

Review

# Multidimensional signal decoding via anisotropic hydrogels for motion monitoring

Yuanyuan Wu,<sup>1,2</sup> Yonghuan Chen,<sup>1,2</sup> Bingtian Su,<sup>2,\*</sup> and Fengyu Li<sup>1,2,\*</sup>

<sup>1</sup>College of Chemistry and Materials Science, Jinan University, Guangzhou 510632, China

<sup>2</sup>Guangdong Provincial Key Laboratory of Speed Capability Research, Su Bingtian Center for Speed Research and Training, Jinan University, Guangzhou 510632, China

\*Correspondence: 343472471@qq.com (B.S.), lifengyu@jnu.edu.cn (F.L.)

<https://doi.org/10.1016/j.xcrp.2026.103117>

## SUMMARY

Driven by demands in sports competition, rehabilitation training, and multifunctional electronic skin, wearable hydrogel sensors for continuous real-time monitoring of complex activities are being designed and developed. The biomimetic design of anisotropic hydrogel sensors (AHSs) enables the decoupling of complex motion information and multiscale sensing, offering a promising approach to enhance the efficiency of motion monitoring. This paper reviews recent advances in AHSs for motion monitoring. First, we systematically introduce the material types and performance tuning strategies for anisotropic hydrogels, where performance tuning primarily involves interfacial and mechanical design, targeted optimization of electrical properties, and synergistic regulation of multiple functions. We also summarize various synthesis methods for anisotropic hydrogels (including ice templating, 3D printing, electrospinning, and molecular self-assembly). Furthermore, we delve into the application of AHSs in motion sensing from a multiscale perspective. Finally, we explore the challenges and future development directions for AHSs.

## INTRODUCTION

### Significance

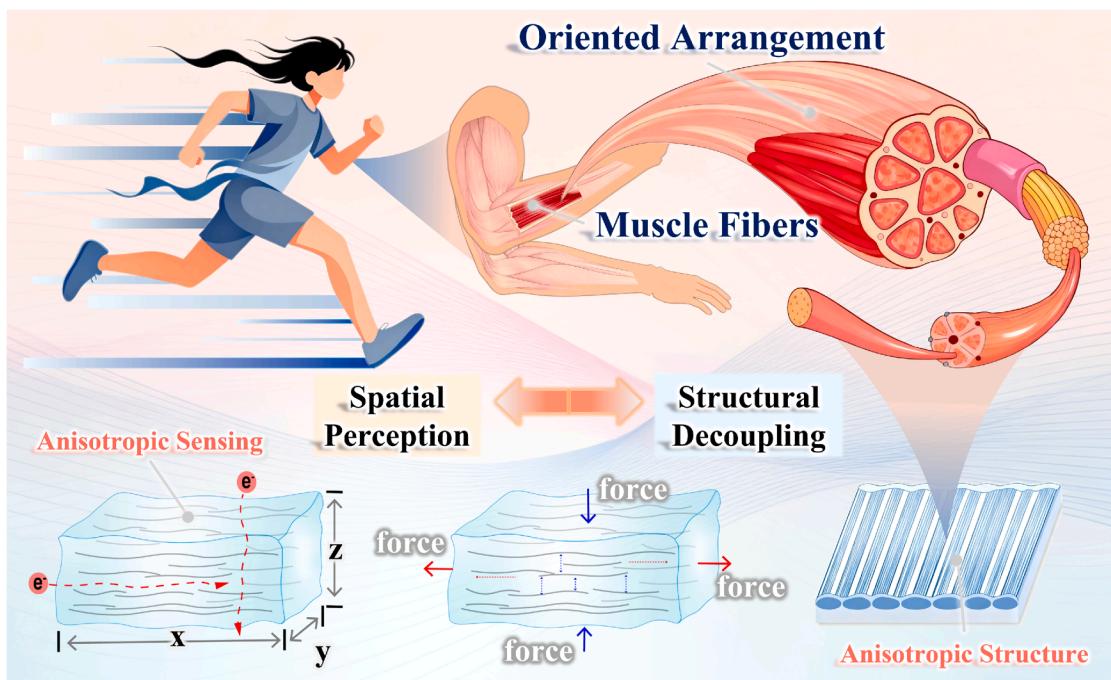
Human movement represents one of the most intricate and sophisticated biomechanical processes within living organisms.<sup>1</sup> The multidimensional signals generated span all levels, from fundamental physiological states to higher-order neural regulation.<sup>2,3</sup> The precise monitoring of these signals holds critical significance across competitive sports, athletic rehabilitation, human-machine interaction, and advanced diagnostics.<sup>4</sup> Consequently, there is a growing demand for continuous, real-time monitoring via wearable devices to enhance athletic performance and assess health status.<sup>5–7</sup> Simultaneously, human bio-systems (such as muscles, skin, and articular cartilage) exhibit distinct hierarchical structures, with anisotropic orientations extending to the macroscale.<sup>8–10</sup> For example, the mechanism of muscle contraction relies on the anisotropic arrangement of actin and myosin within sarcomeres.<sup>11–14</sup> This ordered structure is crucial for generating unique anisotropic functions, such as directional movement and shock absorption.<sup>15–17</sup> Among humanity's diverse physiological sensing mechanisms, electrophysiological signals offer rapid responses to the state of internal tissues or organs.<sup>18–21</sup> However, traditional rigid electronic sensors struggle to meet the demands of next-generation wearables due to inherent limitations such as mechanical modulus mismatch, poor comfort, and inability to capture microphysiological signals.<sup>22,23</sup> The emergence of flexible electronics, partic-

ularly hydrogel-based sensors, offers a highly promising solution to this challenge.<sup>24,25</sup>

Hydrogels constitute 3D network structures formed by hydrophilic polymers, possessing sufficient flexibility to function akin to natural tissues.<sup>26,27</sup> Owing to their high water content, excellent biocompatibility, and tissue-like mechanical properties, hydrogels are regarded as ideal materials for constructing "electronic skin." However, the vast majority of hydrogel sensors are based on isotropic designs, in which the random polymer network confers identical physical properties in all directions, limiting their application in monitoring complex movements.<sup>28,29</sup> This often leads to signal coupling distortion and high misrecognition rates. Furthermore, their mechanical properties mismatch with naturally anisotropic human tissues, readily inducing interfacial stress concentrations. This results in motion artifacts and wearing discomfort.<sup>30–33</sup> Therefore, anisotropic hydrogels (distinct physicochemical properties in different spatial orientations<sup>34,35</sup>) are emerging as a key strategy to address these challenges. By mimicking the ordered microstructures of biological tissues, anisotropic hydrogels achieve directional dependence in mechanical and electrical properties, providing a physical foundation for directional capture and separation analysis of motion signals.<sup>36–40</sup>

Inspired by linearly arranged muscle fibers and layered bundle crosslinking by hydrogen bonds, human muscles exhibit outstanding mechanical properties and anisotropy.<sup>41–44</sup> This review schematically illustrates the relationship between muscle





**Figure 1. Bioinspired design and motion monitoring of anisotropic hydrogel sensors**  
AHS, anisotropic hydrogel sensor.

fiber arrangement, anisotropic hydrogel design, and motion monitoring, elucidating the bioinspired design rationale of anisotropic hydrogels and their pivotal role in enhancing motion-monitoring efficiency (Figure 1). More and more anisotropic hydrogels with directional internal networks are fabricated. Their ordered structure endows anisotropic functional properties. When integrated into motion-monitoring devices, these anisotropic hydrogels enable efficient signal decoupling (e.g., distinguishing movements in different directions),<sup>45,46</sup> thereby enhancing the accuracy and reliability of motion signal acquisition and analysis. Therefore, we summarize the latest developments in anisotropic hydrogel sensors (AHSs) across four dimensions (Figure 2). We first explore the material types of AHSs for motion monitoring based on their anisotropy formation mechanisms and core functional components. Second, we investigate performance tuning strategies and corresponding fabrication methods to meet complex motion-monitoring demands, and we focus on the multi-scale applications of AHSs, such as microphysiological signal acquisition, joint motion analysis, and on-site motion monitoring. Finally, we outline future development directions of AHSs.

### Evolution

Given the rapid advancement of AHSs in the field of motion monitoring, a systematic review of this emerging area is warranted. Recently, their development trajectory has followed the classic innovation path of “demand-driven, technology-propelled,” progressing from researching synthetic methods for constructing ordered structures to integrating diverse functional properties and achieving practical applications. As illustrated in Figure 3,<sup>36,47–59</sup> as early as late 2004, Kaneko et al.<sup>47</sup> achieved oriented

PVA@AHSs by chemically crosslinking the network chains of freeze-thawed polyvinyl alcohol (PVA) hydrogels under mechanical stretching conditions, followed by immersion in salt solutions to fix structural orientation.<sup>25</sup> Between 2004 and 2021, while enhancing the mechanical properties of AHSs, researchers explored synergistic effects of reactions, though applications in sensing remained nascent. Haque and colleagues synthesized a macroscopically sized multifunctional anisotropic hydrogel that exhibits reversible and tunable structural color under controlled stress/strain conditions, enabling its application in advanced stress/strain sensors.<sup>49</sup> Since 2021, there has been a conscious effort to leverage anisotropy for the directional resolution of sensing characteristics. A stretchable, breathable, and multimodal hydrogel sensor developed by Wang and colleagues enables wireless human-machine interaction systems, and it can be integrated into smart prosthetics, transmitting data to terminals via Bluetooth modules for intelligent gesture recognition and real-time temperature monitoring.<sup>55</sup> The coordinated development of multiple anisotropy strategies has commenced, with wireless technology enabling motion detection and propelling motion monitoring toward systematic applications. Beginning in 2024, the integration of anisotropic design with artificial intelligence and computational algorithm training has accelerated the advancement of smart wearables,<sup>57</sup> opening possibilities for transitioning from “single-point sensing” to “whole-body motion digitization.”

### MATERIAL TYPE

The primary advantage of AHSs lies in their directionally engineered structure or material composition, enabling highly



Figure 2. Material types, design strategies, and multiscale applications of AHSs

sensitive responses to mechanical signals in specific directions, such as tension, bending, and torsion. Simultaneously, they retain the inherent flexibility, biocompatibility, and hydrophilicity characteristic of hydrogels. Materials can be systematically classified based on the mechanism of anisotropy formation and the primary function of their active components.

#### Structural anisotropy

The structure and functions of materials are key factors determining their application scenarios. In recent years, based on accumulated research in the field of hydrogel structure construction and functional design, increasing attention has been paid to the integration of internal properties with structural design.<sup>60–62</sup> Structural anisotropy is the most intuitive and common type, achieved by constructing ordered physical structures (such as fibers, lamellae, and pores) at the micro- and nano-scales.

Inspired by the structural characteristics of muscle tissue, Lin et al.<sup>56</sup> prepared an anisotropic PVA/polyacrylic acid/Fe<sup>3+</sup> (PVA-PAA/Fe<sup>3+</sup>) hydrogel with an oriented structure through a combination of pre-stretching and ion crosslinking (Figure 4A). Cross-sectional SEM images of the isotropic hydrogel showed no evidence of oriented fiber structures, whereas side views of the pre-stretched PVA-PAA/Fe<sup>3+</sup> hydrogel revealed distinct oriented fiber structures, with the polymer

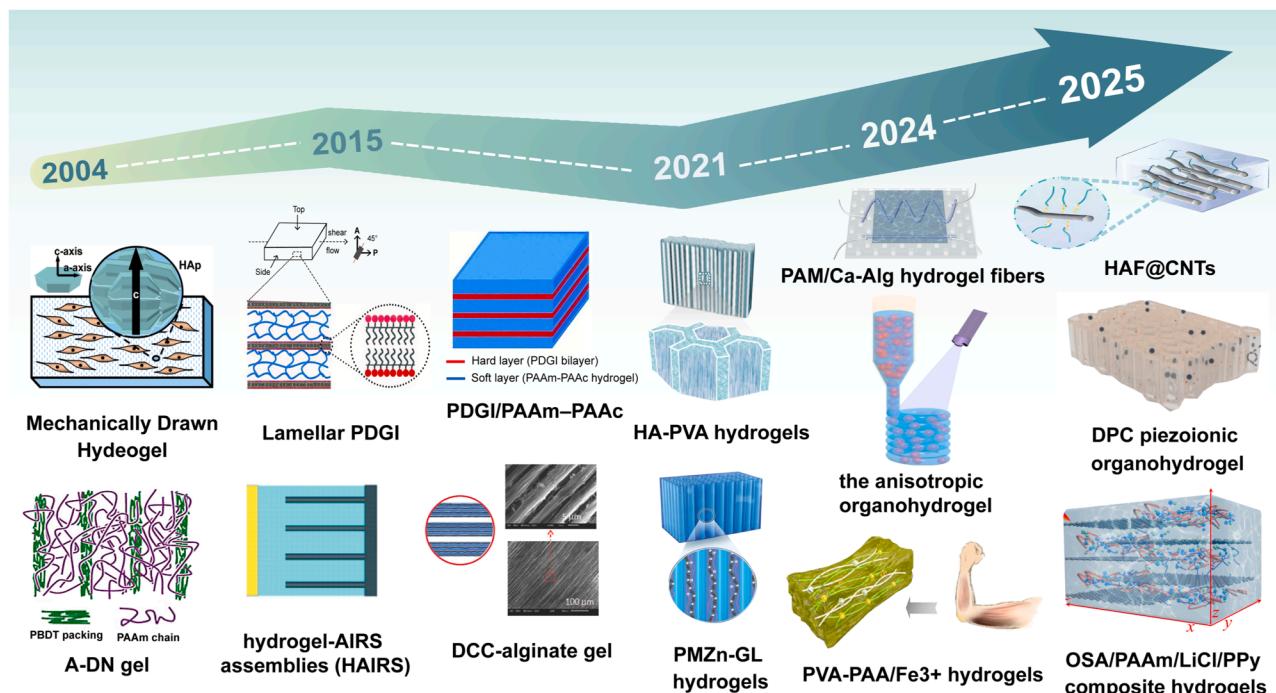
network linearly aligned along the pre-stretching direction. He and colleagues constructed a photonic bamboo scaffold with an anisotropic porous structure by *in situ* modifying natural bamboo lignin.<sup>63</sup> Subsequently, flexible polyacrylamide (PAM) was *in situ* polymerized within this scaffold to prepare an anisotropic bamboo/PAM composite hydrogel featuring an internal oriented microstructure (Figure 4B), characterized by an internally oriented microstructure. Wang et al.<sup>64</sup> employed thermal stretching and directional freezing techniques to align PVA chains along the stretching direction, forming anisotropic microstructures within PVA/NaCl hydrogels (Figure 4C). Concurrently, they constructed anisotropic ion channels based on PVA chain orientation, endowing the hydrogel with anisotropic sensing properties. Ouyang et al.<sup>65</sup> prepared gradient anisotropic hydrogels with directional diffuse crosslinking of carboxymethyl cellulose (CMC) with aluminum ions and applied them to measure deformation. Figure 4D demonstrates the presence of gradient layered structures and directional channels in the gradient CMC@AHS.

#### Electrical anisotropy

Electrical anisotropy refers to the significant variation in a material's electrical conductivity across different orientations, exhibiting direction-dependent conductivity. This property is crucial for decoupling multidimensional electrical signals. For instance, Chen and colleagues designed muscle-inspired anisotropic conductive hydrogels by combining pre-stretching and ion crosslinking strategies.<sup>66</sup> These directionally oriented, anisotropic conductive hydrogels were assembled into AHSs exhibiting enhanced directional ion conduction, endowing the hydrogels with electrochemical performance along specific orientations. Feng et al.<sup>54</sup> developed anisotropic MXene conductive hydrogels via directed freezing to confer superior mechanical and electrochemical properties in specific directions. Qi and colleagues proposed a strategy significantly enhancing the electrical anisotropy of hydrogel materials.<sup>67</sup> Highly oriented Janus nanoribbons were employed as building blocks to avoid interactions between conductive and insulating materials, resulting in highly anisotropic conductive hydrogel materials.

#### Other types

The functional anisotropy manifests directly as directional dependence in sensing performance, typically arising from



**Figure 3.** The evolution of anisotropic hydrogel materials over the past two decades

the combined effects of the aforementioned mechanisms. Prachishree and colleagues report a strategy for fabricating anisotropic hydrogel materials featuring dual physical crosslinking (hydrophobic association and metal-ion ligand crosslinking) and their potential application in anisotropic resistive strain sensing.<sup>68</sup> They further demonstrated the application potential of these hydrogels in anisotropic resistive sensing and anisotropic actuation. AHSs exhibited enhanced sensitivity in the direction parallel to the pre-stretch orientation, with the gauge factor (GF) values along the parallel direction approximately doubling compared to the perpendicular direction within the 20%–50% strain range. Li et al.<sup>69</sup> developed carbon-fiber-reinforced hydrogels exhibiting exceptionally high anisotropic sensitivity and thermoresponsive shape deformation. Strain sensitivity in the parallel direction (specific coefficient GF = 647) markedly exceeded that in the perpendicular direction (GF = 15). Furthermore, magnetically anisotropic hydrogels, achieved by introducing magnetically oriented nanomaterials, demonstrated significantly differential magnetic responses across different orientations. Inspired by mussels, Yan et al.<sup>70</sup> developed anisotropic hydrogels through a simple yet effective magnetic field alignment strategy, wherein magnetically aligned cellulose/polydopamine composites serve as the key component. Lamellar nanocomposites replace conventional nanoparticles or nanowires, with their high-level alignment conferring unique anisotropy to the hydrogel. This anisotropic hydrogel facilitates assembly into multifunctional wearable devices for monitoring both large-scale and subtle human movements. Chen et al. reported a series of anisotropic PAM hydrogels that oriented 2D magnetic bilayers under weak rotating mag-

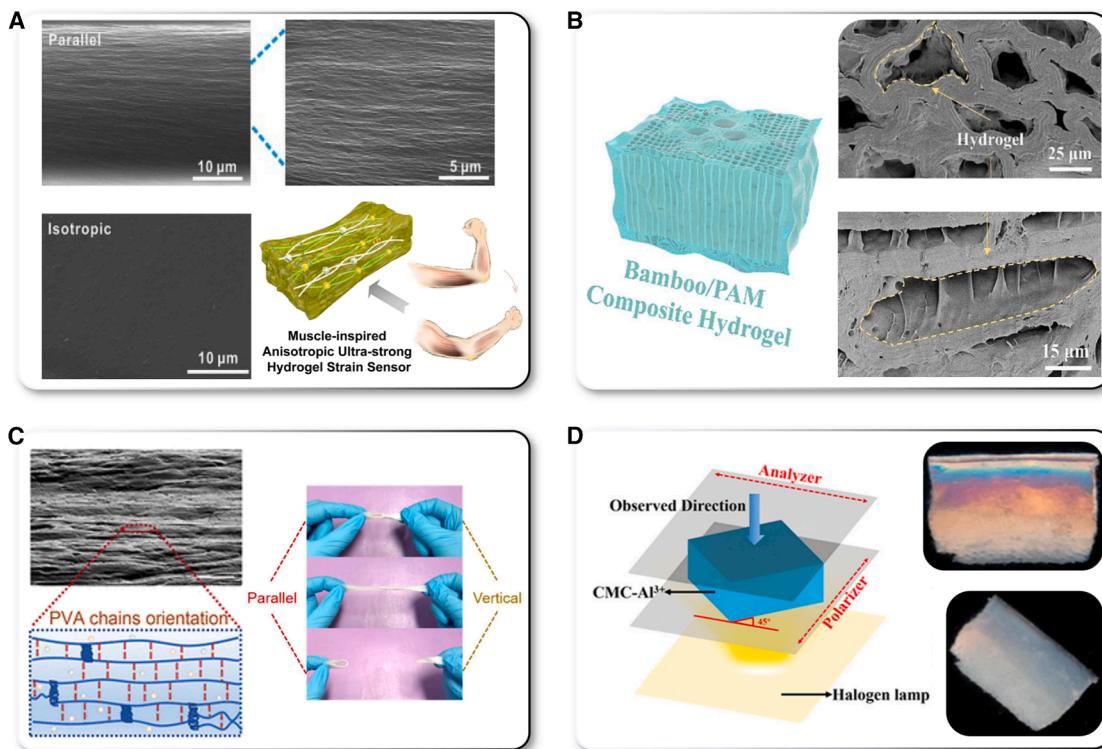
netic fields, subsequently polymerizing to fix the ordered structure.<sup>71</sup>

## PERFORMANCE TAILORING

The first step in fabricating AHSs involves constructing anisotropic structures, with the core challenge being precisely controlling sensing performance to meet the demands of complex motion monitoring. Therefore, the following sections will detail how to optimize interfaces and mechanical properties, electrical properties, and multi-performance synergies.

### Interfacial and mechanical performance

Achieving comfortable and stable monitoring during physical activity requires self-healing hydrogels to form a symbiotic interface with human tissues while exhibiting matching mechanical properties.<sup>72</sup> Duan and colleagues utilized bio-based cellulose and lignin as building blocks to prepare robust, conductive, and asymmetrically bonded Janus hydrogels via sequential casting and *in situ* polymerization (Figure 5A).<sup>73</sup> The non-tacky top layer combines cellulose dissolved in a zinc chloride solution with acrylic acid and a high-viscosity initiator, delivering outstanding anti-soiling properties and conductivity. A tacky bottom layer is formed using a low-viscosity sodium lignosulfonate-acrylamide solution with an initiator, providing exceptional elasticity and skin adhesion. An interpenetrating polymer network formed by specific monomers and crosslinkers polymerizing at the interlayer interface endows the double-sided hydrogel with robust interfacial strength. Chen et al.<sup>57</sup> fabricated a highly absorbent alginate fiber composite gel (HAFG@CNTs)



**Figure 4. Structures of anisotropic hydrogels**

(A) Cross-sectional SEM comparison between isotropic hydrogel and anisotropic PVA-PAA/Fe<sup>3+</sup> hydrogel. Reproduced with permission from Lin et al.<sup>56</sup> Copyright 2024, Elsevier.

(B) The internal structure of the composite hydrogel prepared using a photonic bamboo skeleton with a graded anisotropic porous structure exhibits directional alignment. Reproduced with permission from He et al.<sup>63</sup> Copyright 2024, Elsevier.

(C) PVA/NaCl hydrogels exhibit anisotropic microstructures. Reproduced with permission from Wang et al.<sup>64</sup> Copyright 2022, ACS Publications.

(D) Gradient layered structures and oriented channels exist within CMC hydrogels. Reproduced with permission from Ouyang et al.<sup>65</sup> Copyright 2022, ACS Publications.

with a muscle-like structure. Due to the fiber-binder interference employed, the tensile strength of HAFG@CNTs was significantly enhanced, exhibiting anisotropic mechanical properties with a modulus and toughness in the parallel fiber direction that were 2.31 and 3.75 times higher than those in the perpendicular fiber direction, respectively.

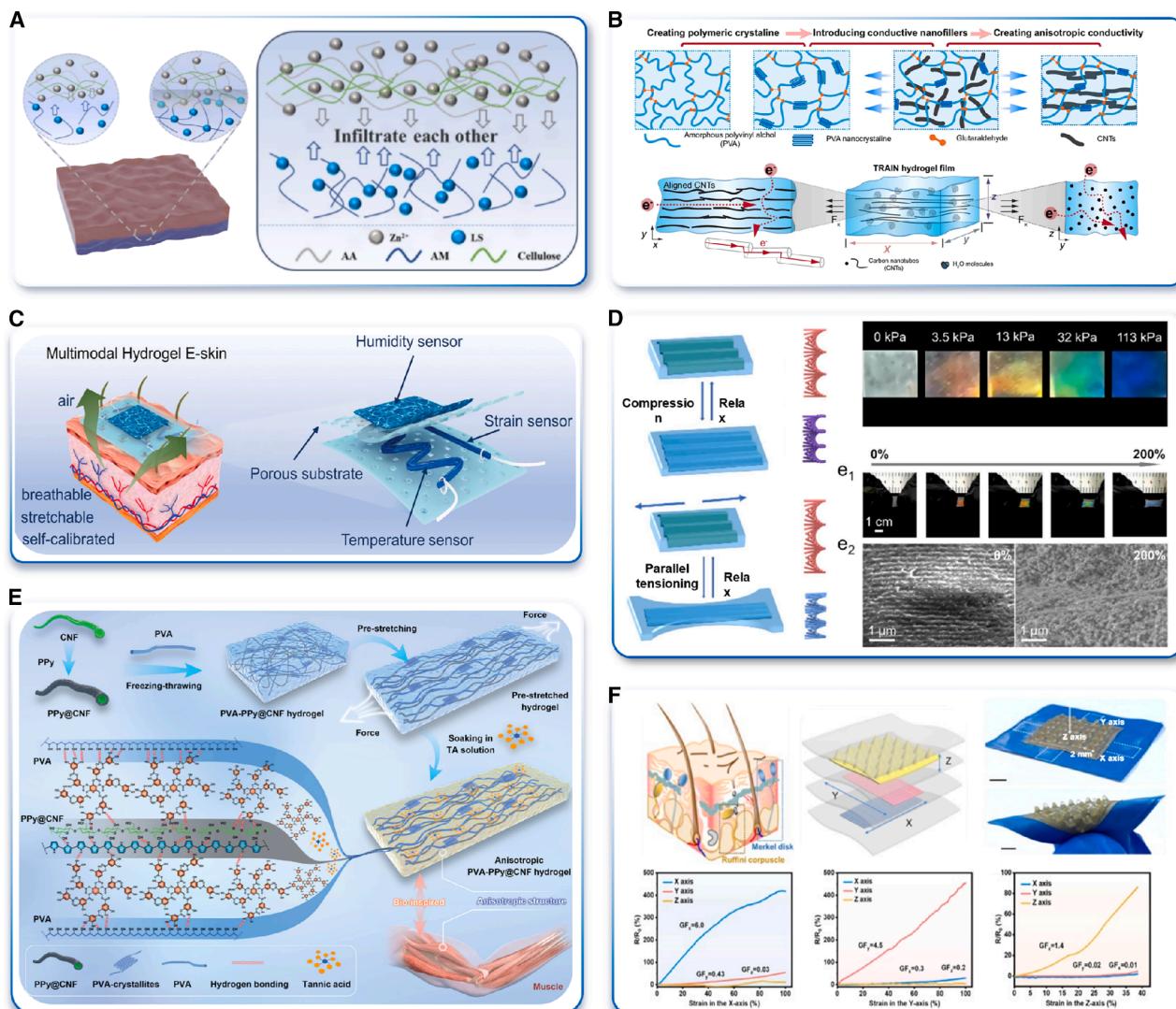
### Electrical properties

The anisotropy of electrical properties forms the physical basis for signal decoupling. Leveraging the self-alignment characteristics of nanofillers in polymers under repeated stretching, Huang and colleagues incorporated high-aspect-ratio conductive carbon nanotubes into semi-crystalline PVA hydrogels to construct electrically anisotropic filtration channels.<sup>74</sup> They further observed that along the cyclic stretching direction, the axial orientation of the aligned nanofillers and the corresponding anisotropic impedance gradually weakened, while the anisotropic conductivity aligned with the stretching direction significantly increased after cyclic stretching (Figure 5B). Jiang et al.<sup>77</sup> constructed a wearable multidirectional sensing system capable of decoupling and identifying in-plane strain/pressure within a segmented embedded hydrogel (SEH). The SEH exhibits anisotropic electrical con-

ductivity at the macroscopic level due to its embedded anisotropic local structures.

### Multi-performance cooperation

The practical application environment for motion monitoring is complex, often requiring the coordination and trade-offs of multiple functionalities such as mechanical, electrical, and adhesive properties.<sup>78–80</sup> Human skin possesses intricate sensors for perceiving 3D environmental stimuli, making skin-inspired flexible sensors with multidimensional and directional sensing capabilities highly promising.<sup>81</sup> Wang and colleagues designed microstructural hydrogels with distinct properties and porous elastomer encapsulation membrane structures featuring layered framework designs to develop a stretchable, breathable, and multimodal electronic skin capable of self-calibrated measurements for any two parameters among strain, temperature, and humidity (Figure 5C).<sup>55</sup> Zhang et al.<sup>75</sup> reported the synthesis and structure of an ion-conductive hydrogel based on cellulose nanocrystals (Figure 5D). This material exhibits anisotropic mechanical color changes and mechanical resistivity characteristics, showing promise as a multidirectional, multimodal anisotropic strain sensor for motion detection.



**Figure 5. The interfacial and mechanical, electrical, and synergistic multiple properties in AHSs**

(A) Schematic of an asymmetric Janus hydrogel. Reproduced with permission from Duan et al.<sup>73</sup> Copyright 2025, Elsevier.

(B) The incorporation of high-aspect-ratio conductive carbon nanotubes enhances the anisotropic electrical conductivity of hydrogels. Reproduced with permission from Huang et al.<sup>74</sup> Copyright 2025, Springer Nature.

(C) A stretchable, breathable, and multimodal electronic skin. Reproduced with permission from Wang et al.<sup>55</sup> Copyright 2024, John Wiley & Sons.

(D) CNC-based ion-conductive hydrogels exhibit anisotropic mechanical color change and mechanical resistivity. Reproduced with permission from Zhang et al.<sup>75</sup> Copyright 2025, Elsevier.

(E) Hydrogel networks exhibiting anisotropic adhesive properties and direction-dependent electrical conductivity. Reproduced with permission from Lin et al.<sup>76</sup> Copyright 2024, John Wiley & Sons.

(F) A wearable multilayer AHS. Reproduced with permission from Li et al.<sup>36</sup> Copyright 2024, Elsevier.

Lin and colleagues incorporated tannic acid into hydrogel networks, permanently fixing their layered anisotropic structures through multiple hydrogen bonds.<sup>76</sup> This endowed the hydrogels with superior mechanical properties (tensile strength of 11.41 MPa and toughness of 12.44 MJ·m<sup>-3</sup>), anisotropic cohesive strength, and direction-dependent conductivity (Figure 5E). Li et al.<sup>36</sup> developed a wearable multilayer AHS by macro-assembling microstructurally anisotropic organic hydrogel sensing units with strong interfacial adhesion, mimicking the skin's ability

to detect specific stimuli from different directions. Each sub-sensor responds to strain or stress along the x, y, or z axis (Figure 5F). The assembled AHS can directionally distinguish external forces and recognize human movements. Qi et al.<sup>82</sup> constructed Janus nanoribbon hydrogel films integrating dual functionalities of conductive and fluorescent anisotropy, demonstrating outstanding sensitivity in real-time monitoring.

In summary, performance regulation serves as the pivotal component for tailoring anisotropic hydrogels to meet

motion-monitoring requirements. Diverse regulatory strategies have converged upon three core objectives: interfacial and mechanical performance, electrical properties, and multi-performance cooperation. These approaches have yielded distinct technical pathways, each exhibiting pronounced specificity in its applicable scenarios and limitations. Interfacial and mechanical performance regulation strategies, by optimizing tissue compatibility and mechanical adaptability, are better suited for scenarios prone to interfacial stress or mechanical fatigue, such as skin-adherent long-term monitoring and high-intensity sports. However, multilayer structural designs may face risks of interfacial delamination, and the long-term stability of natural biomass-based systems requires further validation.<sup>36,57,72</sup> The directional electrical performance optimization strategy focuses on targeted signal capture and decoupling, making it an ideal choice for monitoring microphysiological signals and multi-degree-of-freedom joint movements. However, directional conductive networks are prone to structural relaxation under complex deformations, potentially leading to sensitivity degradation.<sup>74,77,83</sup> Multi-performance synergistic optimization strategies balance mechanical, electrical, and responsiveness properties to adapt to complex scenarios such as dynamic motion monitoring and extreme environments. However, the introduction of multiple components and structures often increases fabrication complexity, and synergistic balancing between certain functions remains a challenge requiring further breakthroughs.<sup>55,75,76,82</sup>

## MATERIAL SYNTHESIS STRATEGIES

### Micro-nano-structural engineering

Through physical templating or advanced manufacturing techniques, ordered structures are directly sculpted. By precisely controlling the microstructure and spatial arrangement of materials through physical means, the structural order is tailored to meet functional requirements with precision. Concurrently, leveraging interfacial interactions and structural synergistic effects enhances the material's mechanical stability and functional response efficiency.<sup>84–87</sup> Qi and colleagues employed parallel electrospinning to fabricate highly oriented Janus-like nanoribbons, ultimately achieving conductive, fluorescent, and anisotropic bifunctional Janus-like nanoribbon hydrogel array films (Figure 6A).<sup>82</sup> Zhang et al.<sup>88</sup> employed extrusion-based 3D printing and solvent exchange to fabricate organic gels exhibiting rapid self-healing, exceptional stretchability, conductivity, and freeze resistance (Figure 6B). Jiang and colleagues proposed a simplified strategy to enhance the mechanical properties of embedded segmented structures.<sup>77</sup> By utilizing structures with inherent anisotropy to achieve structural decoupling, the constructed multidirectional AHS can sense and precisely identify tensile and compressive strains in orthogonally oriented planes (Figure 6C). Feng et al.<sup>54</sup> employed directional cryopreservation to fabricate hydrogels with internally oriented structural order. Li et al.<sup>36</sup> utilized 3D printing to assemble precisely engineered organic hydrogel precursor solutions with extrusion-direction-dependent rheological properties into multidimensional flexible AHSs capable of distinguishing strain directions and recognizing human movements. Hu stabilized anisotropic structures formed

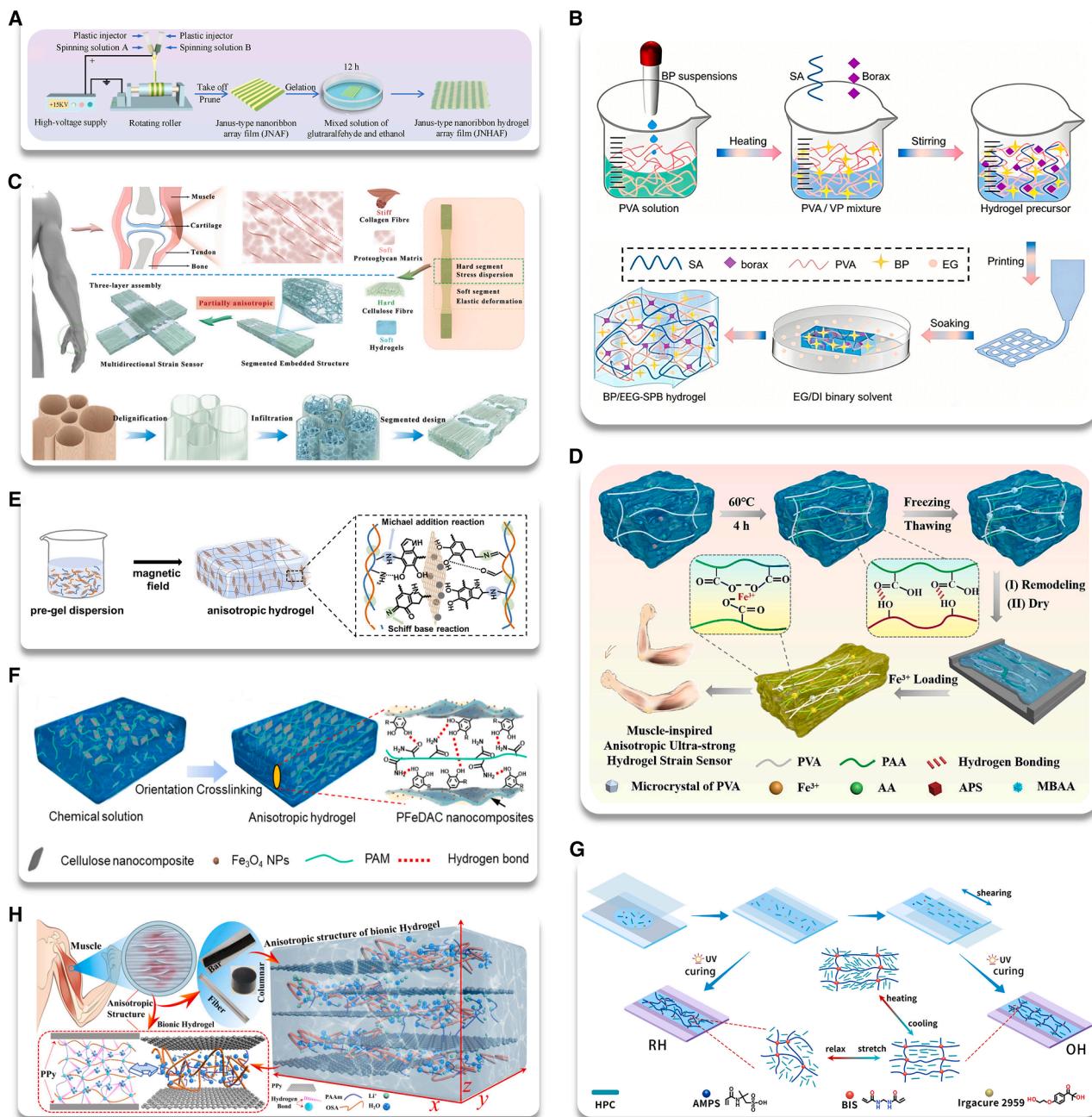
by cryogenic casting through a combined strategy of salting-out-assisted UV curing.<sup>89</sup> The multifunctional conductive organic hydrogels produced by this method exhibit toughness, long-term adhesion, and fatigue resistance, enabling precise and reliable detection of complex movements.

### Induced orientation in physical fields

This type of synthesis strategy employs external physical fields (such as mechanical forces, electric fields, and magnetic fields) to align the polymer chains, nanofillers, or microstructures within the hydrogel along a specific direction.<sup>92,93</sup> Lin et al.<sup>56</sup> prepared anisotropic, ultra-high-strength conductive hydrogels via tensile remodeling and ionic coordination crosslinking (Figure 6D). Strong magnetic responsiveness facilitates the formation of oriented structures within hydrogels under magnetic fields.<sup>94,95</sup> Li and colleagues utilized magnetoelectric graphene nanosheets as an orientation component to fabricate hydrogels exhibiting anisotropic mechanical and conductive properties (Figure 6E).<sup>90</sup> Yan et al.<sup>70</sup> employed a simple yet effective magnetic-field-oriented strategy to fabricate hydrogels exhibiting strong adhesion and anisotropic properties (Figure 6F). External physical fields provide directional driving forces that disrupt the random distribution within materials, prompting functional components to align orderly along the force direction or field gradient.<sup>96–98</sup> This forms directional conduction pathways or mechanical support networks. Such directed alignment not only enhances material performance strength in specific orientations but also optimizes functional transfer efficiency through component synergy, enabling anisotropic performance regulation.<sup>56,70</sup>

### Inner-driven anisotropy

In addition to the two types of synthetic strategies mentioned above,<sup>83,99,100</sup> the formation of ordered structures through spontaneous intermolecular interactions and self-assembly is also a common method for preparing anisotropic hydrogels. Typically, this relies on the spontaneous synergistic interaction of non-covalent bonds, such as intermolecular hydrogen bonds and hydrophobic forces, to drive component self-assembly into ordered microstructures.<sup>101,102</sup> Concurrently, macroscopic control mechanisms further guide the directionality of this self-assembly process. This combination of intrinsic driving forces and external regulation ensures structural stability while endowing the material with anisotropic mechanical and functional properties, thereby achieving synergistic optimization of structure and performance.<sup>103,104</sup> Shi and colleagues utilized mechanical shearing and UV curing to obtain large-area, single-domain anisotropic hydrogels (Figure 6G).<sup>91</sup> Wang and colleagues reported a solvent-exchange-assisted wet-stretching strategy to prepare anisotropic fiber-based multifunctional hydrogels.<sup>105</sup> The added glycerol forms hydrogen bonds with PVA chains, spontaneously creating anisotropic structures through intermolecular forces between PVA chains. Bao and colleagues employed molecular self-assembly to integrate sodium alginate with two unit-chain conductive materials (poly(pyrrole) and LiCl) into a precursor solution.<sup>59</sup> Unidirectional rotation applied shear stress to this solution, yielding a conductive hydrogel with a layered structure and anisotropic properties (Figure 6H). In segmented-embedded hydrogels developed by Jiang



**Figure 6. Fabrication of AHSs**

- (A) Preparation of AHS via parallel electrospinning. Reproduced with permission from Qi et al.<sup>82</sup> Copyright 2025, Elsevier.
- (B) Organic gels were prepared using extrusion-based 3D-printing technology and the solvent displacement method. Reproduced with permission from Zhang et al.<sup>88</sup> Copyright 2024, Elsevier.
- (C) Synthesis of AHS by utilizing the inherent anisotropy of embedded structures via the template method. Reproduced with permission from Jiang et al.<sup>77</sup> Copyright 2023, John Wiley & Sons.
- (D) Preparation of AHS via stretch-induced remodeling. Reproduced with permission from Lin et al.<sup>56</sup> Copyright 2024, Elsevier.
- (E and F) Under the influence of a magnetic field, a directional structure forms within the hydrogel. Reproduced with permission from Li et al.<sup>90</sup> Copyright 2023, Elsevier. Reproduced with permission from Yan et al.<sup>70</sup> Copyright 2022, Elsevier.
- (G) Obtaining AHS through mechanical shear forces. Reproduced with permission from Shi et al.<sup>91</sup> Copyright 2023, ACS Publications.
- (H) Preparing layered structures and AHSs via molecular self-assembly. Reproduced with permission from Bao et al.<sup>59</sup> Copyright 2025, Elsevier.

et al.,<sup>77</sup> hard and soft segments are tightly integrated through macroscopic mechanical topology and hydrogen bonding, enhancing overall ductility while preserving partial anisotropic structures of the embedded materials.

#### Comparative analysis and research trends

The construction of anisotropic structures is pivotal to achieving directional functionality in hydrogels. Current approaches fall into three broad categories: micro/nano-structuring engineering, external field-induced orientation, and internally driven anisotropy.<sup>106</sup> Each exhibits distinct advantages and limitations regarding preparation efficiency, structural controllability, and scalability potential. The progress is advancing toward precision, low-cost implementation, and multifunctional integration.<sup>107–109</sup> From the perspective of technical principles and performance, micro/nano-structuring enables precise structural control at the micrometer or even nanometer scale (e.g., electrospinning,<sup>82</sup> 3D printing,<sup>88</sup> and the directed alignment of Janus nanoribbons<sup>67</sup>). However, these methods are typically characterized by high equipment dependency and complex processes. Recent research has simplified the process through the combined use of cryogenic precipitation and UV curing<sup>89</sup> while simultaneously enhancing structural stability. Externally applied forces for oriented structures (e.g., magnetic-field-induced alignment techniques<sup>90</sup>) offer non-contact advantages, while mechanical stretching strategies further enhance structural orientation and uniformity. Internally driven anisotropy relies on material intrinsic properties, eliminating complex external apparatus and enabling large-scale fabrication, though structural controllability remains limited, and “molecular template regulation” (e.g., sodium-alginate-induced oriented aggregation of poly(pyrrole))<sup>59</sup> has significantly enhanced structural order. Core breakthroughs in construction strategies lie in multiscale structural co-construction, such as (1) integration of nanoscale fiber alignment with macroscopic layered structures to achieve precise translation from micro/nano-structures to macroscopic properties; (2) dynamically tunable anisotropy, where photo- or thermo-responsive material design enables reversible orientation regulation in hydrogels under external stimuli, catering to dynamic motion-monitoring requirements; and (3) green and low-cost fabrication, utilizing natural biomass materials (e.g., bamboo<sup>63</sup>) alongside simplified processes to reduce production costs and enhance biocompatibility. Table 1 clearly demonstrates that anisotropy-building strategies achieve targeted optimization of sensing performance through precise control of material network structures. This “strategy-structure-performance” adaptation logic precisely underpins the differentiated application requirements of motion monitoring across diverse scenarios.

#### MULTISCALE APPLICATIONS

AHSs are advancing motion monitoring through their direction-dependent sensing capabilities, enabling multidimensional coverage in this field. They can precisely capture microphysiological signals during movement, track joint activity in real time, and adapt to on-site exercise scenarios such as running and

rehabilitation training.<sup>54,77,105,110</sup> This provides comprehensive technical support for motion-monitoring needs across various levels.

#### Microphysiological signal capture

Microphysiological signals are typically accompanied by minute strains (<1%), demanding AHSs with exceptionally high sensitivity and interference resistance. As shown in Figure 7A, the multidimensional hydrogel AHS designed by Li and colleagues exhibits highly anisotropic sensitivity.<sup>36</sup> The multidimensional wearable electronic skin, featuring macro-to-micro-structural assembly, as described in the performance regulation section, can detect the magnitude and direction of external forces applied to a volunteer’s hand. When uniaxial stress is applied along the x axis on the hand, the multidimensional AHS responds by generating a distinct signal in the x axis channel. Vertical pressure induces a real-time signal in the z channel, while in-plane forces (at 45° to the y axis) elicit responses in both the x and y axis channels. The AHS also clearly identifies signals during the volunteer’s dumbbell-lifting motion, transmitting data via Bluetooth to a smartphone for real-time motion monitoring. Bao and colleagues designed a complex closed-loop drive system using AHSs to realistically replicate signal fluctuations observed in electromyography, particularly those reflecting physiological responses during movement (Figure 7B).<sup>59</sup> During testing, varying knee flexion angles at different movement speeds yielded distinct signal values. The flexible AHS developed by Feng et al.<sup>54</sup> demonstrated precise capture of subtle motion signals even in low-temperature environments (Figure 7C). The AHS designed by Chen et al.<sup>66</sup> can perceive minute human movements due to their extremely low detection threshold and high sensitivity (Figure 7D).

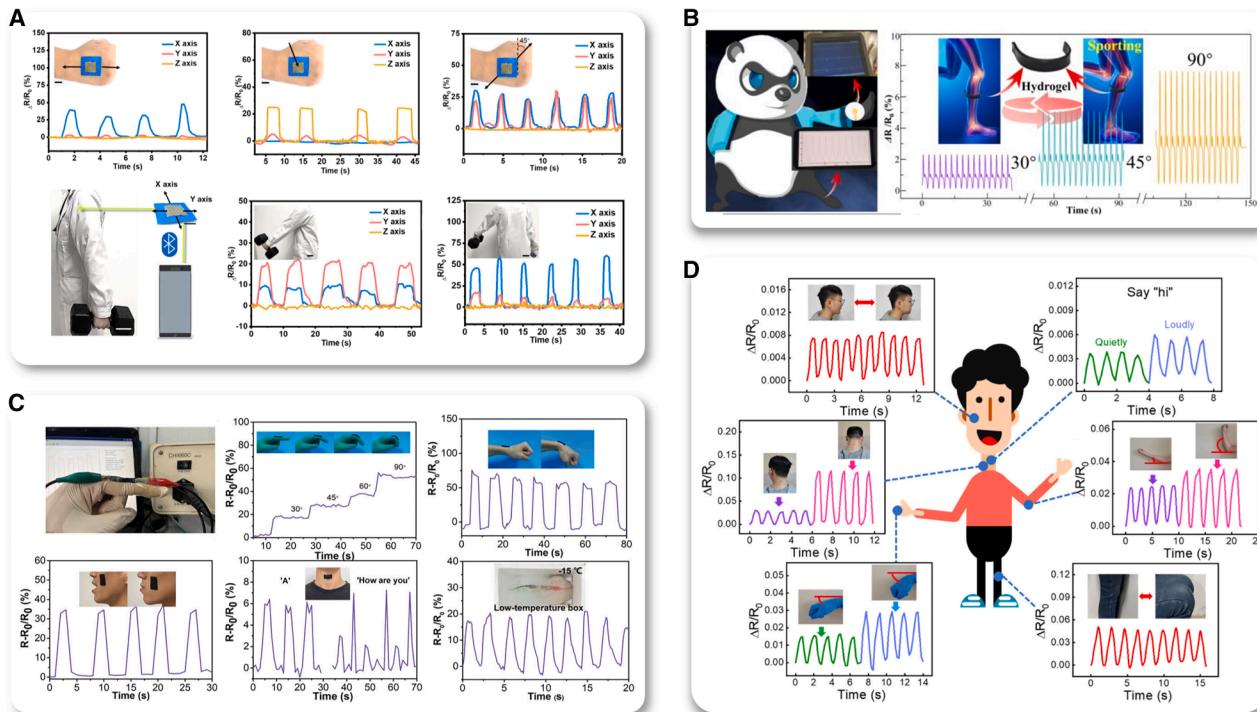
#### Joint motion analysis

Joint motion is a multi-degree-of-freedom composite movement. Unique anisotropic structural materials can achieve directional sensing through structural decoupling,<sup>111–114</sup> making it the primary application domain where anisotropic sensors demonstrate their decoupling advantages.

Jiang and colleagues constructed a wearable multidirectional sensing device capable of monitoring joint motion across multiple degrees of freedom.<sup>77</sup> Figure 8A demonstrates complex movements during wrist monitoring. Bending, twisting, and twisting-bending (bending plus twisting) are represented by wrist flexion, ulnar deviation, and rotation, respectively. Pressure deformation along the z axis induces capacitive signal changes. By synergizing with in-plane resistive signals, more complex motions can be detected. Inspired by muscle arrangement structures and ancient brush-coating techniques, Kang et al.<sup>115</sup> developed a highly anisotropic ionic conductive AHS for detecting electromyographic signals (Figure 8B). The AHS exhibited sensitive and stable signals, with real-time monitoring data clearly demonstrating the developed sensor’s proficiency in detecting a range of human activities, providing valuable insights into these movements. Guo et al.<sup>116</sup> demonstrated the potential of MXene-containing anisotropic conductive hydrogels in practical applications by attaching AHSs to human skin to detect body movements (monitoring elbow and knee joint extension

**Table 1.** Research on AHSs in the field of sports monitoring

Material	Preparation method	Structural characteristics	Application scenarios	Physical and chemical properties	Reference
PVA-PAA/Fe <sup>3+</sup> hydrogel	pre-stretching and ion crosslinking	linearly arranged fibrous network	human movement monitoring; morse code information transmission	parallel direction (47.26 MPa and 292.64 mS/m); perpendicular direction (12.42 MPa and 169.09 mS/m); GF <sub>//</sub> > GF <sub>⊥</sub> (the gauge factor)	Lin et al. <sup>56</sup>
Bamboo/PAM composite hydrogel	natural bamboo delignification	hierarchically anisotropic porous structure	joint movement monitoring; rehabilitation training assistance	axial tensile strength is 123.5 MPa, which is 35.7 times the radial tensile strength; ionic conductivity is stable	He et al. <sup>53</sup>
PVA/NaCl hydrogel	thermal stretching and directional freezing	directionally aligned polymer chains	whole-body joint movement monitoring	parallel orientation (1596 kPa, 3.69 MJ/m <sup>3</sup> ); vertical orientation (883.1 kPa, 1.96 MJ/m <sup>3</sup> ); low detection strain (0.5%)	Wang et al. <sup>64</sup>
Cellulose/lignin Janus hydrogel	stepwise casting	bifunctional heterostructure	minute deformation; facial expression monitoring	tensile strength of 133 kPa; compressive strength of 120 kPa; asymmetric adhesion	Duan et al. <sup>73</sup>
PMZn-GL hydrogel	oriented freezing	oriented porous network and directional MXene distribution	finger/joint flexion; muscle contraction; extreme environments	wide temperature tolerance ranging from -36°C to 25°C	Feng et al. <sup>54</sup>
CMC-Al <sup>3+</sup> gradient hydrogel	oriented diffusion cross-linking	gradient layered structure	micro-movement detection	good sensing performance; GF = 3.1	Ouyang et al. <sup>65</sup>
PAM/(Ca-Alg) DN hydrogel	template method	linear hydrogel fibers	intelligent gesture recognition; sports monitoring and underwater monitoring; real-time temperature monitoring	low strain detection limit (0.03% strain); good strain linearity ( $R^2 = 0.990$ ); high-temperature sensitivity (1.77%/°C); wide humidity response range (33–98% relative humidity [RH])	Wang et al. <sup>55</sup>
Magnetic cellulose/polydopamine hydrogel	magnetic field induction	nanocomposite oriented arrangement network	large and subtle human motion monitoring	parallel direction (tensile strength 0.22 MPa); perpendicular direction (tensile strength 0.03 MPa)	Yan et al. <sup>70</sup>



**Figure 7. Capturing microphysiological signals in AHSs for motion monitoring**

(A) AHSs enable distinct signal recognition as a multidimensional wearable electronic skin. Reproduced with permission from Li et al.<sup>36</sup> Copyright 2024, Elsevier.  
 (B) Anisotropic conductive hydrogels can monitor fluctuations in signals from human physiological responses. Reproduced with permission from Bao et al.<sup>59</sup> Copyright 2025, Elsevier.

(C) Flexible AHS capable of accurate motion monitoring at low temperatures. Reproduced with permission from Feng et al.<sup>54</sup> Copyright 2021, John Wiley & Sons.  
 (D) AHS for perceiving subtle human movements. Reproduced with permission from Chen et al.<sup>66</sup> Copyright 2022, ACS Publications.

and flexion). The response to motion signals remained stable throughout the cycling process (Figure 8C). When the hydrogel deforms under force, the processor detects and analyzes the resulting resistance changes and then wirelessly transmits signals via Bluetooth to a smartphone for display. He et al.<sup>63</sup> constructed a high-strength anisotropic bamboo/PAM composite hydrogel and designed a bending AHS to monitor human motion signals. This AHS accurately and stably responds to changes in joint bending angles (Figure 8D) and holds promise as a robotic electronic skin for transmitting diverse signals, simultaneously monitoring movement and assisting rehabilitation exercises.

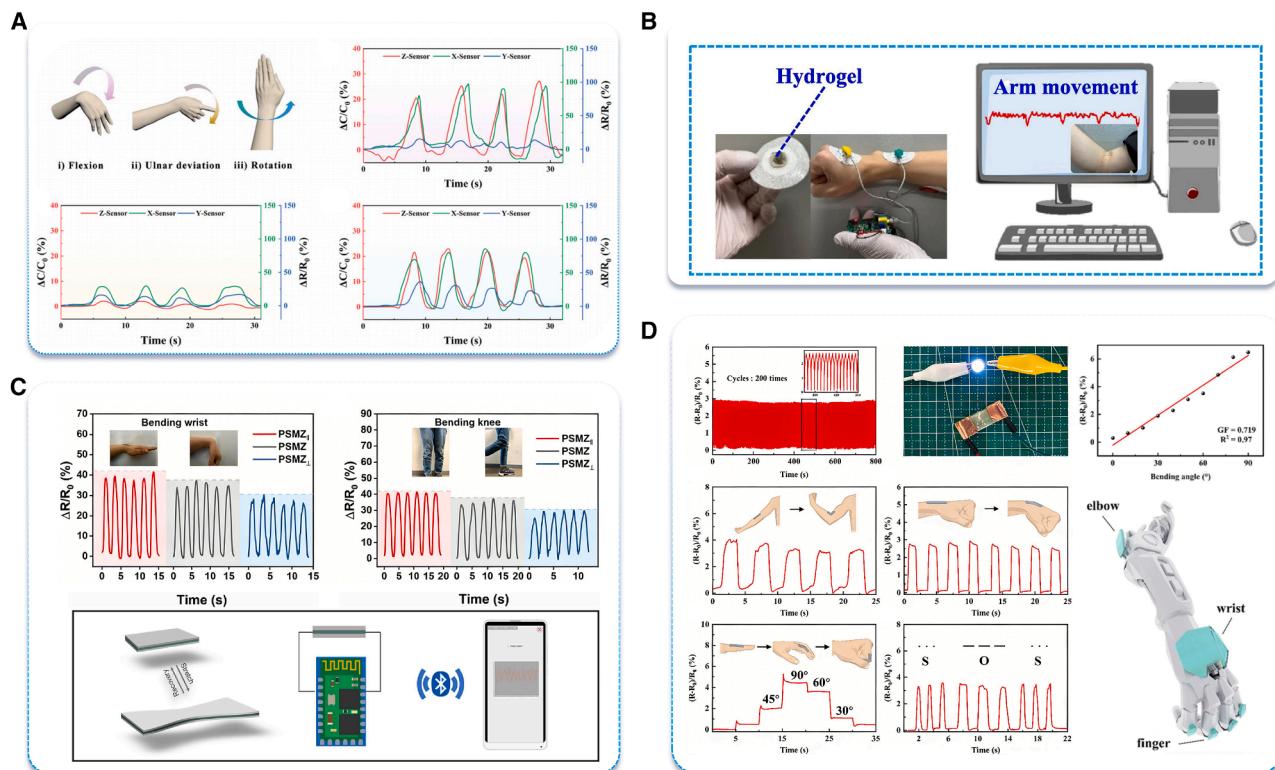
#### On-site motion and extreme environments

On-site application value must be validated in complex, dynamic environments. For prolonged high-intensity activities such as long-distance running, soccer, cycling, or athletic training, sweat and mechanical fatigue pose significant challenges for AHSs.<sup>117–119</sup>

Jiang and colleagues further evaluated the performance of their multidirectional sensors for monitoring joint motion during jump rope and badminton experiments.<sup>77</sup> The AHS data were transmitted via Bluetooth to a mobile phone for real-time display and analysis. For the jump rope experiment, the sensor data enabled the identification of incorrect postures (such as excessive knee flexion and arm swing rotation range) alongside correct

postures, achieving the highest accuracy rate (98.7%) through machine learning (Figure 9A). In badminton posture training, multidirectional strain sensors were worn on the wrist to record real-time motion signals, enabling posture correction and feedback during movement. Feng et al.<sup>54</sup> similarly utilized wearable flexible AHSs to transmit data wirelessly to a smartphone for monitoring human motion (Figure 9B). Hang et al.<sup>57</sup> developed an HAFG@CNT AHS capable of real-time monitoring of various human movements. Furthermore, by employing artificial intelligence data processing algorithms,<sup>120</sup> they analyzed and processed response signal data to accurately and effectively predict different signals from HAFG@CNTs. This enabled real-time detection and correction of incorrect postures and muscle fatigue levels during diverse movements (Figure 9C).

Due to its high sensitivity to various external stimuli, high deformability, and breathability compared to other skins,<sup>121–123</sup> the hydrogel-based multimodal electronic skin can monitor human movement and body temperature changes in daily life by attaching to specific locations on the body. The hydrogel multimodal electronic skin designed by Wang et al.<sup>55</sup> not only measures motion variations during diverse activities but also detects post-exercise respiratory rate changes and temperature shifts. For instance, during bicycle riding, the electronic skin's relative electrical conductivity rapidly increased before stabilizing. Correspondingly, hand temperature gradually rose from



**Figure 8. AHSs for joint motion analysis**

- (A) Wearable multidirectional sensing devices capable of monitoring joint motion across multiple degrees of freedom. Reproduced with permission from Jiang et al.<sup>77</sup> Copyright 2023, John Wiley & Sons.
- (B) Inspired by muscle arrangement and ancient brush-painting techniques, the ionic AHS excels at detecting a range of human activities. Reproduced with permission from Kang et al.<sup>115</sup> Copyright 2025, Elsevier.
- (C) Anisotropic conductive hydrogel sensors containing MXene for monitoring human movement. Reproduced with permission from Guo et al.<sup>116</sup> Copyright 2023, Elsevier.
- (D) The curved AHS holds promise as a robotic “electronic skin” capable of transmitting various signals. Reproduced with permission from He et al.<sup>63</sup> Copyright 2024, Elsevier.

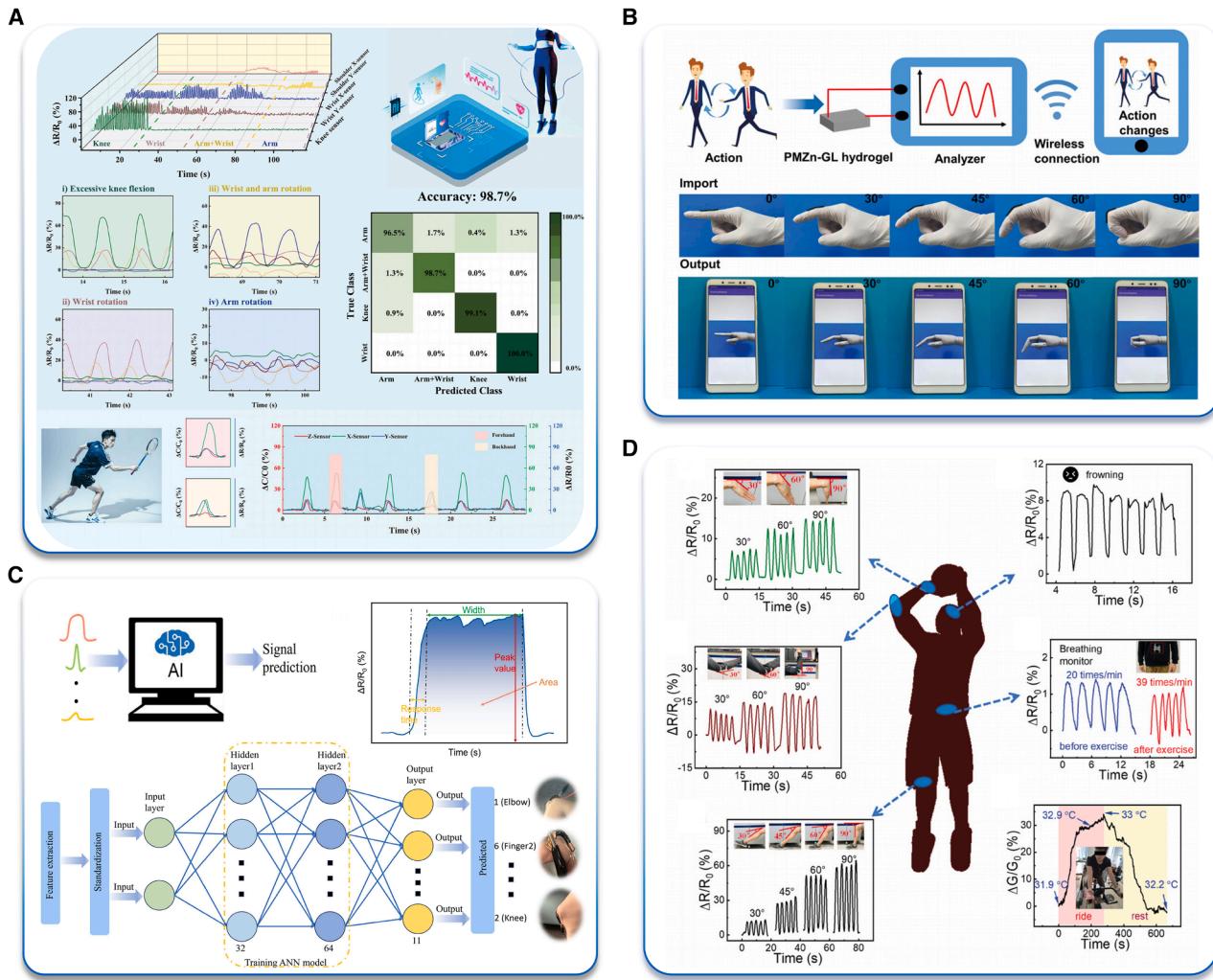
31.9°C to 32.9°C, ultimately stabilizing at  $\approx$ 33°C. Upon cessation of cycling, the sensor’s conductivity gradually returned to its initial value, indicating a slow decrease in body temperature that ultimately reached a stable value (32.2°C), close to the initial body temperature (Figure 9D). These findings demonstrate that this electronic skin can accurately and in real time capture physiological changes in the human body during different movement states. It holds promise for health and performance monitoring during exercise, providing guidance for training.

## CHALLENGES AND OUTLOOK

By transcending the functional limitations of traditional isotropic materials, AHSs enable directional decoding of complex motion information and multiscale perception, driving wearable electronics from “sensing” toward “cognition.” This paper reviews recent advancements in anisotropic hydrogel development and their applications in motion sensing. It categorizes anisotropic hydrogels by material type, performance tuning, and fabrication strategies. Multiscale applications of AHSs in motion sensing are discussed in detail. This research field presents significant

opportunities for future development while also facing major challenges: first, achieving a balance between mechanical properties and functional compatibility. Existing approaches enhance mechanical strength by incorporating coordination networks or nanofillers, but excessive crosslinking may compromise ionic conductivity. For instance, dynamic hydrogen bonds and topological entanglement achieve low hysteresis and high toughness, yet further exploration is needed to enhance fatigue resistance while maintaining high sensitivity. Layer-by-layer assembled multilayer hydrogels may delaminate due to insufficient interfacial bonding.

In addition, precision and stability in anisotropy regulation require further coordination. Although Janus surface designs (e.g., dual-network systems such as carbon black/gelatin and dibromo fluorene/gelatin) achieve conductivity anisotropy up to  $1.12 \times 10^5$ , maintaining stable directional response during complex motion remains challenging. For example, pre-stretch-induced oriented structures may relax under long-term cyclic loading, leading to sensitivity degradation. Furthermore, while external stimuli such as electric or magnetic fields can modulate anisotropy, they may induce material degradation or



**Figure 9. Motion monitoring with AHSs in dynamic environments**

(A) Performance evaluation of multidirectional AHSs in jump rope and badminton experiments. Reproduced with permission from Jiang et al.<sup>77</sup> Copyright 2023, John Wiley & Sons.

(B) Sensors monitor human movement in real time via wireless devices. Reproduced with permission from Feng et al.<sup>54</sup> Copyright 2021, John Wiley & Sons.

(C) HAFG@CNT AHSs leverage artificial intelligence to detect and correct incorrect postures and muscle fatigue in real time during various movements. Reproduced with permission from Hang et al.<sup>57</sup> Copyright 2025, Elsevier.

(D) Hydrogel multimodal electronic skin capable of detecting changes in respiratory rate and body temperature following exercise. Reproduced with permission from Wang et al.<sup>55</sup> Copyright 2024, John Wiley & Sons.

electrochemical side reactions. Third, signal reliability in complex environments remains a concern. Underwater motion monitoring faces swelling and ionic interference issues, with environmental factors potentially generating mechanical noise. Insufficient adhesion at the skin-sensor interface causes signal drift.

Finally, manufacturing processes face scalability bottlenecks. Technologies such as electrospinning and 3D printing enable microstructural control, yet complex processes limit mass production efficiency. The development of AHSs stands at the intersection of material innovation, intelligent sensing, and application advancement. Future breakthroughs must focus on two core technologies, multi-physics field-coordinated regulation

and cross-scale structural design, while strengthening full-chain optimization from materials to devices to systems. By integrating self-healing, biodegradable, and multimodal sensing capabilities, these AHSs hold promise for large-scale applications in sports medicine, competitive athletics, and aging health management, ultimately driving deep integration between flexible electronics and precision medicine.

#### ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (22474049), the Guangdong Provincial Key Laboratory of Speed Capability Research (2023B121201009), the Key Research and Development Project

of Guangdong Province (2023A1515011031), and the Outstanding Innovative Talents Cultivation Funded Programs for Graduate Students of Jinan University (2025CXY320).

#### AUTHOR CONTRIBUTIONS

Y.W. and Y.C. drafted the manuscript. B.S. and F.L. revised and finalized the manuscript. All authors approved the submitted version.

#### DECLARATION OF INTERESTS

The authors declare no competing interests.

#### REFERENCES

- Kang, T.W., Kim, K.R., Lee, Y.J., Kim, H., Lee, S.H., Kwon, Y., Yi, H., Kim, H., Kim, H., Harp, A., et al. (2025). Wireless Soft Athlete Bioelectronics for Monitoring Carbon Dioxide Ventilation and Physiological Performance. *Adv. Sci.* 12, e03880. <https://doi.org/10.1002/advs.202503880>.
- Zhu, Y., Sun, F., Jia, C., Zhao, T., and Mao, Y. (2021). A Stretchable and Self-Healing Hybrid Nano-Generator for Human Motion Monitoring. *Nanomaterials* 12, 104. <https://doi.org/10.3390/nano12010104>.
- Lian, C., Li, W.J., Kang, Y., Li, W., Zhou, D., Zhan, Z., Chen, M., Suo, J., and Zhao, Y. (2026). Enhanced human lower-limb motion recognition using flexible sensor array and relative position image. *Pattern Recognit.* 171, 112142. <https://doi.org/10.1016/j.patcog.2025.112142>.
- Gao, J., Fan, Y., Zhang, Q., Luo, L., Hu, X., Li, Y., Song, J., Jiang, H., Gao, X., Zheng, L., et al. (2022). Ultra-Robust and Extensible Fibrous Mechanical Sensors for Wearable Smart Healthcare. *Adv. Mater.* 34, 2107511. <https://doi.org/10.1002/adma.202107511>.
- Yao, S., Swetha, P., and Zhu, Y. (2018). Nanomaterial-Enabled Wearable Sensors for Healthcare. *Adv. Healthc. Mater.* 7, 1700889. <https://doi.org/10.1002/adhm.201700889>.
- He, C., Zhang, J., Wang, H., Wu, D., Zheng, H., Guo, Z., Xie, J., Zhu, W., Xie, M., Zhong, J., et al. (2025). Accurate and Reliable Detection of Dynamic Electrophysiological Signals via In Situ Formation of Epidermal Electrodes. *Adv. Funct. Mater.* 36, e09372. <https://doi.org/10.1002/adfm.202509372>.
- Lee, D.H., Valenzuela, S.A., Dominguez, M.N., Otsuka, M., Milliron, D.J., and Anslyn, E.V. (2021). A self-degradable hydrogel sensor for a nerve agent tabun surrogate through a self-propagating cascade. *Cell Rep. Phys. Sci.* 2, 100552. <https://doi.org/10.1016/j.xcrp.2021.100552>.
- He, Z., Chen, Y., Cheng, N., Li, C., and Li, F. (2024). Touchable gustatory sensing. *Innovation* 5, 100688. <https://doi.org/10.1016/j.xinn.2024.100688>.
- Zhao, M., Wu, T., Wang, X., Liang, L., Lu, H., Xie, Z., Yuan, T., and Fang, G. (2024). Intrinsically conductive polymer reinforced hydrogel with synergistic strength, toughness, and sensitivity for flexible motion-monitoring sensors. *Cell Rep. Phys. Sci.* 5, 102178. <https://doi.org/10.1016/j.xcrp.2024.102178>.
- Huang, H., Han, L., Fu, X., Wang, Y., Yang, Z., Pan, L., and Xu, M. (2020). Multiple Stimuli Responsive and Identifiable Zwitterionic Ionic Conductive Hydrogel for Bionic Electronic Skin. *Adv. Electron. Mater.* 6, 2000239. <https://doi.org/10.1002/aelm.202000239>.
- Wang, Z., Grange, M., Wagner, T., Kho, A.L., Gautel, M., and Raunser, S. (2021). The molecular basis for sarcomere organization in vertebrate skeletal muscle. *Cell* 184, 2135–2150.e13. <https://doi.org/10.1016/j.cell.2021.02.047>.
- Herzog, W., and Schappacher-Tilp, G. (2023). Molecular mechanisms of muscle contraction: A historical perspective. *J. Biomech.* 155, 111659. <https://doi.org/10.1016/j.jbiomech.2023.111659>.
- Fujita, K., Ohmachi, M., Ikezaki, K., Yanagida, T., and Iwaki, M. (2019). Direct visualization of human myosin II force generation using DNA origami-based thick filaments. *Commun. Biol.* 2, 437. <https://doi.org/10.1038/s42003-019-0683-0>.
- Xia, Y., Zhou, X., Wang, Z., Zhang, L., Xiong, X., Cui, Y., Zhang, R., Zhang, J., Luo, G., Shen, Q., and Cui, J. (2025). Muscle-Inspired Self-Growing Anisotropic Hydrogels with Mechanical Training-Promoting Mechanical Properties. *Adv. Mater.* 37, 2416744. <https://doi.org/10.1002/adma.202416744>.
- Zhao, Y., Zeng, H., Nam, J., and Agarwal, S. (2009). Fabrication of skeletal muscle constructs by topographic activation of cell alignment. *Bio-technol. Bioeng.* 102, 624–631. <https://doi.org/10.1002/bit.22080>.
- Zhao, Z., Fang, R., Rong, Q., and Liu, M. (2017). Bioinspired Nanocomposite Hydrogels with Highly Ordered Structures. *Adv. Mater.* 29, 1703045. <https://doi.org/10.1002/adma.201703045>.
- Choi, S., Choi, Y., and Kim, J. (2019). Anisotropic Hybrid Hydrogels with Superior Mechanical Properties Reminiscent of Tendons or Ligaments. *Adv. Funct. Mater.* 29, 1904342. <https://doi.org/10.1002/adfm.201904342>.
- Wu, J., Xian, J., He, C., Lin, H., Li, J., and Li, F. (2024). Asymmetric Wettability Hydrogel Surfaces for Enduring Electromyographic Monitoring. *Adv. Mater.* 36, 2405372. <https://doi.org/10.1002/adma.202405372>.
- Khan, Y., Thielens, A., Muin, S., Ting, J., Baumbauer, C., and Arias, A.C. (2020). A New Frontier of Printed Electronics: Flexible Hybrid Electronics. *Adv. Mater.* 32, e1905279. <https://doi.org/10.1002/adma.201905279>.
- Shen, B., Peng, W., Su, B., Wu, L., Liu, Z., Xu, H., Zhao, J., Feng, P., and Li, F. (2022). Elastic-Electric Coefficient-Sensitive Hydrogel Sensors toward Sweat Detection. *Anal. Chem.* 94, 1910–1917. <https://doi.org/10.1021/acs.analchem.1c05363>.
- Amjadi, M., Kyung, K.-U., Park, I., and Sitti, M. (2016). Stretchable, Skin-Mountable, and Wearable Strain Sensors and Their Potential Applications: A Review. *Adv. Funct. Mater.* 26, 1678–1698. <https://doi.org/10.1002/adfm.201504755>.
- Chen, S., Fan, S., Qi, J., Xiong, Z., Qiao, Z., Wu, Z., Yeo, J.C., and Lim, C.T. (2023). Ultrahigh Strain-Insensitive Integrated Hybrid Electronics Using Highly Stretchable Bilayer Liquid Metal Based Conductor. *Adv. Mater.* 35, 2208569. <https://doi.org/10.1002/adma.202208569>.
- Qiao, Y., Luo, J., Cui, T., Liu, H., Tang, H., Zeng, Y., Liu, C., Li, Y., Jian, J., Wu, J., et al. (2023). Soft Electronics for Health Monitoring Assisted by Machine Learning. *Nano-Micro Lett.* 15, 66. <https://doi.org/10.1007/s40820-023-01029-1>.
- Wu, H., Li, C., Zhao, P., Zhu, L., Li, Y., Ghomi, E.R., Cao, H., Zhang, M., Weng, X., Zhang, Q., et al. (2025). DNA-Like Double-Helix Wrinkled Flexible Fibrous Sensor with Excellent Mechanical Sensibility for Human Motion Monitoring. *Adv. Fiber Mater.* 7, 1260–1273. <https://doi.org/10.1007/s42765-025-00560-7>.
- Chen, Y., He, Z., and Li, F. (2025). Hofmeister Effect in Flexible Devices. *Adv. Mater.* 37, 2502890. <https://doi.org/10.1002/adma.202502890>.
- Lu, W., Si, M., Liu, H., Qiu, H., Wei, S., Wu, B., Wang, R., Yin, G., Zhang, J., Theato, P., et al. (2021). A panther chameleon skin-inspired core@-shell supramolecular hydrogel with spatially organized multi-luminogens enables programmable color change. *Cell Rep. Phys. Sci.* 2, 100417. <https://doi.org/10.1016/j.xcrp.2021.100417>.
- Thakur, S., Thakur, V.K., and Arotiba, O.A. (2018). History, Classification, Properties and Application of Hydrogels: An Overview. In *Hydrogels: Recent Advances*, V.K. Thakur and M.K. Thakur, eds. (Springer), pp. 29–50. [https://doi.org/10.1007/978-981-10-6077-9\\_2](https://doi.org/10.1007/978-981-10-6077-9_2).
- Sano, K., Ishida, Y., and Aida, T. (2018). Synthesis of Anisotropic Hydrogels and Their Applications. *Angew. Chem. Int. Ed. Engl.* 57, 2532–2543. <https://doi.org/10.1002/anie.201708196>.
- Yao, C., Liu, Z., Yang, C., Wang, W., Ju, X.-J., Xie, R., and Chu, L.-Y. (2015). Poly(N-isopropylacrylamide)-Clay Nanocomposite Hydrogels with Responsive Bending Property as Temperature-Controlled Manipulators. *Adv. Funct. Mater.* 25, 2980–2991. <https://doi.org/10.1002/adfm.201500420>.

30. Zhou, Y., Xu, W., Ji, Y., Zhou, G., Wu, W., Chen, Z., Wang, B., Gui, X., and Li, X. (2023). Differential design in homogenous sensors for classification and decoupling kinesthetic information through machine learning. *Appl. Phys. Rev.* 10, 021407. <https://doi.org/10.1063/5.0144956>.
31. Lin, H., Wang, R., Xu, S., Li, X., and Song, S. (2023). Tendon-Inspired Anisotropic Hydrogels with Excellent Mechanical Properties for Strain Sensors. *Langmuir* 39, 6069–6077. <https://doi.org/10.1021/acs.langmuir.3c00145>.
32. Zhang, F., Ma, P.C., Wang, J., Zhang, Q., Feng, W., Zhu, Y., and Zheng, Q. (2021). Anisotropic conductive networks for multidimensional sensing. *Mater. Horiz.* 8, 2615–2653. <https://doi.org/10.1039/d1mh00615k>.
33. Chen, H., Jing, Y., Lee, J.H., Liu, D., Kim, J., Chen, S., Huang, K., Shen, X., Zheng, Q., Yang, J., et al. (2020). Human skin-inspired integrated multidimensional sensors based on highly anisotropic structures. *Mater. Horiz.* 7, 2378–2389. <https://doi.org/10.1039/d0mh00922a>.
34. Zhang, X.H., Wang, Y.Q., and Zheng, Q. (2024). Rheological Behavior of Biomimetic Composite Hydrogels with Anisotropic Structures. *Acta Polym. Sin.* 55, 1069–1080. <https://doi.org/10.1177/j.issn1000-3304.2023.23275>.
35. Kong, W., Wang, C., Jia, C., Kuang, Y., Pastel, G., Chen, C., Chen, G., He, S., Huang, H., Zhang, J., et al. (2018). Muscle-Inspired Highly Anisotropic, Strong, Ion-Conductive Hydrogels. *Adv. Mater.* 30, e1801934. <https://doi.org/10.1002/adma.201801934>.
36. Li, S., Xiao, Z., Yang, H., Zhu, C., Chen, G., Zheng, J., Ren, J., Wang, W., Cong, Y., Ali Shah, L., and Fu, J. (2024). A skin-inspired anisotropic multidimensional sensor based on low hysteresis organohydrogel with linear sensitivity and excellent robustness for directional perception. *Chem. Eng. J.* 499, 156581. <https://doi.org/10.1016/j.cej.2024.156581>.
37. Mredha, M.T.I., and Jeon, I. (2022). Biomimetic anisotropic hydrogels: Advanced fabrication strategies, extraordinary functionalities, and broad applications. *Prog. Mater. Sci.* 124, 100870. <https://doi.org/10.1016/j.pmatsci.2021.100870>.
38. Chen, Q., Zhang, X., Chen, K., Wu, X., Zong, T., Feng, C., and Zhang, D. (2022). Anisotropic hydrogels with enhanced mechanical and tribological performance by magnetically oriented nanohybrids. *Chem. Eng. J.* 430, 133036. <https://doi.org/10.1016/j.cej.2021.133036.38>.
39. Ge, G., Zhang, Y., Shao, J., Wang, W., Si, W., Huang, W., and Dong, X. (2018). Stretchable, Transparent, and Self-Patterned Hydrogel-Based Pressure Sensor for Human Motions Detection. *Adv. Funct. Mater.* 28, 1802576. <https://doi.org/10.1002/adfm.201802576>.
40. Chen, Y., Yu, W., Zhu, Q., Huang, Y., Xia, F., and Li, F. (2025). Polymer/Hydrogel Integrated Solid-State Nanochannel Composite Membranes. *ACS Nano* 19, 22493–22503. <https://doi.org/10.1021/acsnano.5c06303>.
41. Chen, Y., Valenzuela, C., Liu, Y., Yang, X., Yang, Y., Zhang, X., Ma, S., Bi, R., Wang, L., and Feng, W. (2025). Biomimetic artificial neuromuscular fiber bundles with built-in adaptive feedback. *Matter* 8, 101904. <https://doi.org/10.1016/j.matt.2024.10.022>.
42. Kim, J.H., Kim, I., Seol, Y.J., Ko, I.K., Yoo, J.J., Atala, A., and Lee, S.J. (2020). Neural cell integration into 3D bioprinted skeletal muscle constructs accelerates restoration of muscle function. *Nat. Commun.* 11, 1025. <https://doi.org/10.1038/s41467-020-14930-9>.
43. Chen, Z., Wang, H., Cao, Y., Chen, Y., Akkus, O., Liu, H., and Cao, C.C. (2023). Bio-inspired anisotropic hydrogels and their applications in soft actuators and robots. *Matter* 6, 3803–3837. <https://doi.org/10.1016/j.matt.2023.08.011>.
44. Cai, Y., Shen, J., Yang, C.W., Wan, Y., Tang, H.L., Aljarb, A.A., Chen, C., Fu, J.H., Wei, X., Huang, K.W., et al. (2020). Mixed-dimensional MXene-hydrogel heterostructures for electronic skin sensors with ultrabroad working range. *Sci. Adv.* 6, eabb5367. <https://doi.org/10.1126/sciadv.abb5367>.
45. Guo, F., Ren, Z., Wang, S., Xie, Y., Pan, J., Huang, J., Zhu, T., Cheng, S., and Lai, Y. (2025). Recent Progress of Electrospun Nanofiber-Based Composite Materials for Monitoring Physical, Physiological, and Body Fluid Signals. *Nano-Micro Lett.* 17, 302. <https://doi.org/10.1007/s40820-025-01804-2>.
46. Yuan, S., Bai, J., Cao, Y., Li, S., Zhu, H., Zhang, T., and Li, T. (2025). A High Environmentally Stable Ionic Hydrogel for Pressure-Temperature Bimodal Passive Flexible Tactile Sensor. *Adv. Funct. Mater.* 36, e15806. <https://doi.org/10.1002/adfm.202515806>.
47. Kaneko, T., Ogomi, D., Mitsugi, R., Serizawa, T., and Akashi, M. (2004). Mechanically Drawn Hydrogels Uniaxially Orient Hydroxyapatite Crystals and Cell Extension. *Chem. Mater.* 16, 5596–5601. <https://doi.org/10.1021/cm0490975>.
48. Yang, W., Furukawa, H., and Gong, J.P. (2008). Highly Extensible Double-Network Gels with Self-Assembling Anisotropic Structure. *Adv. Mater.* 20, 4499–4503. <https://doi.org/10.1002/adma.200801396>.
49. Haque, M.A., Kamita, G., Kurokawa, T., Tsujii, K., and Gong, J.P. (2010). Unidirectional Alignment of Lamellar Bilayer in Hydrogel: One-Dimensional Swelling, Anisotropic Modulus, and Stress/Strain Tunable Structural Color. *Adv. Mater.* 22, 5110–5114. <https://doi.org/10.1002/adma.201002509>.
50. Sidorenko, A., Krupenkin, T., Taylor, A., Fratzl, P., and Aizenberg, J. (2007). Reversible switching of hydrogel-actuated nanostructures into complex micropatterns. *Science* 315, 487–490. <https://doi.org/10.1126/science.1135516>.
51. Yue, Y.F., Haque, M.A., Kurokawa, T., Nakajima, T., and Gong, J.P. (2013). Lamellar Hydrogels with High Toughness and Ternary Tunable Photonic Stop-Band. *Adv. Mater.* 25, 3106–3110. <https://doi.org/10.1002/adma.201300775>.
52. Mredha, M.T.I., Guo, Y.Z., Nonoyama, T., Nakajima, T., Kurokawa, T., and Gong, J.P. (2018). A Facile Method to Fabricate Anisotropic Hydrogels with Perfectly Aligned Hierarchical Fibrous Structures. *Adv. Mater.* 30, 1704937. <https://doi.org/10.1002/adma.201704937>.
53. Hua, M., Wu, S., Ma, Y., Zhao, Y., Chen, Z., Frenkel, I., Strzalka, J., Zhou, H., Zhu, X., and He, X. (2021). Strong tough hydrogels via the synergy of freeze-casting and salting out. *Nature* 590, 594–599. <https://doi.org/10.1038/s41586-021-03212-z>.
54. Feng, Y., Liu, H., Zhu, W., Guan, L., Yang, X., Zvyagin, A.V., Zhao, Y., Shen, C., Yang, B., and Lin, Q. (2021). Muscle-Inspired MXene Conductive Hydrogels with Anisotropy and Low-Temperature Tolerance for Wearable Flexible Sensors and Arrays. *Adv. Funct. Mater.* 31, 2105264. <https://doi.org/10.1002/adfm.202105264>.
55. Wang, W., Yao, D., Wang, H., Ding, Q., Luo, Y., Ding, H., Yu, J., Zhang, H., Tao, K., Zhang, S., et al. (2024). A Breathable, Stretchable, and Self-Calibrated Multimodal Electronic Skin Based on Hydrogel Microstructures for Wireless Wearables. *Adv. Funct. Mater.* 34, 2316339. <https://doi.org/10.1002/adfm.202316339>.
56. Lin, H., Yuan, W., Shao, H., Zhao, C., Zhang, W., Ma, S., Li, Y., and Song, S. (2024). Muscle-inspired anisotropic hydrogel strain sensors with ultra-strong mechanical properties and improved sensing capabilities for human motion detection and Morse code transmission. *Eur. Polym. J.* 202, 112642. <https://doi.org/10.1016/j.eurpolymj.2023.112642>.
57. Hang, C., Guo, Z., Li, K., Yao, J., Shi, H., Ge, R., Liang, J., Quan, F., Zhang, K., Tian, X., and Xia, Y. (2025). Anisotropic hydrogel sensors with muscle-like structures based on high-absorbent alginate fibers. *Carbohydr. Polym.* 349, 123015. <https://doi.org/10.1016/j.carbpol.2024.123015>.
58. Deng, Y., Liu, J., Lei, Y., Huang, G., Zhang, Z., and Sha, J. (2025). Anisotropic cellulose nanofibril piezoelectric organohydrogel fabricated by directional freezing for flexible strain sensors. *Int. J. Biol. Macromol.* 307, 142187. <https://doi.org/10.1016/j.ijbiomac.2025.142187>.
59. Bao, D., Guan, F., Ji, X., Zhang, X., Xu, Y., Yang, Q., Yao, Q., Zhang, S., and Guo, J. (2025). Unidirectionally arranged layered structured hydrogels with high strength multifunctional integration, and somatosensory actuators. *Chem. Eng. J.* 505, 159294. <https://doi.org/10.1016/j.cej.2025.159294>.

60. Chen, G., Yang, Z., Pan, H., Zhang, J., Guo, Y., Zhou, Z., Zheng, J., Zhang, Z., Cao, R., Hou, K., and Zhu, M. (2025). A Review of Hydrogel Fiber: Design, Synthesis, Applications, and Futures. *Chem. Rev.* 125, 5991–6056. <https://doi.org/10.1021/acs.chemrev.5c00159>.
61. Nepal, D., Kang, S., Adstedt, K.M., Kanhaiya, K., Bockstaller, M.R., Brinson, L.C., Buehler, M.J., Coveney, P.V., Dayal, K., El-Awady, J.A., et al. (2023). Hierarchically structured bioinspired nanocomposites. *Nat. Mater.* 22, 18–35. <https://doi.org/10.1038/s41563-022-01384-1>.
62. Wang, S., Yu, L., Jia, X., Zhang, L., Liu, H., Gao, E., and Chen, C. (2024). Cellulose nanofibril-guided orienting response of supramolecular network enables superstretchable, robust, and antifatigue hydrogel. *Innov. Mater.* 2, 100092. <https://doi.org/10.59717/j.xinn-mater.2024.100092>.
63. He, X., Bai, T., Lu, J., Hu, Y., Wang, Q., Yan, J., Yao, H., Han, G., and Cheng, W. (2024). High-strength, anisotropic bamboo hydrogel via in situ lignin modification for ion-selective transport and sensor. *Chem. Eng. J.* 481, 148416. <https://doi.org/10.1016/j.cej.2023.148416>.
64. Wang, Q., Zhang, Q., Wang, G., Wang, Y., Ren, X., and Gao, G. (2022). Muscle-Inspired Anisotropic Hydrogel Strain Sensors. *ACS Appl. Mater. Interfaces* 14, 1921–1928. <https://doi.org/10.1021/acsami.1c18758>.
65. Ouyang, K., Zhuang, J., Chen, C., Wang, X., Xu, M., and Xu, Z. (2021). Gradient Diffusion Anisotropic Carboxymethyl Cellulose Hydrogels for Strain Sensors. *Biomacromolecules* 22, 5033–5041. <https://doi.org/10.1021/acs.biomac.1c01003>.
66. Chen, L., Chang, X., Chen, J., and Zhu, Y. (2022). Ultrastretchable, Anti-freezing, and High-Performance Strain Sensor Based on a Muscle-Inspired Anisotropic Conductive Hydrogel for Human Motion Monitoring and Wireless Transmission. *ACS Appl. Mater. Interfaces* 14, 43833–43843. <https://doi.org/10.1021/acsami.2c14120>.
67. Qi, H., Huang, H., Hu, Y., Li, N., Yang, L., Zhang, X., Li, Y., Zhao, H., Li, D., and Dong, X. (2025). Design and electrospinning synthesis of red luminescent-highly anisotropic conductive Janus nanobelt hydrogel array films. *Mater. Chem. Front.* 9, 710–724. <https://doi.org/10.1039/D4QM00852A>.
68. Panda, P., Maity, P., Dutta, A., and Das, R.K. (2025). Anisotropic Anti-Swelling Hydrogels with Hydrophobic Association and Metal-Ligand Cross-Links for Applications in Underwater Strain Sensing and Anisotropic Actuation. *Langmuir* 41, 13301–13314. <https://doi.org/10.1021/acs.langmuir.5c01032>.
69. Li, S., Yang, H., Zhu, N., Chen, G., Miao, Y., Zheng, J., Cong, Y., Chen, Y., Gao, J., Jian, X., and Fu, J. (2023). Biotissue-Inspired Anisotropic Carbon Fiber Composite Hydrogels for Logic Gates, Integrated Soft Actuators, and Sensors with Ultra-High Sensitivity. *Adv. Funct. Mater.* 33, 2211189. <https://doi.org/10.1002/adfm.202211189>.
70. Yan, G., He, S., Chen, G., Tang, X., Sun, Y., Xu, F., Zeng, X., and Lin, L. (2022). Anisotropic, strong, self-adhesive and strain-sensitive hydrogels enabled by magnetically-oriented cellulose/polydopamine nanocomposites. *Carbohydr. Polym.* 276, 118783. <https://doi.org/10.1016/j.carbpol.2021.118783>.
71. Dai, C.F., Khoruzhenko, O., Zhang, C., Zhu, Q.L., Jiao, D., Du, M., Breu, J., Zhao, P., Zheng, Q., and Wu, Z.L. (2022). Magneto-Orientation of Magnetic Double Stacks for Patterned Anisotropic Hydrogels with Multiple Responses and Modular Motions. *Angew. Chem. Int. Ed. Engl.* 61, e202207272. <https://doi.org/10.1002/anie.202207272>.
72. Li, Z., Wang, B., Lu, J., Xue, Y., Wang, J., Jia, B., Han, G., Zhao, Y., Qurashi, M.A.K., Yu, L., et al. (2025). Highly Stretchable, Self-Healable, and Conductive Gelatin Methacryloyl Hydrogel for Long-Lasting Wearable Tactile Sensors. *Adv. Sci.* 12, e02678. <https://doi.org/10.1002/advs.202502678>.
73. Duan, C., Ma, Q., Ma, R., Liu, X., Yang, K., Nie, X., and Chen, Y. (2025). A bio-based Janus hydrogel from cellulose and lignin with bilayer structure and asymmetric adhesion for accurate and sensitive human motion monitoring. *Int. J. Biol. Macromol.* 306, 141718. <https://doi.org/10.1016/j.ijbiomac.2025.141718>.
74. Huang, S., Xiao, R., Lin, S., Wu, Z., Lin, C., Jang, G., Hong, E., Gupta, S., Lu, F., Chen, B., et al. (2025). Anisotropic hydrogel microelectrodes for intraspinal neural recordings in vivo. *Nat. Commun.* 16, 1127. <https://doi.org/10.1038/s41467-025-56450-4>.
75. Zhang, Y., Li, J., Yu, X., Han, D., and Xu, Y. (2025). Micro-corrugated chiral nematic cellulose nanocrystal films integrated with ionic conductive hydrogels leads to flexible materials for multidirectional strain sensing applications. *Int. J. Biol. Macromol.* 295, 139569. <https://doi.org/10.1016/j.ijbiomac.2025.139569>.
76. Lin, F., Yang, W., Lu, B., Xu, Y., Chen, J., Zheng, X., Liu, S., Lin, C., Zeng, H., and Huang, B. (2025). Muscle-Inspired Robust Anisotropic Cellulose Conductive Hydrogel for Multidirectional Strain Sensors and Implantable Bioelectronics. *Adv. Funct. Mater.* 35, 2416419. <https://doi.org/10.1002/adfm.202416419>.
77. Jiang, H., Jiang, S., Chen, G., and Lan, Y. (2024). Cartilage-Inspired Multidirectional Strain Sensor with High Elasticity and Anisotropy Based on Segmented Embedded Strategy. *Adv. Funct. Mater.* 34, 2307313. <https://doi.org/10.1002/adfm.202307313>.
78. Li, Z., Lu, J., Ji, T., Xue, Y., Zhao, L., Zhao, K., Jia, B., Wang, B., Wang, J., Zhang, S., and Jiang, Z. (2024). Self-Healing Hydrogel Bioelectronics. *Adv. Mater.* 36, 2306350. <https://doi.org/10.1002/adma.202306350>.
79. Huang, Y., Luo, C., Xia, F., Song, Y., Jiang, L., and Li, F. (2022). Multi-analyte sensing strategies towards wearable and intelligent devices. *Chem. Sci.* 13, 12309–12325. <https://doi.org/10.1039/D2SC03750E>.
80. Wang, X., Yu, H., Kold, S., Rahbek, O., and Bai, S. (2023). Wearable sensors for activity monitoring and motion control: A review. *Biomim. Intell. Robot.* 3, 100089. <https://doi.org/10.1016/j.birob.2023.100089>.
81. Zhang, J., Liu, Z., Tang, Y., Wang, S., Meng, J., and Li, F. (2024). Explainable Deep Learning-Assisted Self-Calibrating Colorimetric Patches for In Situ Sweat Analysis. *Anal. Chem.* 96, 1205–1213. <https://doi.org/10.1021/acs.analchem.3c04368>.
82. Qi, H., Jing, X., Hu, Y., Wu, P., Zhang, X., Li, Y., Zhao, H., Ma, Q., Dong, X., and Mahadevan, C.K. (2025). Electrospun green fluorescent-highly anisotropic conductive Janus-type nanoribbon hydrogel array film for multiple stimulus response sensors. *Compos. Pt. B-Eng.* 288, 111933. <https://doi.org/10.1016/j.compositesb.2024.111933>.
83. Shu, T., Zheng, K., Zhang, Z., Ren, J., Wang, Z., Pei, Y., Yeo, J., Gu, G.X., and Ling, S. (2021). Birefringent Silk Fibroin Hydrogel Constructed via Binary Solvent-Exchange-Induced Self-Assembly. *Biomacromolecules* 22, 1955–1965. <https://doi.org/10.1021/acs.biomac.1c00065>.
84. Feng, Y., Wang, Y., Chen, C., Wang, Z., and Liu, J. (2024). Bioinspired multiscale regulation for hydrogels with superior mechanics. *Innov. Mater.* 2, 100105. <https://doi.org/10.59717/j.xinn-mater.2024.100105>.
85. Liu, C., Morimoto, N., Jiang, L., Kawahara, S., Noritomi, T., Yokoyama, H., Mayumi, K., and Ito, K. (2021). Tough hydrogels with rapid self-reinforcement. *Science* 372, 1078–1081. <https://doi.org/10.1126/science.aaz6694>.
86. Zhu, R., Zhu, D., Zheng, Z., and Wang, X. (2024). Tough double network hydrogels with rapid self-reinforcement and low hysteresis based on highly entangled networks. *Nat. Commun.* 15, 1344. <https://doi.org/10.1038/s41467-024-45485-8>.
87. Yao, X., Chen, H., Qin, H., Wu, Q.-H., Cong, H.-P., and Yu, S.-H. (2024). Solvent-adaptive hydrogels with lamellar confinement cellular structure for programmable multimodal locomotion. *Nat. Commun.* 15, 9254. <https://doi.org/10.1038/s41467-024-53549-y>.
88. Zhang, J., Wang, Y., Wei, Q., Li, M., and Chen, X. (2024). 3D printable, stretchable, anti-freezing and rapid self-healing organogel-based sensors for human motion detection. *J. Colloid Interface Sci.* 653, 1514–1525. <https://doi.org/10.1016/j.jcis.2023.09.183>.
89. Hu, G., Wang, Q., Lin, Y., Shi, J., Xu, X., Jia, R., and Chang, S. (2024). High-Sensitivity Conductive Copolymer Hydrogel for Multifunctional Flexible Wearable Sensors Based on Salting-Out after Freeze-Casting Assisted UV-Curing. *ACS Appl. Polym. Mater.* 6, 8223–8234. <https://doi.org/10.1021/acspolm.4c01127>.

90. Li, X., Tan, Z., Guo, B., Yu, C., Yao, M., Liang, L., Wu, X., Zhao, Z., Yao, F., Zhang, H., et al. (2023). Magnet-oriented hydrogels with mechanical-electrical anisotropy and photothermal antibacterial properties for wound repair and monitoring. *Chem. Eng. J.* 463, 142387. <https://doi.org/10.1016/j.cej.2023.142387>.
91. Shi, H., Deng, Y., and Shi, Y. (2023). Cellulose-Based Stimuli-Responsive Anisotropic Hydrogel for Sensor Applications. *ACS Appl. Nano Mater.* 6, 11524–11530. <https://doi.org/10.1021/acsnano.3c01551>.
92. Zhu, Q.L., Dai, C.F., Wagner, D., Daab, M., Hong, W., Breu, J., Zheng, Q., and Wu, Z.L. (2020). Distributed Electric Field Induces Orientations of Nanosheets to Prepare Hydrogels with Elaborate Ordered Structures and Programmed Deformations. *Adv. Mater.* 32, e2005567. <https://doi.org/10.1002/adma.202005567>.
93. Antman-Passig, M., and Shefi, O. (2016). Remote Magnetic Orientation of 3D Collagen Hydrogels for Directed Neuronal Regeneration. *Nano Lett.* 16, 2567–2573. <https://doi.org/10.1021/acs.nanolett.6b00131>.
94. Gao, F., Jiang, H., Wang, D., Wang, S., and Song, W. (2024). Bio-Inspired Magnetic-Responsive Supramolecular-Covalent Semi-Convertible Hydrogel. *Adv. Mater.* 36, 2401645. <https://doi.org/10.1002/adma.202401645>.
95. Shi, W., Huang, J., Fang, R., and Liu, M. (2020). Imparting Functionality to the Hydrogel by Magnetic-Field-Induced Nano-assembly and Macro-response. *ACS Appl. Mater. Interfaces* 12, 5177–5194. <https://doi.org/10.1021/acsmi.9b16770>.
96. Liu, M., Ishida, Y., Ebina, Y., Sasaki, T., Hikima, T., Takata, M., and Aida, T. (2015). An anisotropic hydrogel with electrostatic repulsion between cofacially aligned nanosheets. *Nature* 517, 68–72. <https://doi.org/10.1038/nature14060>.
97. Wu, L., Ohtani, M., Takata, M., Saeki, A., Seki, S., Ishida, Y., and Aida, T. (2014). Magnetically Induced Anisotropic Orientation of Graphene Oxide Locked by In Situ Hydrogelation. *ACS Nano* 8, 4640–4649. <https://doi.org/10.1021/nn5003908>.
98. Ahadian, S., Ramón-Azcón, J., Estili, M., Liang, X., Ostrovidov, S., Shiku, H., Ramalingam, M., Nakajima, K., Sakka, Y., and Bae, H. (2014). Hybrid hydrogels containing vertically aligned carbon nanotubes with anisotropic electrical conductivity for muscle myofiber fabrication. *Sci. Rep.* 19, 4271. <https://doi.org/10.1038/srep04271>.
99. Lin, X.Y., Wang, Z.J., Pan, P., Wu, Z.L., and Zheng, Q. (2016). Monodomain hydrogels prepared by shear-induced orientation and subsequent gelation. *RSC Adv.* 6, 95239–95245. <https://doi.org/10.1039/c6ra17103f>.
100. Hu, F., Yu, D., Dong, B., Gong, X., Li, Z., Zhao, R., Wang, Q., Li, G., Wang, H., Liu, W., et al. (2025). Antibacterial conductive hydrogels with freeze-directed microstructures reinforced by polyaniline-encapsulated bacterial cellulose for flexible sensors. *Chem. Eng. J.* 512, 162702. <https://doi.org/10.1016/j.cej.2025.162702>.
101. Morales, D., Bharti, B., Dickey, M.D., and Velev, O.D. (2016). Bending of Responsive Hydrogel Sheets Guided by Field-Assembled Microparticle Endoskeleton Structures. *Small* 12, 2283–2290. <https://doi.org/10.1002/smll.201600037>.
102. Lin, P., Zhang, T., Wang, X., Yu, B., and Zhou, F. (2016). Freezing Molecular Orientation under Stretch for High Mechanical Strength but Anisotropic Hydrogels. *Small* 12, 4386–4392. <https://doi.org/10.1002/smll.201601893>.
103. Wu, Z.L., Kurokawa, T., Sawada, D., Hu, J., Furukawa, H., and Gong, J.P. (2011). Anisotropic Hydrogel from Complexation-Driven Reorientation of Semirigid Polyanion at  $\text{Ca}^{2+}$  Diffusion Flux Front. *Macromolecules* 44, 3535–3541. <https://doi.org/10.1021/ma2001228>.
104. Kim, Y.S., Liu, M., Ishida, Y., Ebina, Y., Osada, M., Sasaki, T., Hikima, T., Takata, M., and Aida, T. (2015). Thermoresponsive actuation enabled by permittivity switching in an electrostatically anisotropic hydrogel. *Nat. Mater.* 14, 1002–1007. <https://doi.org/10.1038/nmat4363>.
105. Wang, S., Lei, L., Tian, Y., Ning, H., Hu, N., Wu, P., Jiang, H., Zhang, L., Luo, X., Liu, F., et al. (2024). Strong, tough and anisotropic bioinspired hydrogels. *Mater. Horiz.* 11, 2131–2142. <https://doi.org/10.1039/d3mh02032k>.
106. Sano, K., Arazoe, Y.O., Ishida, Y., Ebina, Y., Osada, M., Sasaki, T., Hikima, T., and Aida, T. (2018). Extra-Large Mechanical Anisotropy of a Hydrogel with Maximized Electrostatic Repulsion between Cofacially Aligned 2D Electrolytes. *Angew. Chem. Int. Ed. Engl.* 57, 12508–12513. <https://doi.org/10.1002/anie.201807240>.
107. Guo, B., Wu, Y., He, S., Wang, C., Yao, M., Yu, Q., Wu, X., Yu, C., Liu, M., Liang, L., et al. (2023). Anisotropic and super-strong conductive hydrogels enabled by mechanical stretching combined with the Hofmeister effect. *J. Mater. Chem. A* 11, 8038–8047. <https://doi.org/10.1039/D2TA09973J>.
108. He, H., Liu, M., Wei, J., Chen, P., Wang, S., and Wang, Q. (2016). Hydrogel with Aligned and Tunable Pore Via “Hot Ice” Template Applies as Bioscaffold. *Adv. Healthc. Mater.* 5, 648. <https://doi.org/10.1002/adhm.201500707>.
109. Liang, X., Chen, G., Lin, S., Zhang, J., Wang, L., Zhang, P., Wang, Z., Wang, Z., Lan, Y., Ge, Q., and Liu, J. (2021). Anisotropically Fatigue-Resistant Hydrogels. *Adv. Mater.* 33, e2102011. <https://doi.org/10.1002/adma.202102011>.
110. Li, S., Yang, H., Chen, G., Zheng, J., Wang, W., Ren, J., Zhu, C., Yang, Y., Cong, Y., and Fu, J. (2023). 4D printing of biomimetic anisotropic self-sensing hydrogel actuators. *Chem. Eng. J.* 473, 145444. <https://doi.org/10.1016/j.cej.2023.145444>.
111. Pyo, S., Lee, J., Kim, W., Jo, E., and Kim, J. (2019). Multi-Layered, Hierarchical Fabric-Based Tactile Sensors with High Sensitivity and Linearity in Ultrawide Pressure Range. *Adv. Funct. Mater.* 29, 1902484. <https://doi.org/10.1002/adfm.201902484>.
112. Wu, Y., Yan, T., Zhang, K., and Pan, Z. (2021). Flexible and Anisotropic Strain Sensors Based on Highly Aligned Carbon Fiber Membrane for Exercise Monitoring. *Adv. Mater. Technol.* 6, 2100643. <https://doi.org/10.1002/admt.202100643>.
113. Chen, S., Song, Y., Ding, D., Ling, Z., and Xu, F. (2018). Flexible and Anisotropic Strain Sensor Based on Carbonized Crepe Paper with Aligned Cellulose Fibers. *Adv. Funct. Mater.* 28, 1802547. <https://doi.org/10.1002/admt.202100643>.
114. Zhu, S., Wang, S., Huang, Y., Tang, Q., Fu, T., Su, R., Fan, C., Xia, S., Lee, P.S., and Lin, Y. (2024). Bioinspired structural hydrogels with highly ordered hierarchical orientations by flow-induced alignment of nanofibrils. *Nat. Commun.* 15, 118. <https://doi.org/10.1038/s41467-023-44481-8>.
115. Kang, M., Yao, Y., Zhang, Y., Su, X., Jing, G., and Fu, G. (2025). Constructing ionic conductive channels with zwitterionic COFs in anisotropic networks enhances hydrogel sensing performance. *Chem. Eng. J.* 503, 158581. <https://doi.org/10.1016/j.cej.2024.158581>.
116. Guo, B., He, S., Yao, M., Tan, Z., Li, X., Liu, M., Yu, C., Liang, L., Zhao, Z., Guo, Z., et al. (2023). MXene-containing anisotropic hydrogels strain sensors with enhanced sensing performance for human motion monitoring and wireless transmission. *Chem. Eng. J.* 461, 142099. <https://doi.org/10.1016/j.cej.2023.142099>.
117. Wang, W., Deng, X., Tian, Z., and Luo, C. (2023). Anisotropic, ultra-sensitive, self-adhesive, biocompatible, and conductive hydrogels prepared for wearable sensors. *Eur. Polym. J.* 196, 112277. <https://doi.org/10.1016/j.eurpolymj.2023.112277>.
118. Li, C., Yang, Z., Zhu, J., Gao, C., Wang, M., and Gao, Q. (2024). Anti-freezing and moisturizing PAA/PEDOT: PSS ionogels with multiple stimulus responses for flexible wearable electronics. *Eur. Polym. J.* 210, 112934. <https://doi.org/10.1016/j.eurpolymj.2024.112934>.
119. Lu, Y., Yue, Y., Ding, Q., Mei, C., Xu, X., Wu, Q., Xiao, H., and Han, J. (2021). Self-Recovery, Fatigue-Resistant, and Multifunctional Sensor Assembled by a Nanocellulose/Carbon Nanotube Nanocomplex-Mediated Hydrogel. *ACS Appl. Mater. Interfaces* 13, 50281–50297. <https://doi.org/10.1021/acsmi.1c16828>.
120. Li, Q., Zhi, X., Xia, Y., Han, S., Guo, W., Li, M., and Wang, X. (2023). Ultra-stretchable High-Conductivity MXene-Based Organohydrogels for Human Health Monitoring and Machine-Learning-Assisted Recognition. *ACS Appl. Mater. Interfaces* 15, 19435–19446. <https://doi.org/10.1021/acsmi.3c00432>.

121. Tian, C., Khan, S.A., Zhang, Z., Cui, X., and Zhang, H. (2024). Thermo-electric Hydrogel Electronic Skin for Passive Multimodal Physiological Perception. *ACS Sens.* 9, 840–848. <https://doi.org/10.1021/acssensors.3c02172>.
122. Kim, H., Dutta, S.D., Jeon, M.J., Lee, J., Park, H., Seol, Y., and Lim, K.-T. (2025). Bioinspired Shape Reconfigurable, Printable, and Conductive “E-Skin” Patch with Robust Antibacterial Properties for Human Health Sensing. *Adv. Funct. Mater.* 35, 2504088. <https://doi.org/10.1002/adfm.202504088>.
123. Zheng, S., Ruan, L., Meng, F., Wu, Z., Qi, Y., Gao, Y., and Yuan, W. (2025). Skin-Inspired, Multifunctional, and 3D-Printable Flexible Sensor Based on Triple-Responsive Hydrogel for Signal Conversion in Skin Interface Electronics Health Management. *Small* 21, 2408745. <https://doi.org/10.1002/smll.202408745>.