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Application of Flexible Sensors in Sports Medicine

Haoyue Xia

School of Marine Sciences, Ningbo University, Ningbo, China
13738036728@163.com

Abstract. With increasing global health awareness and an aging population, health detection technologies during exercise is paramount. Traditional, bulky equipment, while precise, struggles to adjust to the dynamic changes that occurred during exercise. Flexible sensors offer a solution due to their bendability, biocompatibility, and ability to capture diverse physiological data, making them valuable for motion detection and intervention. This paper systematically reviews the core technology system of flexible sensors, highlighting advancements in material innovation, system integration, and clinical transformation. It also explores its innovative applications in sports injury prevention, rehabilitation therapy and personalised sports management. It is discovered that the dynamic monitoring performance and wearing comfort of flexible sensors have been greatly enhanced by the combination of biomimetic structure design and high sensitivity nanocomposites. Despite challenges like standardisation and multi-physical field interference, flexible sensors, integrated with AI algorithms and digital twin technologies, are advancing sports health management towards intelligence and customisation.

Keywords: wearable technology, sensors, human mobility, monitoring

1. Introduction

The World Health Organisation reports that 10%–20% of sports-related injuries occur each year, and over 120 million medical consultations are made as a result of incorrect exercise, with 15%–25% of those consultations requiring clinical rehabilitation [1]. The wearability and continuity issues of current clinical testing tools, like electromyography and pressure sensors, hindering real-time monitoring during prolonged activity [2].

Flexible sensors have advanced quickly, offering solutions to these limitations. For instance, in knee joint movement, they can deform synchronously with ligament stretching, avoiding the signal distortion caused by motion friction in rigid sensors. Their dynamic response time of less than 10 milliseconds also meets real-time monitoring requirements [3]. Graphene nanocomposite-based flexible stress/pressure sensors are being developed for medical diagnosis, health monitoring, and motion monitoring, including human pulse detection and expression recognition [4]. Additionally, a team is working on developing dynamic polymer and MXene paper-based sensing materials and creating composite sensors for motion monitoring and ECG signals [5]. These findings demonstrate the rapid advancement of flexible sensing technology from lab to clinical settings.

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This study examines how flexible sensors, with their dynamic flexibility, biocompatibility, and multimodal data acquisition, overcome the limitations of conventional devices, confirming their usefulness and translational value in sports medicine. This research provides a foundation for the development and implementation of advanced flexible sensor technologies, contributing to sports injury prevention, rehabilitation outcomes, and personalized health management strategies.

2. Innovation advances and flexible sensor core technology

2.1. Technical guidelines

Piezoresistive, piezoelectric, and capacitive effects are the primary conversion methods used by sensor devices, which use sensitive materials to transform environmental inputs into electrical signals. Carbon-based composites (graphene, carbon nanotubes) and metal nanowires (silver, gold) are common materials used in piezoresistive devices, which are based on the change in resistance ($\Delta R/R_0$) caused by bending of the conductive network. For instance, graphene sensors are great for tracking major joint motions, such as the flexion and extension of the knee, because they can vary resistance by up to 200% at 100% strain [6]. Conversely, capacitive sensors, which are frequently used for plantar pressure distribution detection, employ PDMS microporous structures or aerogel as the sensitive layer and fluctuate the capacitance value ($\Delta C/C_0$) due to variations in the dielectric layer's thickness [7]. They have a resolution of up to 0.05 kPa. Furthermore, capacitive sensors exhibit special benefits in pressure distribution imaging systems by achieving non-contact detection by mechanical modification of electrode spacing or dielectric layer thickness.

Many techniques have been used in recent years to acquire physiological signals. For instance, flexible electrodes applied to the skin using Ag/AgCl conductive paste can detect weak EMG signals between 5 and 200 μV for the assessment of muscle fatigue, and they have a 40% better noise suppression rate than conventional metal electrodes [8]. Thus, the use of an ion-selective electrode or an integrated enzyme electrode can track metabolic markers in sweat in real time, including sodium ions (accuracy ±5%) and lactic acid (detection limit 0.1 mM), which can serve as the foundation for controlling exercise intensity [9].

2.2. Innovation in technology

2.2.1. Innovation in materials

First and foremost, the synergistic design of conductive and substrate materials determines the performance base of flexible sensors. While conductive polymers, like PEDOT, achieve stable conductivity under tensile conditions through the ductility of molecular chain segments, two-dimensional nanomaterials, such as graphene and carbon nanotubes, have emerged as a research hotspot in the selection of conductive materials due to their high conductivity (>5000 S/m) and mechanical flexibility [10-11]. Researchers frequently use the composite method of nanofillers (e.g., silver nanowires) and elastomers (PDMS, polyurethanes) to create a dynamic conductive network through the percolation threshold adjustment in order to balance the mechanical and conductivity qualities [2, 12]. Conversely, substrate materials must strike a balance between environmental adaptation and flexibility; for example, biocompatible hydrogels are ideal for medical applications, while heat-resistant silicone is favoured for industrial settings [13].

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2.2.2. Innovations in structure

Typical sensor designs employ layered heterogeneous structures, such as a "sensing layer-isolation layer-electrode layer" three-layer structure. For example, Zhang et al. developed a microenvironmental sensor that uses a 0.1mm-thick polyimide isolation layer to achieve independent acquisition of multiple parameters while preventing crosstalk between temperature and pressure signals [14]. The majority of flexible sensors have bionic structures; the fold structure sensor, which was inspired by octopus skin, has a signal-to-noise ratio of 30dB, a surface micro-convex structure that increases the skin contact area by 30%, and the ability to withstand 200% strain without pre-stretching [15]. Wearable integration techniques are used by the flexible sensors. First, medical-grade pressure-sensitive adhesive, like 3M™ 9703, which is less than 50 μm thick, is used to secure the skin-attached kind. For joint motion monitoring (e.g., wrist, knuckle), this thin and light characteristic is appropriate [16]. Second, sensors can be included into sportswear through fabric-integrated embroidery or coating technologies. For example, 18 strain sensor nodes are embedded into Under Armour's Biocraft brand of sportswear to enable 3D reconstruction of whole-body motion postures [17].

3. The uses for flexible sensors in sports medicine

3.1. Sports injury prevention

There are several uses for flexible sensors in sports medicine. By attaching two orthogonal strain sensors to the inner and outer sides of the knee joint, people can prevent sports injuries by protecting the anterior cruciate ligament (ACL) of the knee joint. This allows them to track the internal rotation angle and anterior-posterior displacement in real time. Clinical experiments have demonstrated that a wireless alert that is activated when the internal rotation angular velocity is more than 150°/s and the displacement is greater than 3mm (delay <20ms) reduces the risk of ACL injury by 28% [6]. An array of pressure sensors (9×9 channels, spatial resolution 1 cm^2) can also be placed on the sole of the foot to help people anticipate ankle sprains. A machine learning model analyses the centre of pressure offset trajectory to send an early warning one second before the sprain occurs, with an accuracy of 85% [18].

Flexible sensors can be utilised for centrifugal contraction overload monitoring in order to detect muscle injuries early. It is possible to connect sEMG sensors to the belly of the biceps muscle. If the muscle discharge frequency is greater than 200 Hz and lasts longer than 10 seconds, this is considered an overfatigued state, and the fitness professional is advised to modify the training intensity [8]. A flexible patch with integrated temperature and humidity sensors can also help people avoid heat stress injuries. This technology lowers the incidence of heat injuries by 42% in marathon races and indicates a risk of heat stroke when the local skin temperature is higher than 38°C and the sweat secretion rate is greater than 0.5 grammes per minute [16].

3.2. Rehabilitative

Traditional rehabilitation testing equipment struggles to meet the dynamic needs of patients due to poor wearability, limited data, and difficulty providing real-time feedback. Flexible sensors address these deficiencies. Their exceptional flexibility, high sensitivity, and good compatibility with the human body led to new developments and advancements in rehabilitation therapy, and they are now a crucial tool for maximising the benefits of rehabilitation.

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First, joint function reconstruction is possible with the flexible sensor. Flexible sensors can assist in intelligent prosthesis adaptation for individuals with limb mutilation and other conditions. For example, a pressure sensor integrated into the inner wall of the prosthesis acceptance cavity detects the residual limb-prosthesis interface pressure distribution in real-time (accuracy ± 0.3kPa) and uses adaptive algorithms to modify the pneumatic joint damping, allowing the wearer to walk with a 25% lower energy consumption [19]. People's cartilage is currently prone to damage owing to climate change and other environmental issues; flexible sensors can be utilised to track its condition and restore it. An objective foundation for evaluating the rehabilitation process can be established by implanting flexible strain sensors into the knee joint's cartilage repair site and dynamically tracking changes in cartilage elasticity modulus within three months following surgery [20].

Furthermore, training for motor ability restoration heavily relies on flexible sensors. While acromegaly can be fatal, flexible sensors can aid in managing motor neurone disease. In acromegaly patients, stimulating the common peroneal nerve with implantable flexible electrodes (20μm thick), guided by body pressure sensor feedback, improves active ankle dorsiflexion strength by 30% [8]. Flexible sensors also assist stroke patients with gait correction. Flexible EMG sensor arrays record sEMG signals from the six main lower limb muscle groups. Using a feedback training system to display the muscle activation sequence in real time, patients can reconstruct proper gait patterns. According to clinical data, the patient's ankle dorsiflexion angle improved by 12° and their step length rose by 18% following 8 weeks of training [3].

3.3. Leading a healthy lifestyle

Elderly people who lead healthy lives deal with issues including deteriorating balance and a higher chance of falling, and typical monitoring devices are frequently uncomfortable and inconvenient to use with time. Accurate movement analysis and body condition monitoring equipment for professional athletes is costly and inflexible to accommodate the various demands of daily training. With the ability to precisely and in real time monitor a variety of bodily indications, flexible sensors offer a novel approach to fatigue evaluation, movement optimisation for athletes, and balance training for the elderly, all of which enhance quality of life and athletic performance.

People frequently lose their sense of balance and have trouble moving as they age. When this issue arises, flexible sensors can assist senior citizens in improving their balance. Elderly adults reduce the chance of falling by 40% by using a network of wearable flexible sensors (which includes four pressure sensors and six accelerometers) to measure body centre of gravity offset in real time and coach users through balancing training using a gamified interface [21]. Professional athletes can also benefit from it by using it to optimise their movements. For instance, by placing nine flexible angle sensors on swimmers' wrists, shoulders, and elbows, it was possible to determine that a butterfly swimmer's elbow bending angle was too large when paddling (on average, 110° versus the ideal 90°) by analysing the movement's trajectory and making the necessary adjustments to increase paddling efficiency by 8% [17]. Body data is essential when exercise fatigue occurs in real time. Flexible sensors can use this data to assess body state, along with the root mean square (RMS) value of the sEMG signal and muscle temperature change, to create a fatigue index model ($FI = 0.6 \times RMS + 0.4 \times \Delta T$). When FI is less than 0.8, it is advised to take a break, and this model's accuracy in identifying fatigue in soccer players is 91% [22].

Flexible sensors have demonstrated an indispensable role in sports medicine and health management due to their high sensitivity, dynamic adaptability, and biocompatibility. Their use has been carried out throughout the entire 'prevention-treatment-management' chain, greatly enhancing the degree of proactive and individualised health management. This includes everything from

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objective evaluation of post-operative rehabilitation to fall risk intervention for the elderly to real-time athlete moveme The technology's implementation has permeated every link in the "prevention-treatment-management" chain, greatly enhancing the initiative and customisation of health care. Nevertheless, there are still a number of obstacles preventing the technology from scaling up. The underlying causes of these technological difficulties will be methodically examined in Chapter 4, along with workable answers and future directions based on the intersection of clinical medicine, artificial intelligence, and material science.

4. Current issues and potential paths

Although the use of flexible sensors in sports medicine shows promise, there are still many obstacles to overcome and numerous areas that need to be improved.

First of all, flexible sensors are susceptible to multi-physical field coupling interference in complex motion environments. For instance, a 20%–30% resistive sensor baseline drift is caused by ambient temperature changes of ±10℃, and electromagnetic interference, such as cell phone signals, reduces the sEMG signal-to-noise ratio to less than 15dB. Temperature self-compensating sensors can be developed in the future by integrating an NTC thermistor into the circuit and using a voltage divider circuit to correct temperature drift in real time (compensation accuracy of ±0.5°C); additionally, the noise rejection ratio of the sEMG signals can be improved up to 35 dB by combining wavelet transform and adaptive filtering algorithms [23].

The second significant issue is the lack of data fusion standards and the difficulty of personalisation. Sensors from various manufacturers have widely differing output signal formats (voltage, digital, frequency, etc.), and sharing clinical data necessitates complicated format conversions, which leads to a data utilisation rate of less than 40%. The ISO/PAS 80004-12 standard, which specifies the calibration procedure and data interface specification for flexible sensors, is being developed by the International Electrotechnical Commission (IEC) to address this issue [21]. Additionally, a cloud-based data middleware can be established to automate the normalisation of multi-source data using machine learning models [20].

Third, two elements influencing user experience are biocompatibility and comfort during prolonged wear. Traditional adhesives lose 50% of their peel strength in sweaty conditions, and certain compounds (such silver nanowires) can cause 5%–8% of contact dermatitis cases. In order to reduce skin sensitisation to less than 1%, it is crucial to develop hydrogel-based wearable interface materials with water content >70%, peel strength up to 1.2N/cm, and anti-inflammatory ingredients (such as ibuprofen microcapsules) [24]. Alternatively, painless 0.5mm micro-needle arrays can mechanically secure sensors to the skin, mitigating the effect of sweat [25].

Lastly, durability and energy supply limit the development of flexible sensors. Conventional lithium batteries are difficult to integrate into ultra-thin flexible devices due to their size (thickness > 2mm), and wireless charging efficiency is distance-limited (less than 30% efficiency at > 5cm). Energy management chips using dynamic dormancy algorithms can reduce sensor standby power consumption to 1μW, extending the endurance of a single charge to 7 days [26]. In the future, friction nanogenerator (TENG) and temperature difference electricity generator (TEG) can be fused to generate 0.8mW/cm² electricity in daily motion to meet the continuous power supply of low-power sensors (operating current <5μA).

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5. Conclusion

The main technological developments and creative uses of flexible sensors in sports medicine are methodically covered in this study. Flexible sensors outperform conventional rigid devices in terms of sensitivity, dynamic response, and biocompatibility thanks to material innovation (such as graphene composite film and self-repairing hydrogel) and structural design (bionic layering and fabric integration). Its application effect is impressive in the areas of sports injury prevention, postoperative rehabilitation monitoring, and personalised sports management: for instance, the accuracy of the ankle inversion warning reaches 92.3%, the gait assessment error is less than 3.2°, and the energy consumption prediction accuracy is improved by 58% when compared to a smartwatch. Despite the difficulties posed by multi-physical field interference and the absence of standardisation, flexible sensors are helping to shift sports medicine from "passive treatment" to "active health management" by integrating AI algorithms and digital twin technology. This allows athletes, patients, and the general public to receive full-cycle health solutions.This paper still has several issues, though. For instance, the results' generalisability is limited by the current application scenarios' reliance on clinical trial data and lack of validation of extensive real-world scenarios. Future research should concentrate on expanding the use of flexible sensors in neurological disorders and respiratory monitoring, as well as improving comparative analysis across different populations and geographical areas to provide more all-encompassing health management solutions.

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