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Integrated Wearable Motion Sensors for Comprehensive Health and Performance Monitoring: A Narrative Review

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ABSTRACT

As athlete health monitoring and personalized performance management become increasingly data-driven, the development of advanced wearable motion sensors has emerged as a key innovation shaping the future of sports science. Among various fabrication technologies, Chemical Vapor Deposition (CVD) stands out for its ability to produce flexible, durable, and highly sensitive motion sensors, making it particularly suitable for long-term athlete monitoring in real-world training and competition environments. Recent advances in CVD-based sensors have significantly improved the precision and reliability of motion data acquisition, providing real-time insights into movement quality, fatigue, and injury risk, critical factors for optimizing athlete health and performance. This review summarizes the latest progress in CVD-fabricated motion sensors, focusing on their applications in athlete health monitoring systems. Particular emphasis is placed on their dual capabilities: large-scale movement tracking (e.g., gait analysis, bio-mechanical assessment, and sport-specific motion capture) and small-scale physiological motion detection (e.g., micro-joint movements, muscle tremors, and subtle posture shifts). These capabilities offer valuable tools for both performance optimization and early injury detection, supporting personalized training adjustments and evidence-based rehabilitation strategies. Looking ahead, integrating CVD-based sensors into smart wearable systems will not only enhance continuous athlete health surveillance, but also enable re-al-time data feedback, empowering coaches, sports scientists, and medical teams to make more informed decisions during training, competition, and recovery. By bridging advanced sensor technology with practical, athlete-centered applications, this review high-lights how interdisciplinary innovations can drive the evolution of next-generation athlete health monitoring platforms, aligning closely with the vision of this Special Issue. These technologies are expected to benefit not only elite athletes but also recreational sports participants, contributing to broader advancements in sports health management and preventive care.

***Keywords:** Smart Health Technology; Body Motion Sensors; Health Monitoring; Sports Technology; Digital Health.*

1. INTRODUCTION

Traditional inertial methods for capturing highly dynamic body movements are prone to significant drift and instability, which compromises data accuracy and limits their practical applications (Liu et al., 2020).

The performance of sensors, particularly their accuracy, sensitivity, and detection range, critically depends on the sensing elements (Liu et al., 2022). To meet the demands of body motion detection, Chemical Vapor Deposition (CVD) technology is widely applied, as it enables the fabrication of sensors using high-quality, well-crystallized graphene materials suitable for these demanding applications (Baloda et al., 2024).

Graphene's piezoresistive and piezoelectric sensing mechanisms have enabled the creation of high-sensitivity strain sensors used for monitoring joint movements, muscle activity, and respiratory conditions. Additionally, graphene serves as the basis for pressure sensors widely applied in gait analysis, pulse wave monitoring, and blood pressure measurement (Ma, 2024).

Chemical Vapor Deposition (CVD) technology is pivotal in manufacturing high-performance body motion sensors due to its material science advantages (Wen et al., 2022). It enables the creation of highly stretchable, flexible sensors with versatile signal detection capabilities, significantly enhancing performance to meet the demands of wearable applications like remote health monitoring, motion capture, and human-computer interaction (Wen et al., 2022).

Prior research primarily concentrated on analysing materials and manufacturing methodologies, with limited consideration of practical applications (Ferreira et al., 2024). Existing research on flexible sensors tends to be conceptual, with insufficient focus on specific technologies in applied scenarios. To fill this gap, this review investigates the practical applications of CVD technology for flexible sensors, emphasizing sports-related uses. We aim to establish an integrated theoretical and practical framework tailored to the requirements of athletes and sports science.

The review is divided into two main parts: the first section covers the advantages of CVD technology while the second section explores CVD applications in flexible sensors based on specific application scenarios, large-scale motion monitoring such as motion tracking and exercise monitoring, small-scale motion monitoring such as health monitoring, and applications of smart wearable technologies.

This comprehensive examination offers readers profound technical perspectives while also encouraging additional research and real-world applications. The review wraps up with a glance at the possible future research avenues and growth opportunities for CVD in motion sensors.

2. CVD TECHNOLOGY IS PROPELLING ADVANCES IN BODY MOTION SENSORS

The key benefit of CVD is its ability to achieve significant deposition depths, enabling it to coat intricate shapes, which makes it widely useful in various industries that need precise thin films (Schalk et al., 2022). As a sophisticated method for preparing materials, CVD is utilized to create high-performance thin films and layers of material, with the main benefit being the ability to produce coatings that are uniform, stable, and tightly adhered. This technology is vital across multiple sectors, especially in sports technology, where it shows considerable potential for applications. In the realm of sports technology, CVD technology provides three primary advantages (Schalk et al., 2022).

Flexible sensors are frequently employed in sports technology to track muscle activation, joint flexion, and body movements (Faisal et al., 2019). Additionally, they can be used to track health parameters such body temperature, sound, jugular pulse, and heart rate (Trung & Lee, 2016). Usually, these sensors have to stay in close proximity to the human body and adjust to intricate geometries. It is now possible to integrate their ultrathin, low-modulus, lightweight, flexible, and stretchable films over vast regions and conformably laminate them on rough, irregular, and non-flat body structures (Trung & Lee, 2016).

These sensors' ability to be sliced into multiple sizes and folded into diverse forms allows them to adapt to uneven surfaces and the human body (Trung & Lee, 2016), significantly increasing their potential for application in body motion monitoring devices. For instance, flexible sensors can be easily incorporated into garments (Zhou et al., 2022), satisfying the need for flexibility while allowing for real-time body part monitoring.

3. LARGE-SCALE MOTION – MOTION TRACKING AND EXERCISE MONITORING

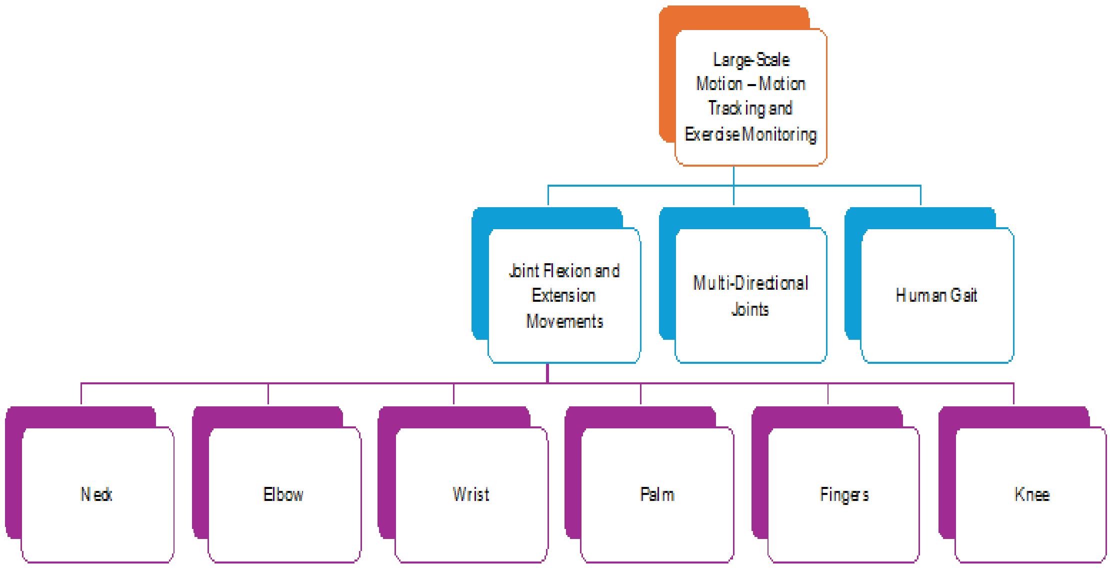

Figure 1. The Current Classification of Study on Motion Tracking and Exercise Monitoring

Flexible sensors for body motion monitoring are most commonly used to test joint flexion and extension movements, detecting large-scale motions such as those of the hands, arms, and legs (Park et al., 2015). For neck joint applications (Zhang et al., 2025), the primary focus is on testing vertical neck flexion, including upward and downward movements. In modern urban life, prolonged use of electronic devices, especially mobile phones, often leads to forward head posture, resulting in neck pain. These data can be used for intervention measures to alleviate neck pain and promote overall spinal health (Zhang et al., 2025).

For elbow joint applications (He et al., 2023), the primary focus is on testing the bending capability to differentiate between various degrees of flexion, as well as re-cording the changes during repetitive flexing. Testing the bending ability to distinguish between different degrees of flexion and documenting the changes after repetitive bending are also the main priorities for wrist joint applications (He et al., 2023). It can be further separated into two categories for palm applications: fist clenching and mouse clicking (Zhang et al., 2025). In order to capture the quick and accurate finger movements that are crucial to long-term computer mouse users, mouse clicking mainly entails applying various forces for mouse slapping and pressing (Zhang et al., 2025).

The application testing for the two approaches show a modest difference. Finger joints are frequently the focus of earlier research on flexible sensors for human motion tracking (Su et al., 2022). Differentiating between different bending degrees and recording the repetitive bending are the primary tests. The benefit of this method is that the sensor may record the resistance curve that first rises and then falls when there is severe bending or spraining during motion monitoring, giving prompt treatment input (Mu et al., 2023).

For knee joint applications (Zhang et al., 2025), the main tests involve differentiating various degrees of bending and recording the repeated bending. These tests typically include movements such as half squats, deep squats, or transitions between sitting and standing. a knee sleeve to house the flexible sensor, enabling the monitoring of knee bending, which makes the application tests more representative of real-life scenarios (He et al., 2023).

Additionally, multi-directional detection is now feasible (Hong et al., 2025). Gesture recognition, wrist rotation, and head rotation are a few examples. Multi-directional strain sensors can differentiate between different wrist movements, and wrist rotation sensing can test side-to-side or forward and backward rotations (Hong et al., 2025).

Technology for gait analysis, especially the employment of several sensors within shoes, can improve technical motions and sports efficiency (Zhang et al., 2025). Athletes can examine important indicators such step length, frequency, and symmetry with the aid of gait analysis, which gives them comprehensive information on each step and movement during training. Additionally, it enhances balance and coordination while precisely recording gait traits including centre of gravity shifts and step stability (Zhang et al., 2025).

4. SMALL-SCALE MOVEMENTS – HEALTH MONITORING

In addition to detecting large-scale motions, human motion monitoring flexible sensors may catch small-scale actions, such as slight movements in the chest and neck while breathing, swallowing, and speaking.

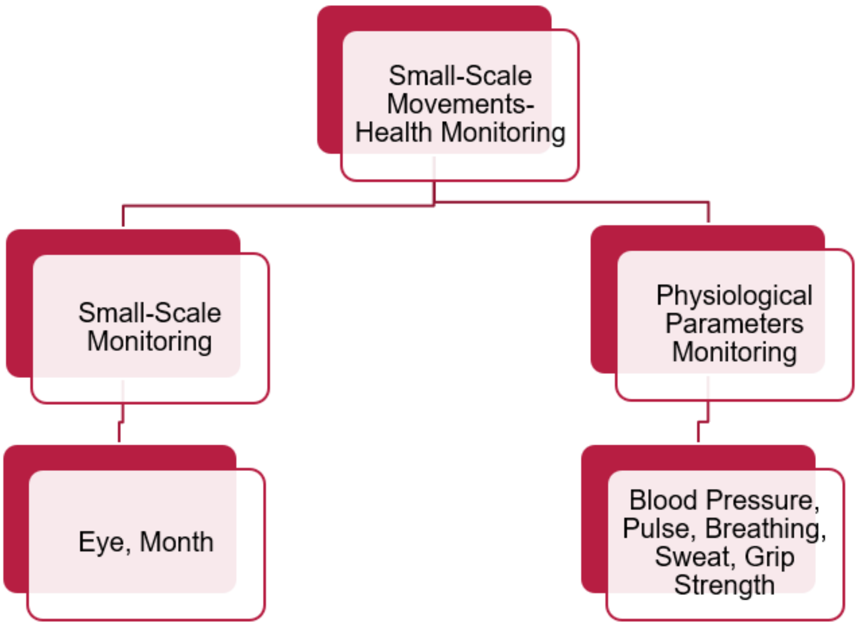

Figure 2. The Current Classification of Research on Health Monitoring

Although less prevalent, face muscle monitoring can reveal an athlete's emotional and physiological state during high-intensity training or stressful situations. For extreme sports or competitive athletes, this can help recognize psychological exhaustion or emotional changes during performance, allowing for appropriate emotional management or stress reduction to boost performance. Eye health monitoring primarily focuses on blink movement as the application for testing (Ahmed et al., 2024). The blinking action is mediated by the interaction between the orbicularis oculi and the levator palpebrae muscles, resulting in the rapid closure and reopening of the eye-lids (Hajra et al., 2025). This helps assess peripheral nerve function around the eyes, track small eyelid movements, and provide timely evaluations of eye health status (Ahmed et al., 2024).

The mouth is not only the site for eating but also for speech production. Previous studies have pointed out that weakened oral muscles may indicate speech disorders and swallowing difficulties (Gelder et al., 2011), making it essential to monitor changes in oral muscles.

The facial muscles near the corners of the mouth, including the zygomaticus major, ri-sorius, buccinator, and depressor anguli oris, play crucial roles in everyday facial expressions, chewing, speaking, and swallowing (Zhang et al., 2025). Additionally, sensors can be placed at the throat to capture the contraction and expansion of throat muscles, clearly recording subtle actions like coughing and swallowing (Zhang et al., 2025).

Blood pressure is a key determinant of human health. Blood pressure monitoring is an important tool for evaluating cardiovascular health (Shenasa & Shenasa, 2017). High or low blood pressure can impair sports performance, and constant monitoring allows athletes to recognize cardiovascular concerns early and alter their training routines accordingly. Respiratory monitoring allows athletes to check their aerobic endurance and respiratory system health. Changes in respiratory rate during high-intensity training or competition can indicate the strain on the respiratory system. Hypertension is the leading cause of hypertensive heart disease and a proven risk factor for sudden cardiac death (Shenasa & Shenasa, 2017).

Dynamic blood pressure monitoring technology, especially systems that provide continuous blood pressure recordings, can describe in detail the different components contributing to overall blood pressure variability over a 24-hour period, including both short-term and more sustained blood pressure changes (Schwenck et al., 2022). This technology provides 24-hour continuous data, which more accurately reflects a person's true blood pressure status compared to traditional static measurements that only capture blood pressure at a single time point. It also reveals blood pressure fluctuations, which can assist in providing more accurate medical treatment based on the data, and is non-invasive and does not require hospitalization (Schwenck et al., 2022).

Pulse waves are an important component of human physiological signals, carrying rich health information that can reveal an individual's condition, including heart problems (such as arrhythmias), blood pressure, vascular aging, exercise, medication use, and sleep status (Meng et al., 2022). Pulse monitoring can better reflect recovery status after exercise. For athletes, pulse changes can indicate whether the cardiovascular system has enough recovery time. A rapid pulse may signal incomplete recovery, requiring adjustments to training or rest periods (Meng et al., 2022). Pulse monitoring using wearable device technology has become common, primarily using optical sensors (Vavrinsky et al., 2022), while flexible sensors measure pulse based on pressure or strain changes. Compared to optical sensors, flexible sensors can tightly adhere to the skin and even capture weaker pulse signals.

Another innovative method by placing sensors on the chest of a person lying down. This design, based on fabric sensors similar to other skin-adhering devices, helps obtain accurate physiological signals from the chest (Homayounfar et al., 2023). Simultaneously, sensors placed on the neck are specifically used to monitor external jugular vein pulse signals, which are synchronized with ECG signals for comprehensive analysis (Homayounfar et al., 2023) .

Breathing is one of the fundamental functions for the survival of most organisms. Long-term monitoring of human breathing activity has various important medical appli-cations, such as the diagnosis of sleep apnea, chest movement monitoring, and airflow analysis, all of which help assess respiratory function (Arlotto et al., 2014). Continuous respiratory monitoring is not only an effective tool for evaluating overall health but also provides crucial data support for early disease warning and health management (Arlotto et al., 2014). In current CVD technology, flexible sensor-based breathing monitoring mainly involves embedding the flexible sensor into a mask to measure the intensity and frequency of airflow during the breathing process (Su et al., 2022).

Sweat provides important information about the body's condition, such as electrolytes reflecting fluid balance and kidney function, lactate reflecting fatigue levels after exercise, sweat glucose indicating its concentration, and cortisol levels in sweat that can reflect the degree of psychological stress (Klous et al., 2020). Sweat monitoring reflects an athlete's dehydration status, electrolyte balance, and metabolic levels. Excessive sweating can lead to dehydration, affecting endurance and physical performance (Klous et al., 2020).

Grip strength detection is an important indicator in physical fitness assessments be-cause grip strength is considered a simple and effective measure of muscle strength(Roberts et al., 2011). Insufficient upper limb strength can affect the ability to perform daily activities and in-crease the risk of sarcopenia.

5. PERFORMANCE AND APPLICATIONS OF SMART WEARABLE TECHNOLOGY

In addition to being characterized as large-scale or small-scale monitoring, the performance and applications of human motion monitoring have evolved. The parts that follow will delve into the performance in terms of comfort and durability, which are two critical elements for the practical application of motion tracking devices, particularly their performance during extended usage and strenuous exercise.

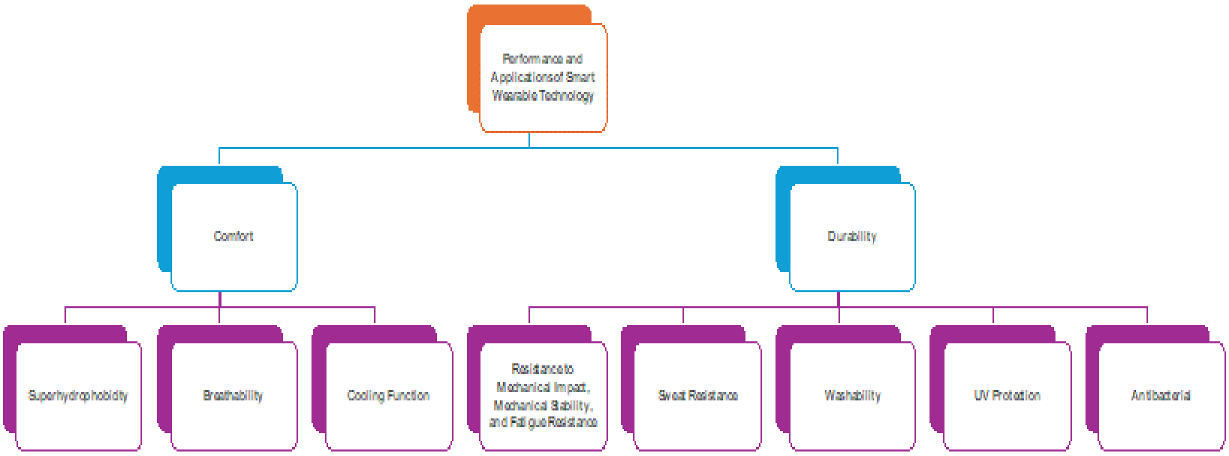

Figure 3. The Current Classification of Research on Performance and Applications of Smart Wearable Technology.

- **a. Comfort**: User comfort is essential when integrating flexible sensors into textiles. Key comfort factors like superhydrophobicity, breathability, and cooling functions improve the wearer's experience, reduce discomfort over long periods, and make the sensors more practical for various environments (Cho et al., 2022).
- **b. Superhydrophobicity**: Current research is applying superhydrophobic coatings to sensors, which cause everyday liquids like milk, cola, soy sauce, tea, and coffee to bead up upon contact (Diaz & Crick, 2023). These droplets then quickly slide off the surface without leaving residue, demonstrating excellent self-cleaning abilities.
- **c. Breathability**: In terms of comfort, hydrophobic layers typically lack breathability due to their need to be water-repellent, which may cause discomfort for the user. To address this issue, researchers developed a sensor that, despite absorbing a small amount of water vapor after being exposed to a humid environment for 24 hours, does not affect the breathability of the sensor (Homayounfar et al., 2023).
- **d. Cooling Function**: Cooling clothing offers significant benefits like enhanced comfort and improved performance, particularly during intense exercise or in hot conditions, by actively aiding the body's cooling process (Tyler et al., 2013). Notably, researchers developed a cooling garment that can achieve a temperature reduction of up to 15°C compared to traditional sun-protective fabrics, ensuring users can still enjoy a comfortable wearing experience in high temperatures (Tyler et al., 2013).
- **e. Durability**: Physical activity during exercise or daily use can easily damage wearable sensors, making durability a critical requirement. Essential durability factors include resistance to mechanical impact and fatigue, overall stability, sweat resistance, washability, UV protection, and antibacterial properties (Muzaffar et al., 2021). These characteristics directly influence the sensor's lifespan in different environments and maintain its reliability and functional stability, especially during long-term wear or intense activities.
- **f. Resistance to Mechanical Impact, Mechanical Stability, and Fatigue Resistance**: Previous studies have demonstrated sensor durability against mechanical impact by developing devices that can endure extreme conditions, such as repeated hammer strikes (Su et al., 2022). Regarding mechanical stability and fatigue resistance, researchers developed the sensors (Zhang et al., 2025) maintained their functionality even after undergoing 1,000 seconds of continuous use testing and stretch cycling load tests, fully showcasing their mechanical stability and fatigue resistance. In addition, the sensor developed by another group of researchers (Homayounfar et al., 2023) has undergone 70,000 cycles of 4-day bending tests and still maintains its stability.
- **g. Sweat Resistance**: Users wearing sensors often sweat, so the sweat resistance of the sensor is also an important

issue. In terms of sweat resistance, previous studies have developed sensors that can withstand sweat, maintaining normal functionality even after being submerged in artificial sweat for up to 120 hours [36] or sprayed with 100 millilitres of saline solution every 30 minutes (Homayounfar et al., 2023). These sensors demonstrate superior sweat resistance. The sensors developed by another group of researchers even maintained high stability when exposed to rain or sweat (Su et al., 2022).

h. **Washability**: When sensors become sweaty or dirty due to daily use, users often need to clean them. In terms of washability, the sensors developed by researchers exhibit excellent washability (Homayounfar et al., 2023). After one hour of washing and after 20 washing cycles, the sensors maintained their sensitivity, further demonstrating their durability in practical applications.

i. **UV Protection**: Prolonged exposure to ultraviolet (UV) radiation can cause certain sensor materials to discolour, become brittle, or even lose their original mechanical properties. Sensors with UV protection can effectively slow down this process, thereby maintaining the stability of their appearance and structure. Therefore, the sensors developed by researchers are equipped with UV protection functionality, and even after 48 hours of exposure to UV radiation, they maintain their durability (Wang et al., 2023).

j. **Antibacterial**: During daily wear, sensors come into contact with various substances, including skin, sweat, dust, bacteria, and other environmental factors, which may lead to the accumulation of bacteria or other microorganisms on their surfaces (Su et al., 2022). Since the COVID-19 pandemic, human hygiene awareness has significantly increased. Antibacterial properties not only help suppress bacterial growth but also prevent bacteria from corroding the sensor materials, thereby reducing wear or performance degradation caused by microorganisms (Su et al., 2022).

6. SUMMARY AND OUTLOOK

This review emphasizes how flexible motion sensors made using CVD are key drivers in transforming digital health and athletic performance monitoring. Their advanced ability to be highly integrated allows them to simultaneously capture large body movements and subtle physiological signals, thus providing a more complete and dynamic understanding of human motion. These capabilities directly enable the development of data-driven performance evaluations, personalized training programs, and proactive injury prevention strategies—all essential building blocks for future smart health systems.

Although technological advancements are boosting digital health applications, a significant gap remains between laboratory breakthroughs and real-world implementation. Most current studies do not adequately address practical challenges like intense physical activity, long-term wearability, and environmental factors such as moisture and sweat. Furthermore, much research still prioritizes material and engineering innovations without sufficiently integrating these technologies into broader digital systems, physiological models, or user-centered applications.

To close this gap, future research must actively embrace digital technology integration, combining artificial intelligence, the Internet of Things (IoT), cloud and edge computing, and advanced data analytics to build comprehensive wearable data ecosystems. These systems should enable real-time feedback, remote monitoring, and decision support functionalities. Achieving this vision requires a shift from isolated technical advancements to interdisciplinary collaboration—bringing together biomechanics, sports medicine, information engineering, data science, and user experience design to create scalable, sustainable, and practically deployable solutions.

Longitudinal, in-the-field validation studies must also become a priority. The development of standardized data formats and interoperable platforms is essential to support cross-institutional and multi-context data integration and sharing. As sensor-generated data becomes increasingly personalized and sensitive, robust data governance frame-works are required to ensure ethical compliance, privacy protection, and informed consent, thereby building transparency and trust in digital health technologies.

In summary, the development of flexible wearable motion sensors represents not only a technological breakthrough but also a symbol of the broader shift toward intelligent, personalized, and precision-driven health systems in the digital age. Only through integrated technological development, real-world validation, and ethical reflection can these innovations reach their full application potential—contributing to a smarter, healthier, and more sustainable future in sports science and digital healthcare.

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