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Original Article

Sensor analysis for the assessment of biomechanical parameters in endurance runners: a systematic review

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Abstract:
Problem Statement: This systematic review focuses on the use of sensors to improve performance in endurance athletes by analyzing biomechanical parameters. *Approach:* The use of sensors in endurance sports has gained popularity in recent years, allowing athletes and coaches to measure and analyze different biomechanical parameters in real-time. *Purpose:* The main purpose of this systematic review is to answer the question of how sensors can be used and applied to improve performance in endurance runners by analyzing the biomechanical parameters they provide. *Methods:* Systematic review analyzing related keywords such as biomechanics, kinematics, kinetics, running, triathlon, ultra running, trail running, Stryd, SHFT, Runscribe, and performance, through scientific research articles from the database of the Electronic Library of the Isabel I University dated 02/2023 in English. A total of 192 investigations were found, of which 168 were excluded. After a detailed review, 15 relevant investigations were included. *Results:* Sensors can be useful to measure biomechanical parameters such as cadence, stride length, leg spring stiffness, ground contact time, and vertical oscillation, which can help to improve performance in endurance athletes. *Conclusions:* Sensors are a suitable tool to analyze performance improvement in endurance athletes by analyzing biomechanical parameters. However, it is important to highlight that not all sensors are similar, that it is necessary to carefully select the most suitable ones for each specific situation, and that biomechanics is also conditioned in each athlete, so universal rules cannot be established.
Key Words: **IMUs, biomechanics, performance, running**.

Introduction

Biomechanics of high-performance running is an increasingly relevant area of research, as it pursues the goal of improving athlete performance by optimizing technique and analyzing body movements (Olaya-Cuartero & Cejuela, 2021). One of the key biomechanical parameters of high-performance running is cadence, which is the number of steps per minute (spm) (Moore, 2016). Increasing running cadence can improve running performance by reducing joint stress and muscle fatigue (Heiderscheit et al., 2011). The optimal proven cadence is between 170 and 190 spm for long-distance runners (Moore, 2016). Another important biomechanical parameter is stride length, which is the distance between two consecutive landings of the same foot (Dorn et al., 2012). The optimal stride length allows runners to maximize their running economy, as shorter strides can increase energy expenditure while longer strides can create loads for larger muscles (Dorn et al., 2012). Vertical oscillation, which is the vertical movement of the body's center of gravity during running, is also an important factor in the running cost economy (Cavagna et al., 1977). Less vertical motion is associated with more economical running, as the amount of energy required to move the body up and down with each step decreases (Cavagna et al., 1977). In addition, the position of the foot at the moment of ground contact also plays an important role in the biomechanics of running performance since contact with the forefoot or midfoot can contribute to running economy by allowing better shock absorption and more efficient use of the elastic energy stored in tendons and muscles (Lieberman et al., 2010). Finally, lower limb stiffness, as measured by the ratio of applied force to change in limb length, is also an important factor in running economy (Arampatzis et al., 2006a). Higher stiffness is associated with better running economy because it allows for greater conservation of elastic energy in the standing phase and less energy loss in the flight phase (Arampatzis et al., 2006a). Biomechanical parameters such as cadence, stride length, vertical oscillation, ground contact time, and leg spring stiffness play an important role in running economy and, therefore, in the performance of trained athletes (Moore, 2016). Optimizing these parameters can help improve energy efficiency which is essential for high-performance training and success in competition (Saunders et al., 2004). Scientific research and collaboration

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between athletes, coaches and biomechanics experts are essential for continued progress in the field and for a better understanding of the relationship between biomechanics, running performance, and athletic performance.

Regarding the current state of the art, the use of sensors in sports has gained popularity in recent years, allowing athletes and coaches to measure and analyze different biomechanical parameters in real-time (Olaya-Cuartero & Cejuela, 2020). In the case of applied high-performance running, some of the most popular devices on the market include Stryd, RunScribe, and SHFT. This paper will examine the biomechanical parameters measured by each sensor and their applicability in measuring these parameters. Stryd is a wearable device that attaches to a runner's shoe and provides information on the power, cadence, vertical oscillation, stride length, ground contact time, and leg spring stiffness (Cerezuela-Espejo et al., 2020). In addition, Stryd was found to be effective in measuring pace, consistent with measurements from optical motion capture systems (Nicolella et al., 2018). RunScribe is a system that uses two sensors located in each shoe to measure a variety of biomechanical parameters, including stride length, cadence, foot contact angle, pronation, and vertical oscillation (Koldenhoven & Hertel, 2018). SHFT is a device consisting of two sensors, one on the shoe and one on the chest, which provide information on cadence, stride length, vertical oscillation, ground contact time, and foot position at contact (Linkis et al., 2021). It is relevant to note that while these devices can provide valuable information on biomechanical running parameters, they are not perfect and may have limitations in terms of reliability and validity, therefore, athletes and coaches must use these devices as a complementary tool along with other biomechanical assessment and analysis methods such as qualitative observation and video analysis (Garcia-Pinillos et al., 2021; Koldenhoven & Hertel, 2018; Linkis et al., 2021). The use of these devices in conjunction with other biomechanical assessment methods can help athletes and coaches identify areas of improvement and optimize running techniques for athletic performance (Nüesch et al., 2017). Generally, devices such as accelerometers and gyroscopes are widely used in biomechanical analysis due to their ability to measure acceleration and angular velocity respectively. With the accelerometer, which measures acceleration in one, two, or three axes, these devices provide crucial information on various parameters of running technique and performance, such as ground reaction force, cadence, ground contact time, and flight time (Najafi et al., 2009). Gyroscopes can be used to measure angular velocity along three axes, which helps to analyze the rotation and orientation of the limbs and trunk during running (Favre et al., 2008). The combination of accelerometers and gyroscopes in a single device, known as inertial measurements units (IMUs), allows for greater accuracy and range in biomechanical analysis by providing information on both linear acceleration and angular velocity (Benson et al., 2022). These devices can be used in conjunction with other sensors, such as insoles or electromechanical devices, to obtain a better contextualization of muscle movement and function during running (Najafi et al., 2009). This systematic review aims to determine how sensors can be applied to analyze biomechanical parameters in improving performance in endurance athletes.

Research Methods

The method selected was a systematic review through the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols (PRISMA-P) 2015 guidelines (Clarke et al., 2015). The purpose of this review is to answer the following research question: How and which biomechanical parameters most commonly measured by sensors can be used to improve performance in endurance athletes? In this methodology, a research question is defined, a systematic review of studies is performed, the selection of these studies, data extraction, evaluation of the risk of bias, and finally the synthesis of the results. In this methodology, rigorous and reliable systematic reviews are conducted to generate a positive impact on decision-making in the health and social sciences. Indeed to the PRISMA-P methodology, it has been followed the indications of Sánchez-Meca (2010), which details the steps to follow to carry out a systematic review efficiently and rigorously: clearly defining the research question, inclusion/exclusion criteria for studies, an exhaustive search of the relevant literature, evaluation of the quality of the included studies, and synthesis of the results.

Eligibility criteria

For this systematic review, eligibility criteria were established according to the PICO (participants, intervention, comparison, outcome) strategy (Clarke et al., 2015). Concerning participants, in the present study, they will be runners in endurance disciplines including long-distance running, trail running, ultra long-distance, and triathlon in all distances, from sprint to long-distance. Neither the age of the participants nor the gender has been taken into account, and articles from elite and recreational athletes have been included. The sample size was not filtered either, as this is not a very homogeneous value in this kind of study.

In the intervention, the focus will be on athletes who have tested devices to assess different parameters related to running biomechanics, preferably Stryd, SHFT, and Runscribe (as these are the most popular), and analyze how reliable these devices are in measuring these parameters. Due to the limited existing literature, it has been searched for all articles and studies that at least mentioned the use of sensors. All literature that was not related to performance was excluded. Studies conducted on the treadmill, outdoors, and on track were considered. As a comparator or control to establish the usefulness of these sensors, the comparison should be made against the gold standard for measuring running biomechanics, which in this case is 3D motion capture

(Pueo et al., 2020). However, to increase the number of articles, it has also included articles where the comparison has been made by other means.

The outcome will determine whether these useful sensors present a reliable alternative for measuring running biomechanics parameters that can be used to guide training for performance improvement, based on the biomechanical parameters measured and their effect on performance. The most significant parameters would be to analyze the relevant biomechanical parameters in endurance runners: cadence, stride length, vertical oscillation, leg spring stiffness, flight time, and ground contact time (1), to determine which sensors are most commonly used to analyze biomechanical parameters (2), and to determine which of the parameters measured are related to performance (3).

Search procedure

Data and information sources

To search for the publications in this systematic review, the Isabel I University Electronic Library, which provides simultaneous access to several databases, was used in preference: Dialnet Plus, Medline PubMed, SPORTDiscus with Full Text, Academic Search Complete, Scopus, Dialnet, Directory of Open Access Journals, OAIster, Scielo, Supplemental Index, British Library EthOS, Business Source Index, Complementary Index, Academic Search Index, and OpenDissertations, with the search taking place on February 26, 2023. All the selected publications (original articles) were also referenced.

Search strategy

The following keywords, considered the most significant, have been used, considering only English as the language: *"biomechanics"*, *"kinematics"*, *"kinetics"* (Group 1), *"running", "triathlon", "ultra running", "trail running"* (Group 2), *"Stryd", "SHFT", "Runscribe"* (Group 3), *"performance"* (Group 4). The Boolean operator *"OR"* has been used to concatenate each of the groups, adding the results of each word, and the Boolean operator *"AND"* to join the 4 groups, and the search has been performed on full text, since being a relatively recent field of research there is not much literature available. The complete query is as follows: *"biomechanics OR kinematics OR kinetics"* AND *"running or triathlon OR ultra running OR trail running"* AND *"Stryd OR SHFT OR Runscribe"* AND *"performance"*.

Methodological quality

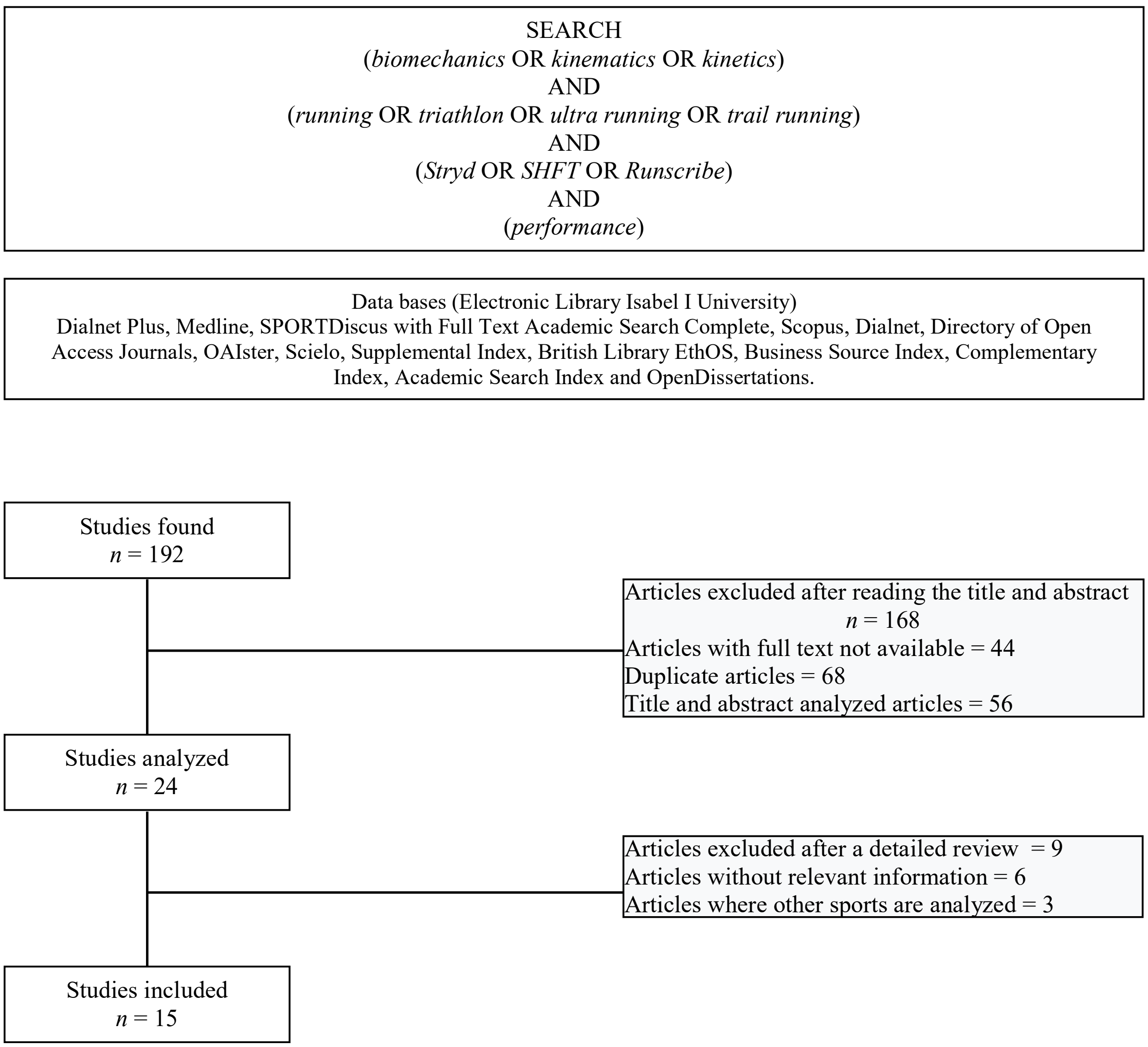
Using the strategy explained in the search strategy, a total of 192 investigations were found during the search process. Of these 192, 168 were excluded after reading the title and abstract: 44 because the full text was not available, 68 because they were duplicated in different databases, and 56 because they were not relevant to the topic after reading the abstract and title. After a detailed reading of the remaining 24 investigations, 6 were excluded because they did not deal with any of the selected sensors or were not focused on biomechanical metrics of running, and 3 more were discarded because they did not explicitly refer to running, but were focused on other sports. This leaves a total of 15 articles. The search and filtering process followed is shown in Table 1. Likewise, Figure 1 details the flow chart and selection of publications used for the systematic review.

Table 1. Search selection process.

Database	**Key words**	**Number of publications**	**Full text articles**	**Selected articles**
Advanced search engine Isabel I University: Dialnet plus, Medline, SPORTDiscus with Full Text Academic Search Complete, Scopus, Dialnet, Directory of Open Access Journals, OAIster, Scielo, Supplemental Index, British Library EthOS, Business Source Index, Complementary Index, Academic Search Index and OpenDissertations.	Full Text: *"Stryd* OR *SHFT* OR *Runscribe"* AND "*biomechanics* OR *kinematics* OR *kinetics*"	541	251	251
	Full Text: *"Stryd* OR *SHFT* OR *Runscribe"* AND "*biomechanics* OR *kinematics* OR *kinetics*" AND *"running* OR *triathlon* OR *ultra-running* OR *trail running"*	272	187	187

	Full Text: *"Stryd* OR *SHFT* OR *Runscribe"* AND "*biomechanics* OR *kinematics* OR *kinetics*" AND "*running* OR *triathlon* OR *ultra-running* OR *trail running*" AND "*performance*"	192	148	15
	Total	**541**	**251**	**15**

Figure 1. Flow chart with the different phases of search, selection, inclusion, and exclusion of research.



Results

Table 2. Articles found and analyzed according to the PICO elements in the systematic review.

Reference	Participants	Intervention	Comparison	Outcomes
(García-Pinillos et al., 2019)	49 endurance runners	Running on a treadmill	Results from portable devices with high-speed video analysis	RunScribe and SHFT show good agreement with video analysis
(Cerezuela-Espejo et al., 2020)	20 long-distance runners	Treadmill at different speeds while measuring its power with the five devices	Repeatability and concurrent validity of devices	High repeatability and good concurrent validity of measurements
(Perrotin et al., 2021)	28 trail runners	Measurement and analysis of spatiotemporal parameters during a trail race	Different types of terrain and sensors	Useful sensors allow the measurement parameters related to running technique speed
(Olaya-Cuartero & Cejuela, 2020)	The study analyzed a total of 9 articles	Systematic review	Repeatability and concurrent validity of technologies for measuring running power output	Good repeatability and concurrent validity
(Olaya-Cuartero et al., 2021)	4 elite triathletes	Outdoor race	Stryd to measure physiological and biomechanical parameters	Modification of certain biomechanical parameters can influence performance
(Jaén-Carrillo et al., 2020)	Systematic review	Systematic review	Different sensors were evaluated in terms of their accuracy and reliability	Some portable sensors are more accurate and reliable than others for measuring mechanical power
(Lepers et al., 2020)	59-year-old former Olympic athlete	Treadmill test to measure the participant's cardiorespiratory capacity and running economy	HR, VO_{2max}, pulmonary ventilation, lactate, cadence, and running economy	Stryd to measure gait kinematics during the participant's run
(Linkis et al., 2021)	20 recreational runners	Treadmill running test at different speeds	Reference system that combined a respiratory gas analysis system with a system to measure the vertical force applied to the ground during running	SHFT is a reliable tool for measuring power during running, with low within-subject variation
(Keath et al., 2020)	21 university students (recreational experience)	The intervention model used was the SHFT handheld device as a virtual running coach	SHFT and data collected by other similar devices	SHFT is a valid and effective virtual running trainer for improving running technique
(Austin et al., 2018)	20 well-trained long-distance runners	Stryd to measure running power in two components: Stryd power and form power	Stryd and portable gas analysis system (COSMED K5)	Positive correlation between running economy and power and form power
(Pardo-Albiach et al., 2021)	15 healthy triathletes	Stress test in a laboratory to measure your $VO_{2\ max}$	Data obtained from portable sensors and results obtained from laboratory equipment	Proper power management is key to maximizing running speed and VO_{2max} correlates with relative power (W/kg)
(Smith et al., 2022)	15 active runners with no injuries in the last 6 months	The treadmill running at 1%	4 different portable devices that measure vertical oscillation during running	The portable devices were valid and reliable for measuring vertical oscillation during running
(Lewin et al., 2022)	20 participants	They walked at a self-selected speed across	Several accelerometers were	Mixed levels of agreement between

		a laboratory treadmill	used as standard laboratory measurements to compare with the RunScribe	RunScribe and standard laboratory walking measurements
(Zeng et al., 2022)	25 previous studies that met inclusion criteria	Systematic review	IMUs and reference system measurements	Some studies have evaluated the validity and reliability of IMUs, but their methodological quality is low to moderate
(Imbach et al., 2020)	20 recreational runners who were preparing for a long-distance race (over 42 km)	The intervention model was an incremental trial of running around a 200m track	Stryd with reference systems	Stryd provided acceptable measures of ground contact time and leg spring stiffness

HR: Heart Rate; **VO_{2max}**: Maximal oxygen uptake; **W/kg**: watts per kilogram (relative power to the weight); **IMUs**: Inertial Measurements Units

Discussion

Throughout this systematic review, an analysis of how sensors can be applied to improve performance in endurance athletes by interpreting the biomechanical data they provide has been carried out. The previous hypothesis was that these sensors provide useful data for performance enhancement. Consequently, according to the results obtained from the analyzed articles, it will be sought to discuss which of these sensors are the most used, which parameters are the most measured, and, of these, which ones present more evidence in the analyzed literature.

Regarding biomechanical parameters, all the most popular sensors, such as Stryd, Runscribe, and SHFT, measure stride length, and their concurrent validity is supported by contrasting it with the high-speed video analysis of Runscribe and SHFT (García-Pinillos et al., 2019) or of the three sensors simultaneously (Zeng et al., 2022). This is similar to the Stryd device in the study by Lepers et al. (2020), in which stride length was assessed during a submaximal threshold endurance test, concluding its validity and reliability for monitoring stride length at running speeds between 8 and 20 km/h. The existence of an optimal stride length for each runner has a direct impact on performance (Jaén-Carrillo et al., 2020). In addition, to being able to provide different running strategies, being useful the use of Stryd, depending on the orography, optimizes energy expenditure (Perrotin et al., 2021). Generally, it has been shown that longer stride length is positively correlated with performance in well-trained athletes, however, in less experienced athletes, it could induce an excessive muscular load and, consequently, deteriorate performance, with the analyzed sensors presenting great help in its optimization (Zeng et al., 2022). Therefore, it is essential to individualize the optimal stride length for each runner, and the sensors are very useful for identifying running patterns among different levels of athletes (Pardo-Albiach et al., 2021). Thus, sensors present a great help to measure stride length during running (Lewin et al. 2022).

Concerning cadence, it is also measured by the main sensors available on the market including Stryd, Runscribe, and SHFT. It can affect running economy and muscle fatigue, highlighting the importance of specific training to optimize it according to the characteristics of each runner (Olaya-Cuartero & Cejuela, 2020). Some authors (Austin et al., 2018; Pardo-Albiach et al., 2021; Zeng et al. 2022) have measured cadence using sensors and concluded that there is a negative correlation with running economy suggesting that a low cadence could imply a higher vertical oscillation at the same running speed, negatively affecting the running economy. On the other hand, it is suggested that endurance runners maintain a cadence of at least 170-180 spm on flat terrain to improve their athletic performance (Olaya-Cuartero & Cejuela, 2020). Sensors are a great help in being able to maintain a target cadence, as they provide real-time information, allowing immediate feedback of the running technique (Keath et al. 2020).

Focusing attention on vertical oscillation, another parameter commonly measured by the three sensors, some studies suggest that lower vertical oscillation is associated with better performance in well-trained runners (Zeng et al., 2022). The literature review provides sufficient evidence about the validity and reliability of sensors to measure vertical oscillation during running (Smith et al., 2022). Evidence has also been found that lower vertical oscillation requires lower oxygen consumption at a constant velocity, so this has a direct effect on running performance (Linkis et al., 2021). The ability of sensors to provide immediate feedback on biomechanical parameters is noted as another advantage, as it allows the running technique to be modified and performance to be optimized. This is shown in the study by Perrotin et al. (2021), in which vertical oscillation is measured to adapt running technique to different terrains in a trail running competition.

Another parameter, provided only by Stryd, is the leg spring stiffness. This refers to leg spring stiffness during running and is considered a kinetic factor related to running economy (Imbach et al., 2020). For example, Austin et al. (2018) used Stryd for this measurement, demonstrating that the device can measure real-time leg spring stiffness and provide information on how changes in this measure affect running economy and power output metrics. The study found a positive correlation between leg spring stiffness and running economy, suggesting that greater stiffness may relate to greater efficiency in power output during running. Similarly, Pardo-Albiach et al. (2021) measured the leg spring stiffness of runners using Stryd, suggesting a relationship between leg spring stiffness and performance, possibly in terms of higher running efficiency and lower metabolic cost.

Ground contact time is a parameter provided only by Runscribe and SHFT. There is enough evidence of the accuracy of these devices to accurately measure this parameter (Garcia-Pinillos et al., 2019; Keath et al., 2020; Lewin et al., 2022). In terms of the relationship between foot-ground contact time and performance, the study by Linkis et al. (2021) using SHFT found a positive correlation between foot-ground contact time and VO_{2max}, suggesting that lower foot-ground contact time may be associated with better performance in recreational runners, highlighting an important relationship between ground contact time and overall running technique, and how this affects other parameters.

Flight time is another parameter measured by SHFT and Runscribe and is found to be inversely related to ground contact time. This systematic review provides moderate evidence of the reliability of sensors to measure this parameter, showing the research of Garcia-Pinillos et al. (2019), which compares SHFT with high-speed video analysis, finding high concurrent validity. Regarding the relationship with performance, both ground contact time and flight time are measures that are associated with stride frequency and leg stiffness, both kinetic factors linked to running economy, therefore, it could be inferred that flight time has a relationship with performance, but this relationship would be established in combination with other parameters (Imbach et al., 2020).

Furthermore, other parameters measured by the sensors are identified in the selected studies, although less frequently and without evidence of a relationship with sports performance. It is observed that not all sensors measure the same parameters, which makes it difficult to establish comparisons. In the study by García-Pinillos et al. (2019), biomechanical variables such as horizontal velocity, rate of change of stride length, and rate of change of step frequency were evaluated, but no relationship was established between these variables and sports performance. Regarding variables such as ankle angular rate of change and knee angular rate of change, no significant correlation was found with performance during running (Linkis et al., 2021). Pardo-Albiach et al. (2021) included more variables such as vertical ratio, running effectiveness, and form power ratio, arguing that some of these may be related to performance in runners showing that the vertical ratio may be an indicator of running technique and that the form power ratio may be an indicator of muscle balance. Lewin et al. (2022) mention several additional biomechanical variables, including pronation velocity, ground reaction rate of force, shock impact, shock braking, and total shock, but, in this study, a direct relationship between these variables and athletic performance is not established. Finally, Zeng et al. (2022) measured other biomechanical variables such as hip rotation velocity and foot acceleration.

Conclusions

Concerning the main purpose of this systematic review, sensors are useful tools to improve performance in endurance sports, providing relevant information for the improvement of running biomechanics and consequently athletic performance. The most used and studied sensor in the reviewed literature is Stryd, followed by Runscribe and SHFT respectively. All three can be considered IMUs as they contain all three technologies (accelerometer, gyroscope, magnetometer). Cadence, stride length, vertical oscillation, ground contact time, and leg spring stiffness are the key parameters measured by sensors and for which there is enough evidence in the literature reviewed. Flight time presents less evidence, but should not be discarded due to its relationship with other parameters.

Conflicts of interest - The authors declare no conflict of interest.

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