; CT: contact; CTT: contact time; DF: dorsiflexion; DISP: displacement; DIST: distal; DM: distal medial; DOR: dorsal; DR: during running; DS: descriptive study; EXT: extension; F: force; FA: flexion angle; FEM: female; FLX: flexion; FREQ: frequency; FS: fast speed; FT: flight time; GRF: ground reaction force; GYRO: gyroscope; HIP: hip; HR: heart rate; Hz: hertz; IMP: impact; IMU: inertial measurement unit; INC: inclination; INCR: incremental; INF: inferior; INT: intensity; INV: inversion; IR: impact rate; IS: imposed speed; IS: intervention study; K/M: kilometer per hour; KG: kilogram; KNEE: knee; KPH: kilometer per hour; L: left; LA: left ankle; LEN: length; LH: left hip; LIN: linear; LK: left knee; LR: loading rate; LS: leg stiffness; M: male; MAG: magnetometer; MAX: maximum; MF: maximum force; MHR: maximum heart rate; MID: middle; MIN: minutes; ML: mediolateral; MS: medium speed; N: number of participants; NUM: number; OBL: obliquity; OSC: oscillation; PCT: percentage; PF: peak force; PFJ: patellofemoral joint; POST: posterior; PROX: proximal; PS: preferred speed; PWR: power; R: right; RA: right ankle; RC: running cycle; RF: reaction force; RH: right hip; RK: right knee; ROM: range of motion; ROT: rotation; RR: recreational runner; RS: reliability study; RUN: running; SEC: seconds; SF: support factor; SPD: speed; SS: slow speed; ST: stride time; STR: stride; SUP: superior; SWT: swing time; TIB: tibia; TIME: time; TRK: trunk; VERT: vertical; VO: vertical oscillation; VS: validity study; WALK: walking; W: woman; YR: years

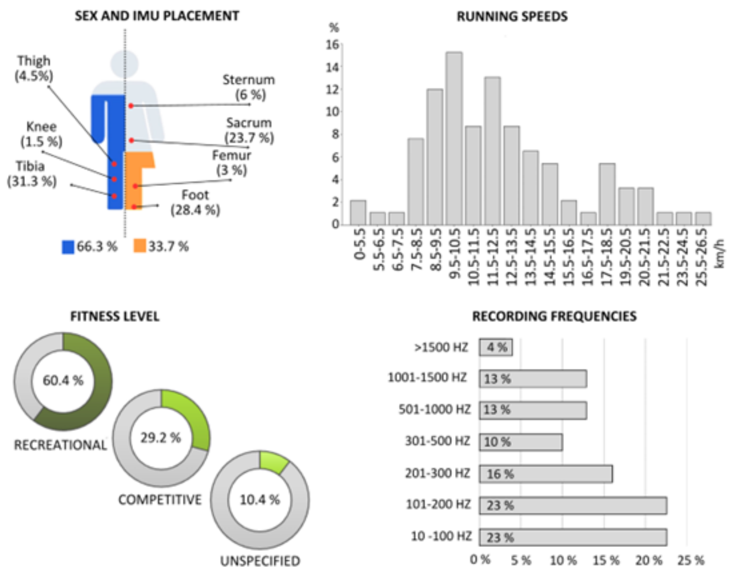
Kinematic parameters

The studies analyzed various kinematic parameters, grouped into three key categories based on their frequency of use and biomechanical relevance. The first category, acceleration, dominates the literature, with accelerometer magnitude being the most frequently used metric: vertical/axial (64%), resultant (26%), anteroposterior (23%), and mediolateral (18%). This predominance is explained by their ability to provide direct information on impact forces and musculoskeletal load transmission, both crucial for assessing injury risk (Benson et al., 2022). These parameters include maximal axial and linear tibial accelerations (García-Pérez et al., 2014), as well as derived variables, such as peak force and vertical loading rate (Doyle et al., 2024), tibial impact and shock attenuation (Sheerin et al., 2020; García-Pérez et al., 2014). Additional outcomes include stride regularity and symmetry in the vertical and anteroposterior axes, control of the center of mass, weight distribution (Clermont et al., 2018), and vertical acceleration symmetry index (Perpiñá-Martínez et al., 2023).

The second category focuses on angular velocity and range of motion, assessing pelvic movements, (tilt, obliquity, and rotation) (Ruiz-Malagón et al., 2023) trunk inclination (Rowlands et al., 2007), and the relationship between angular velocity, center-of-mass stability (Fohrmann et al., 2022) and stride velocity (Uno et al., 2023). These assessments commonly used lumbar sensors.

The third category encompasses spatiotemporal parameters, including cadence, stride length (Pareja-Cano et al., 2024; Perpiñá-Martínez et al., 2023), their coordination (Clermont et al., 2018), ground contact time, flight time (Riglet et al., 2024; Yang et al., 2022), and stance and swing phase durations (Uno et al., 2023) (see Figure 2). Their widespread use is supported by strong metrics, with ICC correlations >0.95 for cadence and validity >0.93 for stride length. Clinically, cadence and contact time are essential for injury prevention and gait retraining, while stride length and flight time are key indicators of running economy and elastic energy utilization (Horsley et al., 2021).

Figure 2. Participant characteristics (sex and fitness level), running speed, IMU placement, and sampling frequency (prepared by the authors using Microsoft Excel, Canva, and Napkin).



Discussion

The purpose of this scoping review was to analyze the methodological protocols of treadmill running assessed with IMU sensors in healthy individuals. The results provide a detailed overview of the effectiveness and accuracy of these protocols, highlighting both their strengths and areas requiring improvement.

The available literature shows a predominant focus on injured populations, with fewer studies on healthy individuals. This represents an obstacle to establishing reference values for running technique training. Such limitation is reflected in contradictory findings: while 62% of studies reported significant differences between injured and healthy runners; 52% found greater variability in injured runners, while only 24% reported reduced variability (Iqbal & Chow, 2025).

Types of studies

The methodological heterogeneity observed reflects the current state of biomechanics as a discipline, where diverse scientific approaches may be enriching but also complicate quality assessment. Previous research has documented growing interest from runners in implementing IMUs, regardless of prior experience with these devices (Clermont et al., 2019). Table 2, column 2, reveals the small sample sizes in some studies, a limitation that compromises both statistical power and generalizability. The inclusion of larger cohorts in future research, particularly to examine sex differences in running biomechanics, would enable more robust comparisons (Aderem & Louw, 2015).

Participant characteristics

All studies included male participants, while 80% included female participants, who represented only 33.8% of the total sample. This distribution contrasts with the findings of Benson et al. (2022), who reported that 50% of studies included both sexes, 35% men only, 3% women only, and 12% did not specify sex. The predominance of male participants in the analyzed studies could introduce selection bias, limiting representativeness of the general running population. This is particularly relevant given the documented biomechanical differences between sexes during running. Future studies should therefore ensure balanced sex representation to appropriately capture these differences.

Musculoskeletal and physiological sex-related differences directly influence running patterns (Perpiñá-Martínez et al., 2023), reinforcing the need for equal representation. Furthermore, 79% of studies focused on recreational runners, while only 21% included competitive runners. This distribution introduces another potential bias, as competitive runners typically display better running economy due to specialized training. Consequently, the predominance of recreational runners may limit the understanding of optimal movement patterns and their implications for performance and injury prevention (Oja et al., 2015). Amateur runners have also been shown to present a higher risk of lower-limb injuries compared with competitive runners, likely due to lower running economy and distinct kinematic profiles (Quan et al., 2021). The underrepresentation of women (33.8%) constitutes an additional methodological limitation, further compromising generalizability.

Instruments

Most studies analyzed employed IMUs combining a triaxial accelerometer, gyroscope, and magnetometer. This reliance on a single technological configuration limits comparability with studies using alternative methods and suggests a potential technological bias in the current literature.

Sampling frequencies ranged from 1 to 1600 Hz, with 200–500 Hz being the most common. While Zhou et al. (2020) suggested that 100 Hz may suffice for daily activities, higher frequencies are required for running to satisfy the Nyquist–Shannon theorem (Hamill et al., 1997). Low-frequency IMUs may lead to information loss at higher running speeds (Hughes et al., 2021), a critical limitation not sufficiently addressed in prior studies.

Frequency selection also carries economic and practical implications. High-frequency IMUs (>1000 Hz) generate large datasets requiring powerful microcontrollers (Aroganam et al., 2019), increasing costs and technical demands. This economic bias restricts access to advanced technology, limiting data quality and comparability across research contexts.

According to Benson et al. (2022), 82% of 251 devices were research-grade, while the remaining 18% were commercial devices (e.g., Adidas Run Genie, Catapult, DorsaVi, Garmin, Google Nexus, Lumo Run, Milestone Pod, Polar, RunScribe, Runteq Zoi, Stryd, Zephyr BioHarness). This gap highlights a lack of translation from academic research to practical application, suggesting the need for validation of commercial devices in biomechanical research.

IMU placement

Performance of IMU-based methods varies substantially across studies, with high accuracy often limited to controlled experimental conditions, particularly for pelvis and foot estimations (Bergamini et al., 2012; Blauberger et al., 2021; Mo & Chow, 2018). Variability is closely linked to sensor placement, which determines measurement accuracy depending on the parameter and anatomical site analyzed (Horsley et al., 2021).

This review found tibia (31.3%), foot (28.4%), and sacrum (23.7%) to be the most common placements, reflecting methodological preferences rather than systematic validation of optimal sites. This distribution aligns with Benson et al. (2022), who reported tibia (35%), sacrum (22%), and foot (16%) as the most frequent placements.

Regardless of site, proper fixation is essential to minimize motion artifacts. Reproducible sensor positioning, ideally based on scaled anthropometric references, is also critical (Hughes et al., 2021). Forefoot placement offers higher reproducibility due to shoe laces serving as anatomical landmarks, whereas tibial placement requires anthropometric references that may be challenging for non-expert or self-placement contexts. Use of thoracic spine placement should be approached cautiously, as it may provide inadequate predictions of gait symmetry and ground reaction forces (Wundersitz et al., 2014). Comparative studies systematically evaluating tibia, foot, and sacrum placement are needed to determine the most accurate anatomical location for specific biomechanical parameters.

Running speed

Running speed is a critical factor in biomechanical analysis, influencing both measurement accuracy and the validity of results (Wolski et al., 2024). Typical speeds studied range from light jogging (6–8 km/h) to sprinting (20–25 km/h), including recreational (10–15 km/h) and competitive (18–22 km/h) running (Wolski et al., 2024; Zeng et al., 2022).

As shown in Table 2 (column 3), most studies analyzed speeds between 9 and 12 km/h, with fewer at <7.5 km/h (6.6%) and >15 km/h (11.7%). These ranges approximate those observed in mass-participation marathons. According to Oficial-Casado et al. (2022), 15.5% of marathon runners exceeded 12 km/h, while 84.6% ran slower, with 10.16% averaging 8.0 km/h. Shorter-distance events typically involve a higher proportion of faster paces, which may not be adequately represented.

Speed directly influences kinematic and kinetic parameters, with increases leading to greater stride length and frequency, the former being more affected (Fukuchi et al., 2017). The methodological protocols analyzed here may therefore limit applicability to high-performance groups with distinct kinematic adaptations. Standardization of speed ranges allows for meaningful comparisons across studies and ensures reproducibility of experimental protocols in running biomechanics research.

This review focused exclusively on treadmill running protocols, as treadmill running has been shown to be representative of overground running (Fellin et al., 2010). Future studies should explore speeds between 12 and 15 km/h, as these reflect the most common range among recreational runners and may improve generalizability beyond elite populations.

Kinematic parameters

Kinematic parameters of running are fundamental for evaluating performance and injury risk factors (Folland et al., 2017). External kinematic indicators provide relevant information on impact forces during stance and have demonstrated utility in differentiating between injured and healthy runners (Johnson et al., 2020b; Matijevich et al., 2019). Training status, speed, fatigue, and injury influence running technique and consequently the kinematic parameters evaluated (Bramah et al., 2018; Fukuchi et al., 2017; Darch et al., 2023; Clermont et al., 2018).

Parameters related to angular velocity and joint ROM show that increased pelvic adduction and excessive internal rotation may contribute to injuries such as iliotibial band syndrome (Bramah et al., 2018) and patellofemoral tendinopathy (Johnson et al., 2020b), particularly in women (Perpiñá-Martínez et al., 2023). Pelvic alignment variables should therefore receive particular attention.

Running stability, defined as the ability to compensate for perturbations to maintain locomotion (England et al., 2007), affects pelvic acceleration variability (Darch et al., 2023), vertical loading (Johnson et al., 2020b), and impact forces (Gómez-Carmona et al., 2019). Assessment of vertical loading and peak forces provides insights into the mechanical demands of running (Doyle et al., 2024). Increased peak force and loading rate have been associated with stress fractures, particularly in high-performance runners or those with higher training volumes (Ceyssens et al., 2019; Lieberman et al., 2015).

Spatiotemporal parameters measured with IMUs include stride length, step frequency, contact time, and flight time (García-Pinillos et al., 2020; Uno et al., 2023). These parameters are critical for understanding running dynamics. Shorter contact times often correlate with better performance (Yang et al., 2022), directly influencing vertical oscillation and efficiency (Folland et al., 2017). Running economy has been associated with stride length and frequency (Folland et al., 2017) in both competitive and recreational runners (Uno et al., 2023).

Effective gait retraining programs often focus on increasing step frequency and reducing stride length at a given running speed (Gaudette et al., 2022; Van Hooren et al., 2020). This approach reduces joint loading without sacrificing efficiency (Perpiñá-Martínez et al., 2023) and is associated with reduced injury incidence (Van Hooren et al., 2020).

IMUs offer considerable utility in training by enabling the identification and modification of biomechanical patterns that may influence injury risk. They allow continuous monitoring, facilitating early detection of biomechanical changes associated with injury onset (Benson et al., 2022). Several studies have reported links between common injuries, specific movement biomechanics, and training load distribution (Lopes et al., 2023). However, evidence regarding the direct role of specific kinematic parameter modifications in injury prevention remains limited and sometimes contradictory (Day et al., 2021). A major challenge for future research will be identifying consistent biomechanical predictors of running-related injuries.

Conclusions

This scoping review demonstrates that IMUs used on treadmills are scientifically valid for measuring kinematic parameters ranging from step cadence to contact time, providing valuable insights into running technique and performance (Echeverry et al., 2018). Sensor placement critically determines measurement accuracy depending on the type of analysis. Sacrum placement offers greater stability for global running cycle metrics such as vertical oscillation and gait symmetry due to its proximity to the center of mass, whereas tibia and foot placement allow more accurate detection of discrete events such as contact and toe-off times.

Running speed systematically influences estimation errors: higher speeds improve event detection but may increase stride length bias if algorithms are not recalibrated.

The sex imbalance observed, with only 33.8% female participants, and the predominance of recreational runners (66.2%) represent methodological limitations that restrict generalizability. Furthermore, the use of relatively low running speeds limits applicability to faster groups, including both competitive and recreational runners. Variability in sensor placement most commonly tibia, foot, or sacrum requires consistent fixation methods to minimize measurement errors and improve reproducibility.

Future studies should address these limitations by including balanced sex representation, faster running speeds, and systematic comparisons of sensor placement. Such approaches will improve the development of evidence-based gait retraining programs, thereby optimizing performance and reducing injury risk in healthy runners of different levels.

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Competing interests

The authors declare that they have no conflicts of interest.

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Annexes

Supplementary Material 1:

Search strategy and key results for each database

Database	Boolean/Phrase	Results	Search date
Medline/Pubmed	Search strategy in MedLine/PubMed run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor AND treadmill* NOT injur* NOT pain* NOT systematic review run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor NOT injur* NOT pain* NOT systematic review	1061	11 january 2025
Web of Science (WOS)	Search strategy in Web of Science ((((((((((TS=(run*)) AND TS=(biomechanic*)) OR TS=(kinematic*)) AND TS=(pelvi*)) OR TS=(hip)) AND TS=(inertial measurement unit)) OR TS=(IMU)) OR TS=(portable sensor))AND TS=(treadmill*)) NOT TS=(injur*)) NOT TS=(pain*)) NOT TS=(systematic review) (((((((((TS=(run*)) AND TS=(biomechanic*)) OR TS=(kinematic*)) AND TS=(pelvi*)) OR TS=(hip)) AND TS=(inertial measurement unit)) OR TS=(IMU)) OR TS=(portable sensor)) NOT TS=(injur*)) NOT TS=(pain*)) NOT TS=(systematic review)	449	11 january 2025
SportDiscus	Search strategy in Sportdiscus run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor AND treadmill* NOT injur* NOT pain* NOT systematic review	2896	11 january 2025
SafeJournal (MDPI)	Search strategy in Safe Journal - MDPI run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor AND treadmill* run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor NOT injur*	643	11 january 2025
Cochrane Library	Search strategy in Cochrane Library run* AND biomechanic* OR kinematic* AND pelvi* OR hip AND inertial measurement unit OR IMU OR portable sensor AND treadmill* NOT injur* NOT pain* NOT systematic review	1129	11 january 2025

Supplementary Material 2:

Checklist items to assess the quality of scientific studies.

1. Is the hypothesis/aim/objective of the study clearly described?

2. Are the main outcomes to be measured clearly described in the Introduction or Methods section? If the main outcomes are first mentioned in the Results section, the question should be answered no.

3. Are the characteristics of the patients included in the study clearly described? In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for controls should be given.

5. Are the distributions of principal confounders in each group of subjects to be compared clearly described? A list of principal confounders is provided.

6. Are the main findings of the study clearly described? Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions. (This question does not cover statistical tests which are considered below).

7. Does the study provide estimates of the random variability in the data for the main outcomes? In non-normally distributed data, the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported. If the

distribution of the data is not described, it must be assumed that the estimates used were appropriate and the question should be answered yes.

9. Have the characteristics of patients lost to follow-up been described? This should be answered yes where there were no losses to follow-up or where losses to follow-up were so small that findings would be unaffected by their inclusion. This should be answered nowhere a study does not report the number of patients lost to follow-up.

10. Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?

External validity All the following criteria attempt to address the representativeness of the findings of the study and whether they may be generalized to the population from which the study subjects were derived.

11. Were the subjects asked to participate in the study representative of the entire population from which they were recruited? The study must identify the source population for patients and describe how the patients were selected. Patients would be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant population exists. Where a study does not report the proportion of the source population from which the patients are derived, the question should be answered as unable to determine.

12. Were those subjects who were prepared to participate representative of the entire population from which they were recruited? The proportion of those asked who agreed should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population.

13. Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive? For the question to be answered yes the study should demonstrate that the intervention was representative of that in use in the source population. The question should be answered no if, for example, the intervention was undertaken in a specialist centre unrepresentative of the hospitals most of the source population would attend.

16. If any of the results of the study were based on "data dredging", was this made clear? Any analyses that had not been planned at the outset of the study should be clearly indicated. If no retrospective unplanned subgroup analyses were reported, then answer yes.

18. Were the statistical tests used to assess the main outcomes appropriate? The statistical techniques used must be appropriate to the data. For example, nonparametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described it must be assumed that the estimates used were appropriate and the question should be answered yes.

20. Were the main outcome measures used accurate (valid and reliable)?

For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work or that demonstrates the outcome measures are accurate, the question should be answered as yes.

27. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is less than 5%? Sample sizes have been calculated to detect a difference of x% and y%.