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Review

The Impact of Wearable Technologies on Marginal Gains in Sports Performance: An Integrative Overview on Advances in Sports, Exercise, and Health

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Abstract: Wearable technologies have become increasingly popular in recent years, as athletes and coaches look for ways to gain a competitive edge. These devices can track a variety of metrics, including heart rate, sleep quality, and movement patterns. This information can be used to identify areas for improvement and make small, incremental changes that can lead to significant gains in performance. The purpose of this narrative review is to provide an integrative overview of the literature on the impact of wearable technologies on marginal gains in sports performance. The literature review was conducted using the Scopus, PubMed, and Web of Science databases, and a total of 55 papers were considered eligible. The results of the literature overview suggest that wearable devices can be classified into three main categories. (1) Location-based wearables (LBW) track an athlete's location and movement, which can be used to analyze training patterns and identify potential injury risks. (2) Biometric wearables (BMW) track physiological data such as heart rate, sleep quality, and body temperature; these data can be used to monitor an athlete's fitness levels and identify signs of overtraining. (3) Performance wearables (PMW) track performance metrics such as power output, speed, and distance; this information can be used to optimize training programs and track progress over time. For each category, this paper provides the five most important data points measured by each suggested device. Additionally, sport-specific examples are provided for each category based on the literature data. The limitations of wearable devices, such as accuracy, validity, reliability, interpretability, and cost, are also discussed. However, despite these limitations, the results of the literature review suggest that wearable technologies can be a valuable tool for athletes and coaches who are looking to improve performance. Ultimately, this technological evolution in sports science is likely to dramatically change the state of the art in athletic monitoring and sports analytics.

Keywords: wearable technologies; marginal gains; sports performance; research

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1. Introduction

The wearable detectors that are available today have amazingly wide-ranging functions. In addition to serving as a valid support tool for athletes in a wide range of sports and performance situations, if used for performance evaluation and monitoring, they will make a valuable addition to sports development teams.

The concept of "marginal gains" gained prominence through the work of British cycling coach Dave Brailsford. This philosophy posits that small, incremental improvements across multiple areas can culminate in significant overall enhancement [1,2]. Brailsford asserted, "It might not seem much, but if a cyclist can save one second every lap, it can make all the difference" [3]. While this perspective has merit, the challenge lies in quantifying these marginal gains to facilitate their management.

Although not all marginal gains can be measured by wearable devices (e.g., wheel pressure, cushion density, seat comfort), these technologies can capture a vast array of data pertinent to sports performance and sports medicine [4,5]. Nevertheless, despite their increasing popularity, a significant number of wearable devices lack rigorous and independent testing to ascertain their accuracy, reliability, and validity [6,7].

There are several types of wearable trackers that may be able to provide information to performance athletes (wristbands, bracelets, smartwatches, headbands, rings, and more) [8]. These wearable detectors are an integral part of a family of technologies called consumer technologies (CSTs) [9]. Consumer technologies (CST) encompass not only smartphones and various sensor types, but also a range of sophisticated devices with clinical applications. These advanced systems are capable of monitoring diverse parameters, including movement [10] and biological [11], physiological [12], and behavioral [13] factors. The data generated by these devices provide coaches with valuable insights, enabling them to make informed decisions regarding the modification of these parameters to optimize athletic performance [14].

Wearable devices, commonly referred to as fitness trackers, have gained significant popularity due to their accessibility, affordability, and non-prescription nature [15]. Initially developed for general health monitoring, these devices primarily focused on basic metrics such as step count and heart rate [16]. However, technological advancements have expanded their capabilities to include more complex physiological measurements, although the scientific validity of some of these measurements remains to be fully established [17].

The integration of triaxial accelerometers has enhanced the functionality of these devices, enabling the detection of movement patterns [10], sedentary behavior [18], and sleep characteristics [19,20]. Recent research has highlighted the importance of these parameters not only for general health, but also for athletic performance [20]. The COVID-19 pandemic has further accelerated the adoption and integration of these technologies [21].

In the realm of sports science and training, wearable technologies have become increasingly prevalent [22]. These devices offer unprecedented access to a wealth of data across various training phases, including active sessions, recovery periods, and off-season intervals. Their non-invasive nature and ease of use allow for continuous data collection without requiring active participation from athletes or medical staff [23].

Despite their widespread adoption, concerns persist regarding the validity, accuracy, and reliability of many wearable devices, particularly with regard to measuring complex physiological parameters such as cardiac function [17,24–26]. This underscores the need for rigorous scientific evaluation of these technologies.

Projections suggest that wearable technology will experience significant growth over the next quarter-century, potentially yielding substantial healthcare cost savings and reducing the need for direct doctor–patient interactions [27,28]. The global adoption of wearable devices has seen rapid growth, with usage increasing from approximately 600 million devices in 2020 to over 1.1 billion in 2022 [28,29].

The distribution of wearable technology usage varies globally, with North America leading at 39.90%, followed by Asia at 28.27%, and Western Europe at 17.45% [30].

This review aims to explore the utility of wearable technologies in athletic performance monitoring, with a particular focus on their potential for identifying marginal gains. We will address several key questions:

- What is the reliability of data collected from wearable devices?
- How do wearable technologies impact marginal gains in sports performance?
- What are the primary categories of wearable technologies used in sports?
- How are these technologies applied in order to enhance sports performance?
- What limitations exist in the current state of wearable technologies in sports?

By addressing these questions, this review seeks to provide a comprehensive overview of the current state and future potential of wearable technologies in sports science and performance optimization.

2. Methodology and Selection Criteria

A comprehensive search of scientific databases, including PubMed, Scopus, and Web of Science, was conducted by two independent authors (GM.M. and J.P.) to collect relevant articles. The data were subsequently extracted and evaluated by two independent reviewers (L.R. and J.P.).

The selection and exclusion criteria were carefully defined to ensure the relevance and quality of the included studies. The following criteria were applied:

- Relevance: studies must focus on wearable devices used in sports contexts, particularly those capable of monitoring body movements, biophysical parameters, and marginal gains in athletic performance.
- Publication Year: to ensure currency, studies published within the last 10 years were prioritized, with seminal works from earlier periods included if deemed crucial.
- Study Design: Preference was given to randomized controlled trials, systematic reviews, and meta-analyses. Observational studies were included if they provided unique insights.
- Language: only articles published in English were considered.
- Peer Review: all included studies must have undergone peer review.
- Device Specificity: studies must focus on wearable devices specifically designed or adapted for sports applications.

Exclusion Criteria Included

- Studies focusing solely on medical applications of wearable devices.
- Non-peer-reviewed articles, including conference abstracts and dissertations.
- Studies with inadequate methodological quality, as assessed by the reviewers.

A three-step process was followed for the selection of documents (Figure 1):

- Title evaluation: titles were screened for relevance to the topic.
- Abstract evaluation: abstracts of potentially relevant articles were reviewed.
- Full-text evaluation: the full text of each selected article was thoroughly examined.

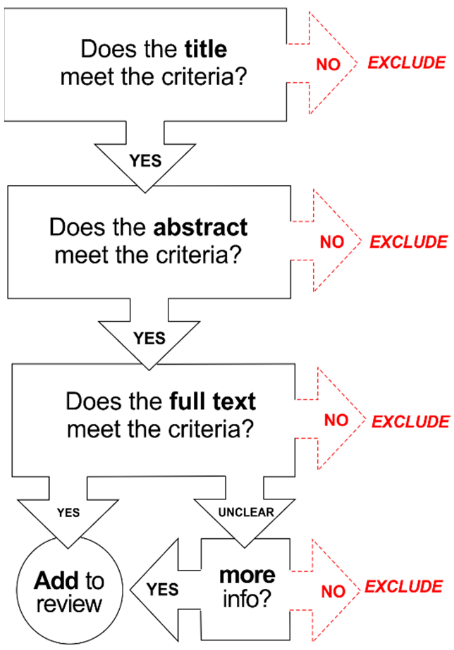

Figure 1. Methodology for selecting documents.

This rigorous selection process ensured that only the most relevant and high-quality studies were included in our review, providing a comprehensive yet focused overview of wearable technologies in sports performance monitoring.

Documents were divided into original articles (65%) and review articles (35%). Details of the keywords used for each database (Pubmed, Scopus, WOS) are shown in Figure 2.

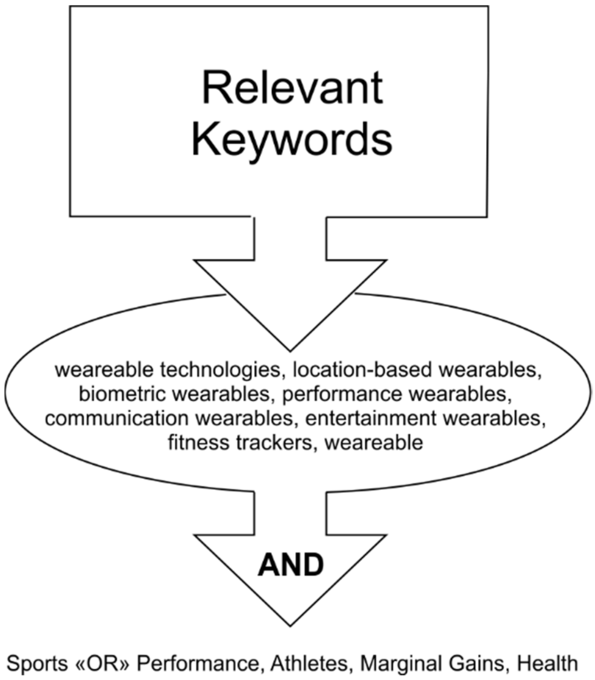

Figure 2. Keyword distribution across the review.

Following the described steps, each document was either accepted or rejected based on the above criteria.

If a document's results were unclear, a further analysis of its contents was conducted by seeking information from external sources. Despite its clarity, one document was rejected by the review without explanation.

A total of 55 documents were included in this review.

3. Applications of Sports Wearables

Wearable technology has been extensively studied in relation to improving sports performance. There are a variety of marginal gains that can be achieved using wearable technology, including the following:

- Training intensity: Wearable technologies can be used to track training intensity, which can help athletes to train at the right level and avoid overtraining [31]. For example, wireless heart rate monitoring has been used by cyclists for several years and is very useful for detecting early overtraining, as well as providing insight into training intensity and cardiac drift [32,33]. Wearable devices, such as heart rate monitors (HR) and power meters (PM), offer similar benefits for athletes' performance. A study on recreational cyclists found that both HR- and PM-based training significantly improved lactate threshold power and 20 km time trial completion times. Both groups increased their power by 17 watts and reduced their time by nearly three and a half minutes. No significant differences were found between the two training methods in improving aerobic capacity (VO2max), indicating that both HR monitors and PMs are equally effective for performance enhancement [34].
- Recovery: Wearable technologies can be used to track sleep quality and other factors that affect recovery. This information can be used to optimize recovery strategies, such as those involving sleep [35] and breathing [36], to ensure athletes are ready

to perform at their best. For example, athletes who used wearable devices to track their sleep quality were more likely to report feeling recovered after training [37]. Wearable devices for monitoring sleep and recovery offer several potential advantages for athletes, even though these benefits are not yet fully validated [38].

- Nutrition: In addition to tracking calorie intake and expenditure, wearable technologies can automate certain aspects of diet logging, such as detecting moments of dietary intake and estimating meal composition with chemical sensors [39]. This information can be used to ensure that athletes are meeting their nutritional needs and to minimize errors. For instance, studies have shown that traditional self-report methods, such as 24 h recalls and food frequency questionnaires, can be up to 50% inaccurate compared to actual food intake [40]. For example, non-invasive wearable and mobile electrochemical sensors, capable of monitoring temporal chemical variations upon the intake of food, vitamins, and supplements, are excellent candidates for bridging the gap between digital and biochemical analyses for a successful personalized nutrition approach [41–45]
- Technique: Wearable technologies can be used to track movement patterns and identify areas for improvement [46]. This information can be used to improve technique and efficiency. For example, there is evidence supporting the use of wearables to improve running performance, track global training loads applied to the runner, and provide real-time feedback on running speed and run cadence [47].

In Australian football, GPS devices have allowed for detailed analysis of player workload and energy expenditure, providing insight previously unavailable through heart rate monitors alone. In American football, sensors integrated into helmets and mouthguards have detected over 95% of impacts, which is crucial for monitoring and preventing concussions. Studies on baseball have shown that wearable sensors can accurately measure elbow torque and shoulder movement, providing data essential for injury prevention. These devices enable real-time feedback and detailed biomechanical analysis, enhancing training and performance while reducing injury risks [45].

The general concept of wearable devices describes electronic devices that are equipped with built-in sensors that can receive information about the wearer or the environment around them. These devices operate wirelessly or by integration with other devices, such as smartphones and tablets. The wearables send information to a processing unit, which may be integrated or located on an external server, and then the processed information is transmitted to the wearer. The use of wearable technologies can provide coaches, trainers, sports scientists, medical doctors, and members of an athlete's team with the data required to make a subsequent evaluation.

Data analysis is conducted according to the EBP Evidence-Based Practice guidelines [48], including, for instance:

- Identify areas for improvement: wearable devices can track several metrics, which can be used to identify areas in need of improvement in an athlete's technique, fitness, and nutritional habits.
- Provide real-time feedback to athletes: some wearable devices can provide real-time feedback to athletes, which can help them adjust their performance during training and competition.
- Communication with coaches: wearable devices can be used to communicate with coaches, who can provide athletes with feedback and advice regarding their performance.
- Prevent injuries and interference that could alter health parameters.

4. Organized Classification of Sports Wearables

Considering the constant growth of the wearable device market, it provides a continuous response to consumers' changing needs, while at the same time, it limits the possibility of definitive classifications.

Generally, wearable smart devices are classified into the following four categories by the International Electrotechnical Committee (IEC):

- Near-body electronics.
  Devices that operate in close proximity to the body without direct skin contact, such as smart glasses, wireless earbuds, and augmented or virtual reality devices. These use short-range sensors and communication technologies to interact with the environment and user, providing contextual information or enhancing sensory experience.
- On-body electronics.
  Devices embedded in clothing or accessories, including smart clothing and jewelry, which use textile-integrated sensors or embedded microelectronics to track movement and biometrics.
- In-body electronics.
  Implantable devices, which are inserted into the body to monitor internal physiological parameters using biosensors that can measure things like glucose levels and heart rhythm.
- Electronic fabrics.
  Fabrics embedded with electronic components and sensors, capable of detecting various forms of physical and environmental interaction through conductive threads and flexible circuits.

Following these four categories, the list below reflects the wearable devices currently used by athletes:

- Watches: basic, smart.
  - Hearables: earphones, earbuds, headsets.
  - Smart clothing: smart shoes, bras, suits (jacket, trousers), shirts, pants, socks.
  - Smart jewelry: bracelets, necklaces, brooches, rings, analog watches, fitness jewelry.
  - Head-mounted displays: AR HDMs, VR HDMs, mixed HDMs.
  - Glasses: smart, AR.
  - Wearable cameras.
  - Body sensors.
  - Implantable.
  - Ingestible.
  - Tattooable.
  - Exoskeletons: active, passive.
  - Location trackers.
  - Gesture control.

We have attempted to categorize wearable devices into a variety of categories in this article, so that we may create a comprehensive classification system that can catalog their use in sports as comprehensively as possible.

Based on the available literature, we believe that we are proposing a classification system that reflects the current usage of wearable devices by athletes.

4.1. Location-Based Wearables (LBW)

These devices typically use GPS, accelerometers, and gyroscopes to collect data. Tracking devices, including smartphones and GPS watches, track the athlete's movement and location. They can be used to measure distance, speed, and pace, as well as to create training maps and track progress over time. Although heart rate data are consistent, calorie expenditure, VO_{2max}, heart rate variability, O_2 saturation, and sleep information should be interpreted with caution due to their high rates of error [19,49–51] (Table 1).

Table 1. Location-Based Wearables examples.

Existing Product	Application
Garmin Forerunner 245 [51]	• GPS smartwatch that tracks distance, speed, pace, and heart rate, as well as a variety of activities, including running, cycling, swimming, and more. • Monitors heart rate and can estimate sleep, stress, and VO_{2max}.
Polar M430 [52]	• GPS watch that tracks heart rate, distance, speed, and pace. With a built-in accelerometer, it can track steps and estimate calories burned and sleep. • Has several training features, including interval training, heart rate zones, and recovery time.
APP Nike + Run Club [53]	• This app uses a phone's GPS to track its owner's runs. • It also provides the owner with coaching tips and offers social media integration.
APP Strava [54]	• Tracks heart rate, average speed, maximum speed, and speed over certain distances, and provides an estimation of calories burned. • It has a good level of validity and reliability [55].
APP MapMyRun [56]	• Tracks distance and provides GPS tracking, heart rate monitoring, and audio coaching.

4.2. Location-Based Wearables in Sports Disciplines

Running: running data can be tracked using LBW, which give runners feedback on their form and help them avoid injuries [57].

Cycling: cyclists can train more effectively and stay motivated using LBW, which can track distance, speed, and elevation gain, as well as provide turn-by-turn directions and help them stay safe [58].

Golf: LBW can provide real-time feedback on shots and help golfers learn from their mistakes by tracking the distance to the hole, the slope of the green, and the wind conditions [59].

Skiing: LBW can provide skiers with information about the terrain and help them avoid hazards, as well as track distance traveled and vertical drop [60].

Swimming: for swimmers and open water swimmers, LBW can be an extremely useful tool to track distance, pace, speed, stroke count, and distance per stroke, as well as to keep an eye on their body position in the water [61].

4.3. Biometric Wearables (BMW)

BMW use various sensors such as photoplethysmography (PPG), electrocardiography (ECG), and bioimpedance sensors. These devices track the athlete's heart rate [17], breathing rate [62], blood pressure [63], blood glucose level [64], and other physiological metrics. They can be used to monitor stress levels [65], assess recovery [66], track sleep [19], and optimize training [67]. Due to increased awareness of the benefits of monitoring one's physiological data, this category is growing rapidly. However, scientific consistency does not support the information that accompanies the sale of these products and not all of the provided information has been validated, so a very weighted interpretation of the data is recommended [6] (Table 2).

Table 2. Biometric Wearables examples.

Existing Product	Application
Apple Watch [68]	• Tracks heart rate and other biometric data with built-in GPS. • Can estimate sleep quantity and energy expenditure.
Fitbit Sense [69]	• Tracks heart rate and can estimate sleep and stress levels. • Has built-in GPS and other features, such a skin temperature sensor.

Table 2. *Cont.*

Existing Product	Application
Oura Ring [70]	• Tracks heart rate and can estimate sleep and activity levels. • Is used to acquire nocturnal heart rate (HR) and HR variability (HRV).
Garmin Forerunner 945 [71]	• Tracks heart rate with good accuracy. • Can be used for prescribing exercise intensity.
Samsung Galaxy Watch [72]	• Tracks heart rate and other biometric data with built-in GPS. • Also provides HRV during sleep times.

4.4. Biometric Wearables in Sports Disciplines

Running: BMW's heart rate monitors are capable of tracking heart rate throughout a run, measuring cardiac drift in real time, and estimating caloric expenditure on a daily basis [73].

Cycling: BMW can monitor heart rate in addition to cadence and power output [74].

Swimming: BMW can monitor heart rate in water in addition to stroke count and distance per stroke [75].

Golf: BMW can monitor heart rate in addition to swing speed and clubhead speed [76].

Boxing: BMW can monitor heart rate in addition to impact, punch force, punch speed, punch time, and recovery [77].

4.5. Performance Wearables (PMW)

These devices track athletes' performance data, including power output, force, cadence, speed, and distance, using sensors such as GPS, gyroscopes, and accelerometers. In addition to improving technique, they can also be used to track an athlete's progress over time; identify areas that need to be improved; prevent injuries by detecting potential problems early; and optimize training programs by analyzing how athletes react to different kinds of training [4] (Table 3).

Table 3. Performance Wearables examples.

Existing Product	Application
Stryd [78]	• Tracks power output, ground contact time, and stride length with foot pod. • Data can be used to improve running economy and efficiency.
Catapult OptimEye [79]	• Tracks movement data, such as speed, acceleration, and distance. • Data can be used to improve technique and performance in sports such as football, rugby, and cricket.
Wattbike Atom [80]	• Tracks power output, cadence, and heart rate with smart bike. • Data can be used to improve cycling performance and efficiency.
Polar OH1 [81]	• Tracks heart rate and heart rate variability with chest strap. • Data can be used to assess recovery and stress levels.
Run Scribe [82]	• Tracks distance, pace, step length and frequency, ground contact time, VGRF, and foot angle and its derivates [83]. • Data can be used to improve running economy, technique, and efficiency.

4.6. Performance Wearables in Sports Disciplines

Running: Performance wearables can track running activity and offer analysis on the athlete's performance. They map the route taken and track the pace achieved. Once a route is completed, the data are uploaded onto the app and website with analysis of the activity and any known limitations, such as calories burned, average speed, maximum speed, speed over certain distances, and heart rate.

Cycling: Performance wearables can track heart rate, cadence, and power output, which can help cyclists to train more effectively and stay motivated. They can also provide turn-by-turn directions and help cyclists to stay safe on the road.

Swimming: Performance wearables can track heart rate, stroke count, and distance per stroke, which can help swimmers to improve their efficiency and swim faster. They can also help swimmers maintain pace and direction during open water swimming.

Golf: Performance wearables can track heart rate, swing speed, and clubhead speed, which can help golfers to improve their accuracy and scoring. They can also provide real-time feedback on shots and help golfers to learn from their mistakes.

Basketball: Performance wearables can track heart rate, distance traveled, and shot accuracy, which can help basketball players to improve their conditioning, efficiency, and shooting. They can also provide real-time feedback on plays and help players to learn from their mistakes.

Soccer: Performance wearables can track heart rate, distance traveled, metabolic power, acceleration, and sprints, which can help soccer players to improve their conditioning, efficiency, and speed. They can also provide real-time feedback on plays and help players to learn from their mistakes.

4.7. Other Wearables

Smart clothing, ingestible and tattooable devices, and virtual reality headsets are examples of devices that do not fit neatly into any of the other categories. Physiological data can be tracked using smart clothing, while training environments can be simulated with virtual reality headsets. Devices are also becoming available that can provide athletes with information, biofeedback, or even elements of concentration, focus, and distraction during training and competition [84] (Table 4).

Table 4. Other Wearables examples.

Existing Product	Application
Athos [85]	• This smart clothing system tracks muscle activity, heart rate, and temperature. • Data can be used to improve strength training performance and prevent injuries.
Oculus Quest [86]	• This virtual reality headset allows athletes to train and compete in virtual environments. • It can be used to improve skills and technique, and it can also be used for entertainment purposes.
Jabra Elite Sports [87]	• These sweat-resistant wireless earbuds allow athletes to listen to music, stay focused, and hear their surroundings if needed.
Leomo Motion Tracking [88]	• This technology tracks movement, acceleration, rotation, and gravity. • It also provides real-time feedback on movement, displayed on a smartphone or tablet.

5. Discussion

Wearable technology has dramatically transformed the sports world, revolutionizing training, performance analysis, and injury prevention. This review classifies wearable devices into three main categories: location-based wearables (LBW), biometric wearables (BMW), and performance wearables (PMW), with each providing unique insights into different aspects of athletic performance. Location-based wearables have shown significant promise in tracking athletes' movements, delivering valuable data on distance, speed, and pace. However, their accuracy can be compromised in certain environments, such as urban areas with tall buildings or dense forests, due to GPS signal interference. Additionally, the sampling rate of LBW is crucial for data quality, especially in sports that involve rapid direction or speed changes. Future research should aim to improve the accuracy of LBW in challenging environments and optimize the sampling rates for specific sports.

Biometric wearables give unprecedented access to physiological data, enabling real-time monitoring of vital signs like heart rate, blood glucose level, and blood pressure. Nevertheless, the accuracy and reliability of these measurements can vary significantly between devices and during intense physical activity. The potential for BMW to detect early signs of overtraining or fatigue is particularly promising, yet more research is needed to establish reliable biomarkers and algorithms for fatigue detection. Furthermore, continuous monitoring of physiological data raises ethical considerations and data privacy concerns that need to be addressed as the technology progresses.

Performance wearables have demonstrated great potential in providing detailed insight into athletic techniques and biomechanics. However, their accuracy and reliability can be affected by factors such as placement, calibration, and environmental conditions. Integrating PMW data with video analysis and artificial intelligence holds significant promise for comprehensive performance assessment and technique optimization. The future of wearable technology in sports will likely be influenced by emerging technologies such as lab-on-a-chip devices, which offer potential for real-time biochemical analysis. Integrating wearable technology with virtual and augmented reality systems may revolutionize training methodologies and performance analysis. However, as the field advances, it is crucial to develop standardized protocols for data collection, analysis, and interpretation, to ensure comparability across different devices and sports.

6. Limitations

While wearable technologies have seen rapid adoption and widespread use in sports performance monitoring, several limitations remain that hinder their full potential [89].

These limitations include the following:

Validity: The accuracy of wearable devices in measuring specific metrics can vary significantly. For instance, heart rate monitors might provide accurate readings under controlled conditions, but may fail to capture accurate exertion levels during high-intensity activities [26].

A potential solution is to develop advanced algorithms that can better interpret data under varying conditions and integrate multi-sensor data to enhance accuracy.

- Reliability: The reliability of data from wearable devices can be influenced by environmental factors and device placement. GPS accuracy can be compromised in urban areas with tall buildings, and biometric readings can be affected by improper device usage or physiological conditions like dehydration. Improving sensor technology and incorporating redundant systems can help mitigate these issues [17,89].
- Interpretability: Wearable devices generate vast amounts of data, which can be challenging to interpret effectively. Athletes and coaches may struggle to make actionable decisions based on complex datasets. Developing user-friendly interfaces and employing artificial intelligence to provide clear, actionable insights can enhance the usability of these devices [25].
- Cost: High-quality wearable devices can be expensive, limiting their accessibility to amateur athletes or teams with limited budgets. Potential solutions include reducing production costs through technological advancements and economies of scale, and developing lower-cost alternatives that still provide valuable insights.
- Ethical and Privacy Concerns: Continuous monitoring of physiological data raises concerns about data privacy and the ethical use of the collected information. Establishing robust data protection regulations and ensuring transparency in data usage policies are essential steps in addressing these concerns.

7. Future Directions

Wearable technologies are expected to continue evolving, driven by advancements in sensor technology, data analytics, and artificial intelligence. Over the past decade, there has been significant growth in the development and adoption of wearable devices, with a focus on enhancing accuracy, reliability, and usability. Key trends include the miniaturization of sensors, integration of multi-sensor platforms, and the use of machine learning algorithms for data interpretation.

Over the next decade, based on current data trends, several key developments are projected:

- Lab-on-a-chip (LOC) technology [90], which miniaturizes lab equipment into microscale devices, includes a new generation of wearable biosensors that directly interface with the human epidermis instead of rigid packages embedded in wristbands or bands. Wearable biosensors have been particularly suitable for point-of-care testing (POCT) [91] due to their distinctive characteristics of light weight, flexibility, and portability. As a result of POCT microfluidic devices, athletes have been able to analyze biofluids, including sweat, urine, interstitial fluid, saliva, tears, urine, blood, chloride, pH, lactate, glucose, cytokines, hormones, amino acids, and exogenous drugs without experiencing discomfort, pain, or needle phobia [22]. By overcoming these challenges, wearable biosensors will be fully commercialized and widely adopted in sports-related fields, dramatically changing state-of-the-art athletic monitoring and sports analytics.
- AI-Enhanced Wearables: Artificial intelligence will play a crucial role in improving the accuracy and interpretability of data from wearable devices. AI algorithms can analyze complex datasets, provide real-time feedback, and predict potential issues like overtraining or injury risks
- Virtual and Augmented Reality: Wearable devices integrated with VR and AR systems will revolutionize training methodologies. Athletes can simulate various training environments and scenarios, allowing for more effective skill development and performance analysis.

Given the rapid pace of technological advancement, predictions of the future of wearable technologies in sports may need to be revised as new innovations emerge. The integration of AI and continuous improvements in sensor technology suggest that the most realistic forecasts will remain fluid, adapting to ongoing developments in the field.

8. Conclusions

Wearable technology has undeniably revolutionized sports science and athletic performance. Categorizing these devices into location-based, biometric, and performance wearables offers a clear framework for understanding their diverse applications and limitations. Despite the unprecedented insight these technologies provide into athletic performance, they also bring challenges related to data accuracy, interpretation, and ethical considerations. The future of wearable technology in sports hinges on developing more accurate, sport-specific devices and integrating advanced data analytics and artificial intelligence. As this field advances, it is crucial to balance technological innovation with practical application, ensuring that the vast amounts of data generated translate into tangible improvements in athletic performance and well-being. While wearable technology has already made significant strides in enhancing sports performance and athlete monitoring, its full potential remains untapped. As the technology evolves, it holds the promise of democratizing sports science, making advanced analytics accessible to athletes at all levels, and potentially reshaping the future of sports training and competition.

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