Application of Hydrogel-Based Flexible Pressure Sensing Film in Smart Taekwondo Protective Gear

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Abstract: *The rapid development of smart sports equipment has placed higher demands on motion monitoring technology. Hydrogel-based flexible pressure sensing films, with their excellent flexibility, biocompatibility, and tunable electrical properties, provide an innovative solution for the development of smart Taekwondo protective gear. This study systematically analyzes the sensing mechanisms and mechanical properties of hydrogel materials, optimizes the film preparation process and conductive network construction strategies, and proposes a distributed sensing network design for high-dynamic impact monitoring. Through simulated impact tests and bio-mechanical validation, it is confirmed that the system can achieve accurate quantification of striking force and analysis of motion data, providing a new technical pathway for the application of flexible sensing technology in the field of competitive sports.*

Keywords: *Hydrogel; Flexible Pressure Sensing; Smart Protective Gear; Taekwondo; Impact Force Monitoring; Sensor Integration*

Introduction

Taekwondo training requires precise mechanical monitoring for technical evaluation and injury prevention. To address the limitation of traditional protective gear in providing real-time force feedback, this study develops a pressure monitoring system for smart protective gear based on hydrogel flexible sensing materials. Hydrogel serves as an ideal sensing medium due to its tissue-like properties. This study optimizes its wide-range response characteristics and interface integration processes to overcome stability challenges in high-dynamic impact environments. The research progresses through three dimensions: material properties, sensing mechanisms, and system integration. It aims to establish a flexible sensing solution suitable for Taekwondo motion monitoring, promoting the practical application of smart protective gear in sports science.

1. Fundamental Analysis of Hydrogel-Based Flexible Pressure Sensing Films

1.1 Basic Characteristics and Selection Criteria for Hydrogel Materials

Hydrogel is a hydrophilic polymer material with a three-dimensional network structure. Its unique physical and chemical properties make it an ideal candidate for flexible electronics, particularly in pressure sensing applications. The hydrophilic groups abundant on hydrogel molecular chains enable them to absorb and retain large amounts of water in aqueous environments, resulting in softness and wetness similar to biological tissues. This high water content directly leads to a low modulus of the material, allowing it to achieve mechanically compatible conformal contact with human skin or soft tissues. This is crucial for smart Taekwondo protective gear that requires close fitting to body contours.

When selecting hydrogels for pressure sensing, conductivity is the primary prerequisite for functionalization. Intrinsically conductive hydrogels can be achieved by introducing charged ions or conjugated conductive polymer chains; a more common strategy involves incorporating nano-conductive fillers such as carbon nanotubes, graphene, or metal nanowires into the polymer network to construct stable conductive pathways. Besides conductivity, mechanical properties are core to the long-term reliable operation of wearable devices. By adjusting the cross-linking density of polymer chains, selecting tougher polymer backbones, or constructing double-network structures, the strength, toughness, and fatigue resistance of hydrogels can be significantly enhanced to withstand the intense and frequent mechanical impacts potentially generated during Taekwondo practice. The environmental stability of hydrogels, including dehydration inhibition and anti-freezing properties, is also a key consideration in practical applications, typically enhanced by adding humectants, binary solvents, or constructing ionic networks.

1.2 Core Operating Mechanisms of Flexible Pressure Sensing

The functional principle of hydrogel-based flexible pressure sensing films primarily relies on physical mechanisms that convert external mechanical signals into measurable electrical signals, with the piezoresistive effect and capacitive effect being the most prevalent [1]. The piezoresistive sensing mechanism depends on the geometric deformation of the hydrogel's conductive network under pressure. When an external load is applied to the film, the structure of its internal conductive pathways changes—through shortened distances between conductive particles, increased contact points, or optimized ion transport paths—leading to a significant change in overall electrical resistance. By monitoring changes in this electrical parameter (resistance), the magnitude of the applied pressure can be indirectly quantified.

The capacitive sensing mechanism is based on the fundamental principle of a parallel-plate capacitor, using the hydrogel itself as either a compressible dielectric layer or an electrode layer. Applied pressure reduces the thickness of the hydrogel dielectric layer or alters its dielectric constant due to density changes, consequently increasing the capacitance value. Capacitive sensors typically exhibit high sensitivity to minute pressures and have low power consumption. In practical applications, the response of the sensing film often results from the synergistic contribution of multiple mechanisms. For smart Taekwondo protective gear, which must monitor impact forces across a broad range, the sensing mechanism needs to exhibit a well-defined linear response and rapid recovery capability over this wide range. The piezoresistive mechanism demonstrates distinct advantages in this scenario due to its structural simplicity and ease of signal acquisition.

1.3 Key Performance Parameters of Hydrogel Pressure Sensing Films

The evaluation of hydrogel-based flexible pressure sensing films requires adherence to a series of standardized key parameters. These parameters directly determine the feasibility and reliability of their application in smart Taekwondo protective gear. Sensitivity serves as the core metric, defined as the ratio of the change in the sensor's output signal to the variation in input pressure [2]. High sensitivity indicates the sensor's capability to effectively detect subtle physiological signals or light impact movements.

The sensing range defines the pressure interval within which the sensor can operate effectively. Taekwondo protective gear requires the sensor to maintain reliable signal output across a broad spectrum of pressures, from light contact to heavy impacts. Response time and recovery time characterize the sensor's reaction speed to the application and removal of pressure, respectively. Rapid response and recovery are crucial for capturing continuous, high-speed striking motions. Stability and durability refer to the sensor's ability to maintain consistent performance under long-term cyclic loading. This demands the hydrogel material to possess excellent mechanical resilience and structural integrity. Hysteresis describes the degree of non-coincidence between the output curves during the loading and unloading processes. Low hysteresis ensures higher consistency and accuracy in sensor readings. Furthermore, signal drift during prolonged use, performance robustness under varying environmental temperature and humidity, and biocompatibility collectively form a comprehensive parameter system for holistically evaluating hydrogel pressure sensing films. This system provides clear direction for subsequent material optimization and device design.

2. Fabrication and Optimization of Hydrogel-Based Flexible Pressure Sensing Films

2.1 Common Preparation Techniques for Hydrogel Flexible Films

2.1.1 Solution Casting and In-Situ Polymerization Techniques

The solution casting method involves forming a homogeneous prepolymer solution by dissolving polymer precursors, cross-linking agents, and functional fillers in a solvent. This solution is then cast onto a substrate and solidified through photo- or thermally initiated cross-linking to form a standalone film. This method is suitable for large-scale production, though the resulting films often exhibit limited mechanical strength and weak adhesion to the substrate.In-situ polymerization technology involves directly coating the prepolymer solution onto a flexible substrate and initiating polymerization. This process enables the hydrogel polymer chains to form physical interlocking or chemical bonding with the substrate, significantly enhancing interface stability. This technique is more suitable for the integration of flexible devices.

2.1.2 Molding Method and Microstructure Construction

The molding method utilizes templates with microstructural features to achieve precise replication of surface morphology through prepolymer solution filling and solidification. The designed microstructures can undergo greater deformation under pressure, thereby enhancing sensing sensitivity by increasing effective contact area or altering local stress distribution. The template material and structural parameters directly affect the molding accuracy and functional characteristics of the microstructures, providing an effective approach for optimizing sensor response in the low-pressure range [3].

2.1.3 Application of Additive Manufacturing Technology

Additive manufacturing technologies, such as direct ink writing, enable the precise fabrication of complex three-dimensional structures by utilizing hydrogel inks designed with specific rheological properties. This technique can produce films featuring porous, gradient, or biomimetic internal architectures. Such structures not only expand the pressure detection range of the sensor but also improve response linearity and fatigue resistance through optimized stress distribution, offering a novel approach for the integrated manufacturing of smart protective gear.

2.2 Construction of Conductive Networks and Performance Enhancement Strategies

2.2.1 Ionic Conductive Networks

Ionic conductive networks are formed by immobilizing mobile ions within a polymer network, relying on ion migration for electrical conduction. This type of conductor demonstrates high sensitivity to micro-deformations and exhibits high sensitivity under low pressure. However, its electrical signals are susceptible to variations in environmental humidity, temperature, and ion concentration, posing challenges to signal stability in dynamic impact environments.

2.2.2 Nanocomposite Conductive Networks

Nanocomposite conductive networks are constructed by dispersing conductive fillers such as carbon-based materials or metal nanowires into a hydrogel matrix, utilizing changes in contact resistance between fillers or tunneling effects for sensing. Optimizing the dispersion and spatial distribution of the fillers is crucial for building efficient conductive networks. Sensors of this type generally exhibit faster response speeds and better environmental stability.

2.2.3 Multi-Element Synergistic Conduction Strategy

The multi-element synergistic strategy constructs hierarchical conductive networks by combining nanomaterials of different dimensions or integrating ionic/electronic conduction mechanisms. For instance, compounding one-dimensional carbon nanotubes with two-dimensional MXene, or introducing electronic conductive fillers into ionic conductors, enables synergistic utilization of different materials' advantages. This approach achieves a balance of high sensitivity and stability across a broad pressure range, meeting the detection requirements for complex impact signals.

2.3 Regulation of Mechanical Properties and Interface Stability of Thin Films

2.3.1 Intrinsic Structural Design for High Strength and Toughness

Double-network hydrogels achieve a combination of high strength and high energy dissipation through the integration of a rigid covalent network and a brittle physical network. The introduction of dynamic covalent bonds or strong physical interactions as reversible cross-linking points can effectively dissipate energy under stress, significantly enhancing the material's toughness, tear resistance, and self-healing ability, thereby improving the durability of the film [4].

2.3.2 Interface Adhesion and Integration Reinforcement

The chemical anchoring method introduces covalent bonding sites through surface modification to achieve robust interfacial connections. The physical interlocking strategy utilizes the infiltration of the prepolymer solution into a porous substrate to form mechanical anchors. The integrated wetting-crosslinking process can form a gradient transition layer of crosslinking density, effectively alleviating stress concentration and preventing interfacial delamination.

2.3.3 Methods for Enhancing Environmental Stability

The introduction of high-boiling-point humectants or low-volatility solvents can effectively inhibit water evaporation. Constructing a high-concentration electrolyte system or a water-organic solvent binary system can significantly lower the freezing point, ensuring the film's flexibility and electrical conductivity in low-temperature environments, thereby guaranteeing the reliable operation of the smart protective gear across varying conditions.

3. Application Adaptation of Hydrogel-Based Flexible Pressure Sensing Films in Smart Taekwondo Protective Gear

3.1 Specific Requirements of Smart Taekwondo Protective Gear for Sensing Systems

3.1.1 Need for Broad-Range Response to High-Dynamic Impact Loads

Taekwondo striking techniques, such as side kicks and spinning kicks, generate impact pressures on protective gear characterized by high peak values and short duration. This requires the sensing system to possess a broad pressure measurement range, with an upper limit capable of capturing and measuring megapascal-level pressures generated by heavy impacts without damage. Simultaneously, the system must maintain sufficient sensitivity in the low-pressure range to effectively detect slight contacts or preparatory movements, thereby providing a complete data spectrum for technical analysis. The linearity of the sensor's pressure-electrical signal response curve is crucial, as it directly determines the accuracy of the output signal and the ease of calibration under impacts of varying intensities [5].

3.1.2 Requirement for Mechanical Robustness Under Complex Multi-Axial Deformation

When protective gear is struck, it is subjected not only to normal pressure but also to significant shear stress and tensile strain. The sensing film must withstand these multi-axial and complex mechanical loads without structural failure or performance degradation. This demands that the hydrogel material itself possesses high fracture toughness, excellent tear resistance, and good elastic recovery. After thousands or even tens of thousands of repeated impact cycles, the film's key performance parameters—such as sensitivity and baseline resistance—should not exhibit significant drift. That is, it must possess outstanding fatigue resistance to endure long-term, high-intensity training and competition schedules.

3.1.3 Requirements for Ergonomic Compatibility and Operational Environmental Stability

The integration of the sensing system must not compromise the inherent wearing comfort and flexibility of the protective gear. Therefore, the hydrogel film must possess ultra-flexibility, a low modulus, and mechanical compatibility with human skin to prevent any foreign body sensation or restriction of joint movement during athletic activity. From an environmental perspective, challenges such as athlete perspiration and variations in ambient temperature and humidity pose significant demands. The sensing system must exhibit excellent hydrophobicity or resistance to sweat corrosion, ensuring its signal output remains largely unaffected by sweat or humidity fluctuations. In low-temperature environments, the material requires anti-freezing design strategies to prevent the loss of flexibility and conductivity due to freezing, thereby guaranteeing reliable functionality across various training and competition venues.

3.2 Design of Integration Schemes for Sensing Films and Protective Gear Matrices

3.2.1 Functional Layered Structure and Interface-Reinforced Integration

An effective integration scheme involves constructing a sandwich-style layered functional structure. This structure uses the hydrogel sensing film as the core functional layer, which is bonded on both its upper and lower surfaces to flexible electrodes and the protective gear matrix via adhesive layers. The flexible electrodes typically employ conductive textiles or stretchable metal wires to ensure overall structural flexibility. The key to successful integration lies in interface reinforcement. For textile-based protective gear, the in-situ polymerization method can be applied to allow the hydrogel precursor to penetrate the fiber gaps, forming a robust physical interlock after curing. For polymer foam-based protective gear, plasma treatment or chemical coupling agents can be utilized to introduce active functional groups on the substrate surface, establishing covalent bonds with the hydrogel network. This achieves a durable chemical interfacial connection, preventing delamination under dynamic impact conditions.

3.2.2 Layout of Distributed Sensing Network and Signal Routing

To achieve spatially resolved perception of both strike location and intensity, multiple sensing units must be deployed in key impact areas of the protective gear—such as the thoraco-abdominal region of the chest protector and the tibial surface of the shin guard—forming a distributed sensing network. Each sensing unit functions as an independent sensing node. The layout must consider human kinematics and impact mechanics, positioning the nodes at locations most likely to experience contact and undergo significant deformation.

The reliability of signal extraction presents another technical challenge. Flexible flat cables or elastic conductive adhesives can be employed, using an "island-bridge" structural design to route signals from the sensing nodes to a miniaturized signal processing module integrated at the edge of the protective gear. This design places the vulnerable wiring sections in low-strain areas while allowing the sensing units to reside in high-strain zones, thereby ensuring overall circuit connectivity under large deformations.

3.2.3 Integrated Encapsulation and Comfort Assurance

To ensure the robustness of the entire system in harsh usage environments, integrated encapsulation is essential. The encapsulation material must be a highly elastic polymer film with moisture-permeable and waterproof properties, such as thermoplastic polyurethane (TPU). Through heat sealing or ultrasonic welding processes, the film is hermetically bonded with the protective gear substrate, fully enclosing the sensing units, electrodes, and internal circuits to provide waterproofing, dust prevention, and mechanical abrasion resistance. The encapsulation design must balance sealing integrity with breathability, preventing sweat accumulation inside due to complete vapor blockage or compromising the gear's inherent thermal and moisture comfort. The final integrated smart protective gear should closely resemble traditional gear in form, weight, and wearing experience, minimizing any negative impact on athletic performance introduced by the technology.

3.3 System Performance Validation for Impact Force Monitoring

3.3.1 Quasi-Static and Dynamic Calibration in Simulated Impact Environments

Performance validation must first be conducted under controlled laboratory conditions. A universal material testing machine is used to perform quasi-static compression tests on the integrated sensing units, enabling precise calibration of their sensitivity, linearity, hysteresis, and repeatability. For characterizing dynamic impact responses, pendulum impact machines or drop-weight impact testers are employed. These devices can simulate instantaneous impacts of varying energy levels. By synchronously recording the electrical signal outputs from both a reference impact force sensor and the hydrogel sensor, the system's dynamic response time, recovery time, peak capture capability, and signal fidelity under high strain rates can be thoroughly analyzed [6].

3.3.2 Specialized Movement Capture and Biomechanical Correlation Analysis

Following laboratory calibration, it is necessary to recruit volunteers for specialized movement testing. The wearers are equipped with the integrated smart protective gear and instructed to perform standardized Taekwondo striking motions, such as fixed-target strikes against the gear and interactive light-contact sparring. During this process, multimodal data acquisition equipment, including high-speed motion capture systems, inertial measurement units (IMUs), and standard force plates, is used synchronously. The electrical signals output by the hydrogel sensors are temporally correlated and cross-analyzed with kinematic data, such as striking speed and acceleration, and kinetic data, such as ground reaction forces recorded by the force plates. This process validates the correlation between the sensor readings and the biomechanical effects of the strikes, thereby converting the sensor outputs into impact force estimates with clear physical significance.

3.3.3 Long-Term Usage Reliability and Environmental Adaptability Assessment

The long-term reliability of the system must be evaluated through accelerated aging tests and cyclic endurance testing. The integrated protective gear samples undergo tens of thousands of repeated impact cycles, with periodic monitoring of the attenuation of their key performance parameters to assess their service life. Environmental adaptability testing requires examining the system's stability under different temperature and humidity conditions. This involves investigating its signal drift in high-temperature and high-humidity environments and verifying its anti-freezing properties and performance consistency in low-temperature settings. Furthermore, the functional integrity of the system must be tested after exposure to sweat immersion, simulated rain splashing, and repeated donning/doffing stretching. All these validation data collectively form the decision-making basis for assessing whether the smart protective gear can transition from the laboratory to practical application scenarios.

Conclusion

This study systematically investigates the application potential of hydrogel-based flexible pressure sensing films in smart Taekwondo protective gear, providing an in-depth exploration spanning material properties, conduction mechanisms, preparation processes, system integration, and performance validation. Research has shown that the mechanical strength and durability of the films can be significantly enhanced through dual-network structural design and dynamic cross-linking strategies. The multi-element synergistic conduction strategy can balance the sensing system's sensitivity, stability, and broad-range response capability. Furthermore, integration schemes based on in-situ polymerization and interface reinforcement effectively ensure the robust bonding between the sensing units and the protective gear substrate. Experimental validation confirms that the designed sensing system can accurately capture dynamic impact signals and establish effective correlations with biomechanical parameters. Future research may focus further on developing the self-healing properties of hydrogel materials, integrating multi-modal sensing information, and constructing lightweight wireless transmission systems to promote the comprehensive application of smart protective gear in athletic training, public fitness, and rehabilitation monitoring.

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