

## WEARABLE ELECTRONICS FOR SKELETAL MUSCLE HEALTH MONITORING

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## Abstract

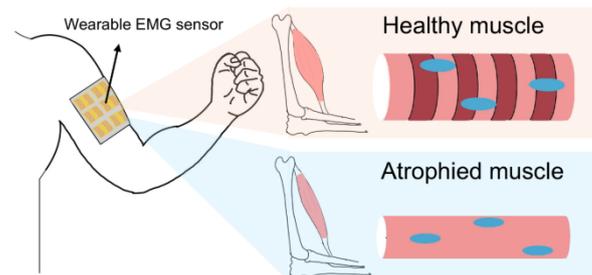
Wearable sensors designed for skeletal muscle monitoring are reshaping how we study, assess, and support muscular function in both clinical and everyday environments. In this review, we examine recent progress in soft and flexible bioelectronic technologies that enable continuous, noninvasive, and high-resolution measurement of muscle activity. Our discussion focuses on three core sensing strategies: mechanical sensors that capture strain and muscle deformation, electrical sensors for surface electromyography (sEMG), and biochemical sensors that detect muscle-related biomarkers such as creatinine in sweat. Special attention is given to the role of advanced materials, particularly flexible and nano-materials, and structural designs that combine high sensitivity with mechanical adaptability, including crack-based sensors, ultrathin stretchable electrodes, and self-powered biosensing systems. Through selected examples, we illustrate how these systems are engineered and applied to monitor muscle contraction, fatigue, and metabolic state. We also reflect on current technical challenges, such as maintaining signal quality during motion, ensuring long-term skin compatibility, and achieving reliable multimodal integration. Altogether, this review highlights how interdisciplinary advances at the intersection of materials science, electronics, and muscle physiology are shaping the next generation of wearable platforms for diagnostics, rehabilitation, and interactive biomedical technologies.

**Keywords:** Wearable electronic, Skeletal muscle monitoring, Muscle atrophy, Surface electromyography, Strain gauge, Sweat sensor, Flexible electronic.

## INTRODUCTION

Skeletal muscle is essential for movement, maintaining posture, and regulating metabolism, representing about 40% of the total body mass in adults<sup>1</sup>. It plays a crucial role in voluntary movement and acts as a sensitive physiological marker for systemic conditions, including neuromuscular disorders, muscular dystrophies, and age-related atrophy<sup>2-4</sup>. **(Figure 1)** In sports science and rehabilitation medicine, real-time assessment of muscle activity, fatigue, and injury recovery is critical for optimizing performance and ensuring safe return-to-play protocols.<sup>5</sup> As a result, the continuous and non-invasive monitoring of muscle function has become an intriguing focus for wearable health technologies.<sup>6,7</sup> The electrophysiological and mechanical characteristics of muscle, including electrical depolarization, mechanical strain during contraction, and biomolecular markers linked to fatigue or injury, provide essential understanding of muscular health.<sup>8</sup> Technologies designed to capture this information encompass electromyography (EMG) sensors for monitoring electrical activity<sup>9</sup>, strain sensors for assessing muscle deformation<sup>10</sup>, and biochemical sensors for analyzing sweat metabolites such as creatinine.<sup>11</sup> However, current monitoring strategies largely rely on rigid materials that pose inherent limitations in conforming to soft, curvilinear muscle surfaces, particularly during dynamic movement.<sup>12,13</sup> These limitations reduce signal quality, user comfort, and long-term biocompatibility, hindering their practical application in real-world. To overcome these challenges, there is a growing shift toward flexible and stretchable electronics that provide intimate, long-term integration with the skin.<sup>14,15</sup>

By minimizing mechanical mismatch and maximizing surface conformity, the devices enable accurate, stable signal acquisition while maintaining the integrity of natural biomechanics.<sup>16</sup> Nevertheless, successful translation of flexible electronics to skeletal muscle monitoring requires addressing several key engineering factors. These include mechanical flexibility to accommodate muscle movement, conformal contact for low-impedance interfacing, breathability to support prolonged wear without skin irritation, and biocompatibility to ensure tissue safety under continuous use.<sup>17</sup> This review explores the latest innovations and ongoing obstacles in the development of wearable electronics for monitoring skeletal muscle activity. We begin by covering the engineering requirements for flexible and curvilinear sensing interfaces and subsequently explore cutting-edge applications in EMG, strain, and biochemical sensing. In conclusion, we explore the trade-offs in fabrication, the limitations of materials, and prospective strategies for the seamless integration of multifunctional sensing platforms into practical applications for muscle health. Through an understanding of key bottlenecks and innovative solutions, we offer a strategic pathway for the advancement of biointegrated monitoring systems for skeletal muscular diagnostics.



**Figure 1. Overview of wearable electronics for monitoring electrophysiological signals of skeletal muscle**

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## Limitation of conventional materials for wearable electronics

The growing demand for wearable electronics that can continuously monitor muscle activity and function has imposed high standards for material selection. Conventional bioelectronic interfaces, mainly made of rigid materials like silicon wafers, glass substrates, and metallic traces, have shown limitations in achieving intimate integration with the soft, curved, and dynamic surfaces of the human body.<sup>13,15</sup> Although these materials demonstrate outstanding electronic performance and ease of manufacturing, their fundamental mechanical and physiological differences with biological tissues hinder their suitability in long-term and high-quality muscular sensing applications.<sup>18</sup> The main limitation stems from the mechanical mismatch between rigid electronic materials and soft muscular tissues. The elastic modulus of human skeletal muscle typically falls between 10 to 100 kPa, making it significantly softer than conventional electronics, which typically exhibit moduli that surpass the GPa range.<sup>16,17</sup> This discrepancy generates stress concentrations at the interface between biological and electronic elements, especially during movement or muscle contraction. This mismatch, thus, leads to delamination of the device, signal instability, and irritation of the tissue. In addition to discomfort, the lack of conformal contact compromises signal quality by increasing contact impedance and reducing spatial resolution, particularly detrimental in applications requiring high-precision electromyographic (EMG) or strain recordings.<sup>12</sup> Moreover, conventional materials lack breathability, a property essential for long-term epidermal or muscular integration. Impermeable substrates hinder evaporative sweat loss and gas exchange, potentially inducing maceration, inflammation, or barrier dysfunction during prolonged wear.<sup>19</sup> Attempts to mitigate this through adhesives or perforation introduce further design complexity and are often insufficient for active users or athletes. Additionally, biocompatibility remains a concern. Repeated mechanical deformation can lead to microfractures or ion leaching, triggering adverse cellular responses.<sup>20</sup> Recent advances in materials science offer promising pathways to address these limitations. The rise of flexible and stretchable electronic materials that are engineered to mimic the mechanical properties of native tissues has allowed the development of wearable electronics. In the following chapters, essential engineering criteria that form the foundation of next-generation wearable electronics for muscular monitoring are discussed.

## Engineering soft and flexible electronics

Addressing the mechanical and physiological obstacles associated with conventional bioelectronic materials requires a fundamental change in the choice of materials and the design of devices. Wearable electronics aimed at ongoing muscular monitoring need to be developed to closely interact with flexible, living tissues while maintaining high signal accuracy and reliability over time. To accomplish this, materials need to be designed not just for electrical conductivity but also for biomechanical compatibility, enabling seamless integration with skin, muscle, and connective tissue. Four design criteria such as flexibility, conformal contact, breathability, and biocompatibility have appeared as essential factors shaping device performance in vivo. (Figure 2) This chapter investigates into the core principles and exemplary strategies employed in the

engineering of wearable electronics that meet these standards, thus enhancing the functionality and practical application of muscle-interfaced bioelectronic systems.

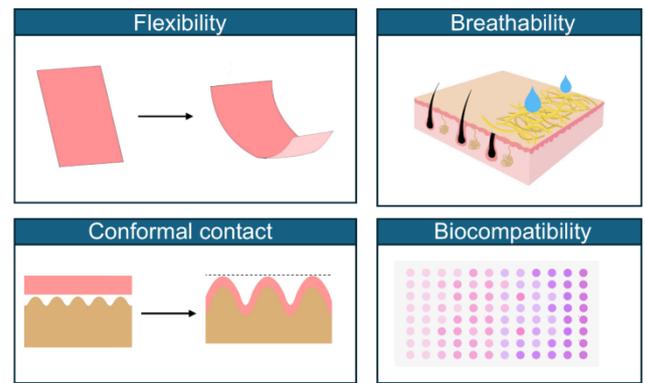


Figure 2. Critical factors for next-generation materials and structural designs for wearable electronics.

## Mechanical property and flexibility

Mechanical flexibility remains a cornerstone in the design of wearable electronics for skeletal muscle sensing. The intrinsic softness and mobility of muscle tissue make it incompatible with conventional rigid electronics, which often fail to maintain conformal contact during motion, leading to poor signal quality or even device delamination. While bulk electrical properties are important, they are rendered irrelevant if the sensor cannot endure the strains imposed by everyday movement. In musculoskeletal applications, particularly during active motion, a device must not only flex but also maintain stable performance over repeated mechanical loading. One major design strategy involves the use of intrinsically soft materials such as hydrogels and conductive polymers. These materials inherently match the modulus of biological tissues typically in the range of tens to hundreds of kilopascals allowing for superior mechanical compatibility. For example, Pan et al. developed an interlocked structure combining hydrogel and elastomer, achieving a modulus around 11.5 kPa while maintaining adhesion during skin movement and preserving signal fidelity for electromyography (EMG) monitoring under dynamic joint flexion.<sup>21</sup> Another approach leverages supramolecular elastomers embedded with conductive nanomaterials. Cheng et al. engineered carbon nanotube (CNT)-reinforced supramolecular networks that combined stretchability with electrical stability over thousands of deformation cycles.<sup>22</sup> These composites remained functional under strains over 100%, highlighting their potential for high-motion applications such as athletic training or rehabilitation monitoring.

In parallel, geometric engineering has enabled the use of rigid conductors in flexible formats. Choi et al. implemented a microphase-separated Ag–Au nanocomposite embedded in a styrene–butadiene–styrene elastomer, achieving a modulus below 40 MPa.<sup>23</sup> This design supported reliable EMG signal acquisition from bending wrist surfaces, emphasizing the utility of microstructured rigid components in soft-device platforms. This approach reduces the mechanical mismatch by dissipating strain through the structure, rather than relying solely on material softness. Beyond intrinsic softness, topological network design has also been used to enhance flexibility in conductive polymers. Jiang et al. incorporated polyrotaxane structures into polyaniline matrices, significantly

reducing the film stiffness from  $\sim 2.5\text{--}3$  GPa to as low as  $0.5\text{--}1$  MPa.<sup>24</sup> These materials were fabricated into flexible noninvasive electrode arrays (FNEs) that could conform to complex biological geometries, including human skin and even octopus musculature, enabling stable and high-fidelity EMG recordings during substantial deformation. While material softness is a fundamental criterion, flexibility alone does not guarantee long-term usability. Fatigue resistance, recovery from repeated loading, and mechanical stability under physiological conditions are equally important. Many soft materials degrade under cyclic mechanical stress due to viscoelastic creep or microstructural fatigue. Therefore, achieving robust mechanical compliance demands a multiscale approach, combining soft interfaces, engineered geometries, and resilient materials, to ensure long-term performance in both clinical and real-world environments.

### Conformal contact for enhanced biointerface

Reliable acquisition of electrophysiological and biomechanical signals from skeletal muscle hinges on the quality of the interface between wearable electronics and biological tissue. Conformal contact minimizes interfacial impedance, prevents motion-induced artifacts, and enhances signal fidelity by maintaining intimate, uniform adhesion across dynamic and irregular surfaces. Unlike conventional gel-based electrodes, which often lose contact during prolonged use or vigorous movement, conformal systems facilitate stable signal transduction by physically integrating with skin and underlying muscle in a soft, non-irritating manner.<sup>12</sup> Muscle and epidermal tissues present a mechanically challenging interface. The skin exhibits surface roughness on the order of tens of micrometers, along with curvature, folds, and continuous strain due to body movement.<sup>15</sup> Rigid sensors tend to lift, delaminate, or shift during activity, which increases contact impedance and degrades signal-to-noise ratio. Hence, conformal integration is not just about mechanical softness but also requires engineering devices to match skin topology and accommodate dynamic strain. Stretchable and ultrathin designs are critical to maintaining seamless contact under real-world mechanical perturbations.

One effective strategy is the development of ultrathin electronic films. As bending stiffness scales with the cube of film thickness, reducing device thickness to sub-micrometer levels allows high conformability without compromising function. Kim et al. introduced gold nanomembrane electrodes fabricated on polyimide substrates with total thicknesses below  $1\ \mu\text{m}$ . These devices could laminate over complex skin geometries, maintaining low interfacial impedance during motion, and enabling high-fidelity EMG acquisition.<sup>13</sup> Similarly, nanomesh electrodes fabricated using lithographic patterning or electrospinning have demonstrated mechanical transparency and skin permeability, eliminating the need for adhesive gels while improving comfort and breathability.<sup>17</sup> Maintaining long-term adhesion without irritation is another critical aspect of conformal design. Bioinspired adhesive systems, such as catechol-modified polymers and micropillar arrays, have been employed to mimic the reversible adhesion properties seen in organisms like mussels and geckos.<sup>25</sup> Mussel-inspired resilient hydrogels with strong skin adhesion and high-sensitivity for wearable device. These systems provide secure yet breathable contact during extended wear. Beyond physical contact, the interface must also facilitate effective electrical coupling. Thin layers of ionically

conductive hydrogels can serve as intermediate layers that bridge ionic skin currents and electronic sensor inputs. This dual-function interface reduces impedance while maintaining mechanical softness, particularly beneficial in high-deformation scenarios such as athletic activity or neuromuscular rehabilitation. In sum, conformal contact is the foundation of stable, long-term muscle monitoring and remains a pivotal design requirement for next-generation wearable electronics.

### Breathability for long-term wearability

Maintaining skin homeostasis is essential for the long-term performance of wearable electronics, especially in applications involving continuous skeletal muscle monitoring. Among the critical yet often underestimated design considerations is breathability, defined as the ability of materials to permit water vapor transmission from the skin surface. Without adequate breathability, sweat accumulation and moisture buildup can trigger skin irritation, allergic responses, or even maceration. Additionally, trapped moisture elevates interfacial impedance, degrades signal quality, and accelerates mechanical delamination of the device problems especially prevalent during exercise, rehabilitation, or extended daily wear.<sup>12</sup> Flexible nanomesh electronics (FNEs) have emerged as a promising solution, offering both mechanical compliance and high water vapor permeability. Miyamoto et al. introduced a PVA-based nanomesh platform that adhered conformally to the skin for over seven days with no signs of inflammation or discomfort.<sup>26</sup> Breathability tests demonstrated water vapor transmission rates (WVTRs) comparable to bare skin, highlighting the system's potential for long-term epidermal user. Translational studies have confirmed the clinical viability of breathable platforms in muscle health contexts. For example, Kwon et al. developed a large-area epidermal electronic system (L-EES) using nanomembrane electrodes embedded in an elastomer-fabric matrix.<sup>27</sup> With a WVTR of  $3.13 \pm 0.18\ \text{g m}^{-2}\ \text{h}^{-1}$ , comparable to commercial Tegaderm films, the device enabled high-fidelity EMG acquisition in patients with spinal cord injuries, without inducing allergic or cytotoxic responses throughout multi-day use. Alternative strategies for achieving breathability focus on microporous or microperforated substrates. Tian et al. engineered a bilayer silicone electrode with tunable porosity, achieving a WVTR greater than  $10\ \text{g m}^{-2}\ \text{d}^{-1}$  while maintaining mechanical integrity and adhesion over large muscle areas. Likewise, Lo et al. implemented sponge-like microstructures with high pore density to enhance skin contact and vapor release.<sup>28</sup> Their sponge electrodes outperformed Ag/AgCl electrodes in impedance and signal-to-noise ratio, achieving SNR values up to 60 dB during muscle activity monitoring.

Zheng et al. extended this approach to create a porous "electronic tattoo" composed of thermoplastic polyurethane and silver nanowire networks.<sup>29</sup> The design yielded a WVTR of  $20.5\ \text{mg cm}^{-2}\ \text{h}^{-1}$  which is substantially higher than traditional medical adhesives. Also the device enabled reliable, unobtrusive EMG signal capture even on compromised skin, such as scarred or sensitive areas. These developments demonstrate that breathability is critical for reliable bioelectronic integration. By engineering material porosity and leveraging breathable substrates, next-generation wearable systems can improve comfort, signal stability, and device longevity, paving the way for widespread, real-world adoption.

## Biocompatibility for stability

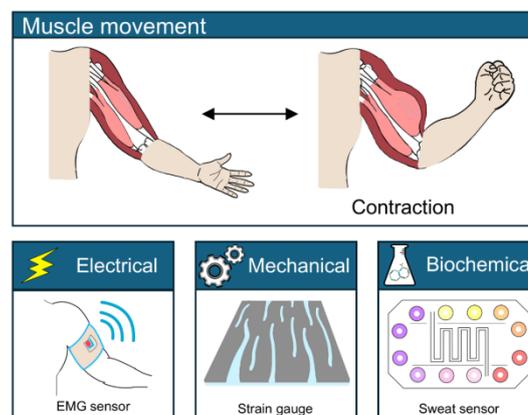
Ensuring biocompatibility is fundamental for wearable electronics designed for skeletal muscle monitoring, particularly under extended use conditions. Unlike short-term diagnostic tools, long-term epidermal devices must avoid eliciting adverse skin reactions while maintaining stable sensor-tissue interaction. As users often wear these devices during exercise or daily activity, the materials used must tolerate sweat, movement, and variable skin pH without causing irritation, inflammation, or degradation in signal performance. Soft elastomers like polydimethylsiloxane (PDMS), polyurethane (PU), and Ecoflex are commonly used due to their flexibility and general safety profile. However, these materials are inherently hydrophobic, which can reduce adhesion and lead to dryness or discomfort over prolonged use. Strategies such as surface oxidation or grafting hydrophilic polymers have been used to improve wettability and user comfort. Hydrogel-based materials have shown particular advantages, not only by mimicking tissue softness but also by maintaining moisture balance at the interface. For example, gelatin-PEDOT:PSS composite hydrogels have demonstrated moderate adhesion and stable sEMG signal acquisition, reducing discomfort and skin damage during repeated application.<sup>30</sup>

Natural biopolymers offer another route toward enhancing biocompatibility. Silk fibroin, in particular, has attracted attention for its skin-conforming properties and breathability. Zhang et al. engineered a silk–resilin copolymer patch that adhered effectively to moist, irregular skin while avoiding residue or irritation even after hours of use.<sup>31</sup> This system featured water-triggered detachment, providing a non-disruptive removal process. This feature is important for repeatable clinical or athletic applications. Besides substrate and adhesion layers, the choice of conductive materials also plays a critical role in biocompatibility. While gold and platinum are well-established for their inertness, emerging carbon-based materials and silver nanowires require more careful consideration due to potential cytotoxicity or inflammatory responses, particularly under oxidative stress. Proper surface functionalization and encapsulation are therefore crucial. Cai et al. demonstrated an encapsulated multilayer sensor system in PDMS that maintained low skin-electrode impedance and high SNR under real-use conditions, illustrating how thoughtful design integration can achieve both performance and safety.<sup>32</sup> Overall, biocompatibility is not just a property of individual materials but an emergent result of all layers working together in harmony with the skin.

## Applications in skeletal muscle monitoring

Flexible and skin-conformable electronics have ushered in a new era of wearable devices capable of interfacing seamlessly with the musculoskeletal system. These platforms are particularly transformative in the context of skeletal muscle monitoring, where continuous, non-invasive tracking of both biomechanical and biochemical parameters is critical for diagnosis, rehabilitation, and performance optimization. The convergence of materials science and bioelectronics has enabled the integration of soft, stretchable sensors that can capture electrophysiological signals such as electromyograms (EMG), mechanical deformations due to muscle contraction, and biochemical markers like sweat metabolites. In this chapter, we explore three representative modalities of wearable

sensors such as EMG sensors, strain sensors, and sweat-based biochemical sensors, as emerging tools for real-time assessment of muscle activity and health status. (Figure 3) These applications exemplify how engineering solutions rooted in flexibility, biocompatibility, and breathability can provide high-quality, longitudinal data while minimizing user discomfort and interference with daily activity.



**Figure 3. Applications of wearable electronic for skeletal muscle monitoring**

## Electrical sensing for wearable EMG sensors

Surface electromyography (sEMG) has become a cornerstone technology for monitoring muscle activity in a wide array of applications, including neuromuscular diagnostics, rehabilitation, prosthetic control, and human–machine interfacing. Central to the evolution of sEMG monitoring is the development of flexible noninvasive electrodes (FNEs) that ensure both high-fidelity signal acquisition and wearer comfort, particularly during extended use and dynamic body motion.

Kwon et al. developed a large-area, stretchable epidermal electronic system (L-EES) that integrates a 16-channel sEMG sensor array within a nanomembrane fabric–elastomer hybrid, optimized for long-term muscle monitoring in patients with spinal cord injuries.<sup>33</sup> The device was engineered to balance stretchability, breathability, and conformal skin contact by embedding ultrathin gold electrodes into a fabric-supported elastomeric mesh. This hybrid design achieved a high water vapor transmission rate of  $3.13 \pm 0.18 \text{ g m}^{-2} \text{ h}^{-1}$ , comparable to commercial medical films, while maintaining electrical stability and skin biocompatibility. In functional tests, the L-EES enabled high-resolution classification of forearm gestures without requiring gels or adhesives, sustaining robust signal quality even under dynamic movements. This work not only demonstrated a clinically relevant EMG platform for neuromuscular rehabilitation but also highlighted the potential of nanomembrane–textile hybrids for scalable, wearable bioelectronics.

Gandla et al. introduced a frame-type, large-area sEMG sensor array fabricated via ultrafast, mask-free laser ablation to enable real-time human–machine interaction through muscle signal acquisition.<sup>34</sup> The sensor array was patterned directly on stretchable Ecoflex/PDMS substrates with resolutions down to  $50 \mu\text{m}$ , and it covered a  $\sim 20 \text{ cm}$  wide area of the human arm substantially broader than typical EMG platforms. This fabrication method achieved 100% yield within four minutes, demonstrating scalability and user accessibility. The substrate's

low modulus (~50 kPa), reversible skin adhesion (~3.3 kPa), and high water vapor permeability (~8 g m<sup>-2</sup> h<sup>-1</sup>) allowed comfortable, long-term skin integration. The stretchable electrodes maintained robust electromechanical properties across 10,000 mechanical loading cycles, ensuring signal reliability under motion. Functionally, the device enabled accurate electromyographic signal acquisition during arm movement and successfully controlled robotic hand gestures, highlighting its promise for wearable robotics, prosthesis actuation, and soft human-machine interfacing.

Lo et al. introduced an elastomeric sponge electrode designed to improve biopotential signal acquisition by reducing contact impedance and enhancing signal-to-noise ratio (SNR) through a porous interface architecture.<sup>28</sup> The device employed a polydimethylsiloxane (PDMS) sponge structure fabricated via sacrificial templating with sugar cubes, followed by dip-coating with the conductive polymer PEDOT:PSS. This porous configuration increased the effective skin-electrode contact area and enabled the sponge to retain more conductive gel, significantly lowering impedance by factors of 5.25 and 6.7 compared to planar PEDOT:PSS and Ag/AgCl electrodes, respectively. As a result, the sponge electrode provided stable, high-SNR sEMG recordings during long-term use, even under movement. Notably, the system was sensitive enough to detect not only skeletal muscle activity but also subtle smooth muscle signals such as uterine contractions from pregnant patients, demonstrating its translational potential in obstetrics and wearable clinical diagnostics.

These three studies exemplify the cutting edge of EMG acquisition technologies by addressing critical challenges such as biomechanical conformity, signal quality under motion, and interface stability over time. Their experimental rigor and translational relevance make them foundational examples in the field of wearable muscle monitoring. As flexible electrode arrays continue to evolve, such systems are poised to become integral components in clinical diagnostics, rehabilitation robotics, and human-machine interaction platforms.

### Mechanical sensing for wearable strain gauges

Mechanical sensors have emerged as indispensable components in wearable electronics, particularly for musculoskeletal monitoring, owing to their ability to translate physical deformations such as strain, pressure, and torsion into quantifiable electrical signals. Unlike bioelectrical signals like sEMG, which are susceptible to electrical interference and motion artifacts, mechanical strain sensors offer high stability, repeatability, and signal-to-noise ratios over prolonged wear. These features make them ideal for applications such as rehabilitation monitoring, sports biomechanics, and human-machine interfaces. Strain sensing in wearable systems is achieved through various transduction mechanisms, including resistive, capacitive, piezoelectric, and triboelectric modalities. Each modality presents trade-offs in sensitivity, stretchability, hysteresis, and long-term durability. For example, resistive sensors often provide high sensitivity and simple readout schemes but are vulnerable to hysteresis under cyclic loading. Capacitive and piezoelectric sensors, on the other hand, offer rapid response and high temporal resolution but may require complex signal conditioning and stable mechanical interfaces. The selection and engineering of sensor materials is central to optimizing performance metrics such as gauge factor, detection limit, linearity, and dynamic range. Yamada et al. developed a

stretchable resistive strain sensor composed of aligned single-walled carbon nanotubes (SWCNTs) capable of detecting strains up to 280% while maintaining low creep and fast temporal response.<sup>10</sup> The working principle relied on the formation of conductive gaps and islands under strain, resulting in a reversible change in electrical resistance suitable for monitoring body motion, respiration, and vocalization in real-time wearable platforms. For low-amplitude mechanical signals, such as arterial pulse or vocal cord vibrations, piezoelectric and capacitive sensors offer distinct advantages in terms of sensitivity and bandwidth. Dagdeviren et al. fabricated a piezoelectric pressure sensor using lead zirconate titanate (PZT) integrated with silicon nanomembrane-based field-effect transistors.<sup>35</sup> The device achieved an ultralow detection limit of ~0.005 Pa and rapid response time of ~0.1 ms, enabling accurate measurement of arterial pulse waves and speech-induced throat movement. Beyond intrinsic material properties, microstructural engineering has proven effective in enhancing sensitivity and selectivity. Pang et al. implemented a bioinspired microhair array in a capacitive pressure sensor to amplify subtle mechanical signals such as wrist pulse.<sup>36</sup> Compared to flat electrodes, the microstructured surface significantly improved SNR and allowed differentiation of cardiovascular conditions through pulse waveform analysis. Similarly, Han et al. introduced a 3D carbon nanofiber network mimicking human dermal architecture, achieving pressure sensitivity of 1.41 kPa<sup>-1</sup> and resilience over >95% compression strain, facilitating detection of phonation, pulse, and joint motion.<sup>37</sup>

A notable advancement in resistive strain sensing is the use of crack-based architectures. A highly sensitive and stretchable crack-based strain sensor was developed by depositing carbon nanotubes (CNTs) and silver nanowires (AgNWs) onto electrospun thermoplastic polyurethane (TPU) fiber mats via vacuum-assisted filtration, leveraging capillary forces to reinforce the conductive network.<sup>38</sup> A prestretching treatment introduced a microcrack architecture that enabled exceptional performance metrics: an ultrawide working range of 0–171% strain, ultrahigh sensitivity with gauge factors along with a fast response time (~65 ms), minimal hysteresis, and durability exceeding 2000 cycles. The sensor, governed by distributed microcrack propagation in an "island-bridge" structure, demonstrated robust real-time monitoring of vibrations and human motions, highlighting its promise for electronic skin and wearable health diagnostics. To further address the complexity of human movement, recent developments emphasize multimodal strain sensors capable of differentiating between stretch, compression, bending, shear, and torsion. Tee et al. introduced a supramolecular polymer composite embedded with nickel nanostructured microparticles that exhibits both pressure sensitivity and ambient-condition self-healing, closely mimicking the dual functionalities of human skin.<sup>39</sup> The material achieved tunable electrical conductivity up to 40 S·cm<sup>-1</sup> by adjusting the nickel content, and demonstrated excellent piezoresistive response to flexion and tactile forces. Upon mechanical rupture, the composite restored ~90% of its initial conductivity within 15 seconds and fully recovered its mechanical properties within 10 minutes. These features highlight its strong potential for use in electronic skin applications for soft robotics and biomimetic prosthetics. Overall, wearable strain sensors have advanced remarkably in precision, stretchability, and multimodal functionality. By integrating nanomaterial-based architectures, bioinspired microstructures, and flexible hybrid interfaces, these systems

now support high-fidelity monitoring of muscle dynamics across diverse settings, from athletic performance tracking to clinical rehabilitation, positioning them as vital tools in the future of personalized healthcare and soft robotics.

### Biochemical sensing for sweat-based creatinine monitoring

Creatinine is a crucial biomarker that reflects skeletal muscle metabolism and renal function. It is produced as a byproduct of the breakdown of creatine phosphate, a molecule that acts as a rapid energy buffer during muscle contraction.<sup>40,41</sup> Because this degradation occurs at a nearly constant rate proportional to muscle mass, creatinine levels in bodily fluids provide a stable indication of muscle activity and kidney clearance. Typically excreted through the kidneys, creatinine accumulation in the body may indicate impaired renal filtration or excessive muscle breakdown.<sup>40,42</sup> In the context of wearable health monitoring, measuring creatinine in sweat offers a unique opportunity to assess both physical exertion and renal status in a noninvasive and continuous manner, particularly relevant for athletes, elderly individuals, and patients with muscle-wasting diseases or chronic kidney disease. For instance, Zhao et al. developed a multiplexed wearable electrochemical sensor platform by integrating sodiated conductive polymers with MXene nanosheets to enable real-time detection of sodium ions and creatinine in sweat.<sup>42</sup> Their system employed sodiated PEDOT:PSS for potentiometric sodium sensing and polypyrrole (PPy) for voltammetric creatinine detection, forming a layered structure between nanoporous carbon-PEG and Ti<sub>3</sub>C<sub>2</sub>T<sub>x</sub> MXene sheets. This configuration stabilized electron transfer across the sensor interface and minimized drift, achieving a signal stability of 0.02 mV/h for sodium and 0.008  $\mu$ A/h for creatinine over 24 hours, with operational integrity maintained over 3,000 cycles. The high capacitance (over 400  $\mu$ F) and durability under repetitive stretching allowed for accurate sweat biomarker tracking during everyday activity, demonstrating its potential for long-term, noninvasive health monitoring.

Material innovations have further expanded the capabilities of creatinine sensors. Li et al. introduced a self-powered biosensing system using stretchable fiber-based triboelectric nanogenerators (F-TENGs) for simultaneous motion sensing and biochemical sweat analysis.<sup>43</sup> Constructed from Ecoflex-coated polyaniline (PANI) conductive fibers and varnished wire electrodes, the F-TENG exploited a triboelectric-enzymatic coupling effect to detect creatinine, glucose, and lactic acid in sweat. The sensor achieved a creatinine response rate of up to 125% without requiring an external power source, and further supported wireless data transmission for IoT applications. By combining motion capture and metabolic sensing in a single stretchable architecture, this platform provides a sustainable and integrated solution for wearable diagnostics. Despite these advancements, several hurdles remain. Sweat rate variability can significantly affect analyte dilution, making normalization strategies such as concurrent electrolyte or osmolarity sensing essential. Furthermore, device durability under mechanical strain and chemical degradation during prolonged wear must be addressed through encapsulation strategies and skin-conformal mechanics.

### Opportunities and challenges in translational application

Wearable electronics for musculoskeletal monitoring have progressed rapidly, integrating advances in soft materials,

microfabrication, and system-level design. Devices such as flexible EMG arrays, crack-based strain sensors, and sweat creatinine detectors now enable continuous, multimodal assessment of muscle activity under real-world conditions.<sup>7,10,36,38</sup> These platforms offer significant potential in personalized rehabilitation, early disorder detection, and sports performance optimization by providing temporally rich data outside clinical environments.<sup>3,7</sup> However, translational deployment faces persistent challenges. Foremost is ensuring measurement reliability under dynamic skin conditions, including motion, sweat, and long-term wear. Although materials like hydrogels, nanocomposites, and bioinspired adhesives offer improved conformability and sensitivity, many lack mechanical durability for extended use.<sup>21,25,27</sup> Moreover, the manufacturing gap remains substantial. Techniques like sputtering or photolithography yield high-performance devices but are ill-suited for scalable production. Alternatives such as screen and inkjet printing require further refinement to match lab-scale precision.<sup>44</sup> System integration also presents hurdles. Power, signal processing, and wireless transmission must be incorporated into ultrathin, biocompatible platforms. While battery-free and chip-embedded systems have emerged<sup>45</sup>, they often rely on rigid modules that compromise flexibility and user comfort. In parallel, ergonomics and clinical usability remain critical. Devices must align with user preferences and healthcare infrastructure, including compatibility with electronic health records and telemedicine platforms.<sup>46</sup>

### Conclusion

The integration of wearable electronics with skeletal muscle has opened a new frontier in personalized health monitoring, sports science, and rehabilitation engineering. This review has highlighted how recent advances in soft materials, sensor architectures, and fabrication strategies are converging to address longstanding limitations of conventional monitoring systems. By leveraging flexible, stretchable, and skin-conformal devices, researchers have significantly improved the ability to track muscle strain, electrical activity, and biochemical changes in real time without compromising comfort or performance. Strain sensors have enabled precise quantification of muscle deformation under dynamic conditions, while high-density EMG arrays now offer improved spatial and temporal resolution for electrophysiological monitoring. Meanwhile, emerging biochemical sensors for metabolites like creatinine are beginning to offer new insights into muscular metabolism and fatigue. These multimodal platforms not only enrich our understanding of muscle physiology but also offer promising routes for early diagnosis of neuromuscular diseases, continuous rehabilitation assessment, and real-world human-machine interfacing. Despite these advances, challenges remain. Ensuring long-term durability under mechanical stress, minimizing signal artifacts during movement, achieving reliable skin adhesion, and integrating power-efficient data transmission are all active areas of investigation. Moreover, translating lab-scale innovations into scalable, manufacturable, and clinically validated products demands cross-disciplinary collaboration between materials scientists, biomedical engineers, and healthcare providers. Looking forward, the field is poised to evolve from isolated sensing elements toward fully integrated, autonomous systems capable of multimodal feedback, self-healing, or therapeutic intervention. As flexible electronics mature, they are likely to become not just tools for observation, but active participants in personalized muscle

care, adapting, responding, and intervening in real time. Through continued innovation at the intersection of mechanics, electronics, and biology, wearable sensors will play a pivotal role in shaping the future of musculoskeletal diagnostics and human performance optimization.

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### REFERENCES

- Lieber, R. L. & Ward, S. R. Skeletal muscle design to meet functional demands. *Philosophical Transactions of the Royal Society B: Biological Sciences* 366, (2011).
- Ji, Y. *et al.* Inflammation: Roles in Skeletal Muscle Atrophy. *Antioxidants* vol. 11 Preprint at <https://doi.org/10.3390/antiox11091686> (2022).
- Wilkinson, D. J., Piasecki, M. & Atherton, P. J. The age-related loss of skeletal muscle mass and function: Measurement and physiology of muscle fibre atrophy and muscle fibre loss in humans. *Ageing Research Reviews* vol. 47 Preprint at <https://doi.org/10.1016/j.arr.2018.07.005> (2018).
- Sayer, A. A. & Cruz-Jentoft, A. Sarcopenia definition, diagnosis and treatment: Consensus is growing. *Age and Ageing* vol. 51 Preprint at <https://doi.org/10.1093/ageing/afac220> (2022).
- Gandevia, S. C. Spinal and supraspinal factors in human muscle fatigue. *Physiological Reviews* vol. 81 Preprint at <https://doi.org/10.1152/physrev.2001.81.4.1725> (2001).
- Bonato, P. Wearable Sensors/Systems and Their Impact on Biomedical Engineering. *IEEE Engineering in Medicine and Biology Magazine* vol. 22 Preprint at <https://doi.org/10.1109/MEMB.2003.1213622> (2003).
- Heikenfeld, J. *et al.* Wearable sensors: Modalities, challenges, and prospects. *Lab on a Chip* vol. 18 Preprint at <https://doi.org/10.1039/c7lc00914c> (2018).
- Farina, D. & Holobar, A. Characterization of Human Motor Units from Surface EMG Decomposition. *Proceedings of the IEEE* vol. 104 Preprint at <https://doi.org/10.1109/JPROC.2015.2498665> (2016).
- Ji, H. *et al.* Skin-integrated, biocompatible, and stretchable silicon microneedle electrode for long-term EMG monitoring in motion scenario. *npj Flexible Electronics* 7, (2023).
- Yamada, T. *et al.* A stretchable carbon nanotube strain sensor for human-motion detection. *Nat Nanotechnol* 6, (2011).
- Koh, A. *et al.* A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Sci Transl Med* 8, 366ra165 (2016).
- Trung, T. Q. & Lee, N. E. Flexible and Stretchable Physical Sensor Integrated Platforms for Wearable Human-Activity Monitoring and Personal Healthcare. *Advanced Materials* 28, (2016).
- Kim, D.-H. *et al.* Epidermal Electronics. *Science (1979)* 333, 838–843 (2011).
- Schwödiauer, R. *et al.* An ultra-lightweight design for imperceptible plastic electronics. *Nature* 499, 458–463 (2013).
- Rogers, J. A., Someya, T. & Huang, Y. Materials and Mechanics for Stretchable Electronics. *Science (1979)* 327, 1603–1607 (2010).
- Wang, C. *et al.* Advanced Carbon for Flexible and Wearable Electronics. *Advanced Materials* vol. 31 Preprint at <https://doi.org/10.1002/adma.201801072> (2019).
- Xu, S. *et al.* Soft microfluidic assemblies of sensors, circuits, and radiis for the skin. *Science (1979)* 344, (2014).
- Someya, T., Bao, Z. & Malliaras, G. G. The rise of plastic bioelectronics. *Nature* 540, 379–385 (2016).
- Li, Z. *et al.* All-Fiber Structured Electronic Skin with High Elasticity and Breathability. *Adv Funct Mater* 30, (2020).
- Cho, K. W. *et al.* Soft Bioelectronics Based on Nanomaterials. *Chem Rev* 122, 5068–5143 (2022).
- Pan, S. *et al.* Mechanically Interlocked Hydrogel–Elastomer Hybrids for On-Skin Electronics. *Adv Funct Mater* 30, (2020).
- Cheng, Y. *et al.* An Elastic and Damage-Tolerant Dry Epidermal Patch with Robust Skin Adhesion for Bioelectronic Interfacing. *ACS Nano* 16, (2022).
- Choi, S. *et al.* Highly conductive, stretchable and biocompatible Ag–Au core–sheath nanowire composite for wearable and implantable bioelectronics. *Nat Nanotechnol* 13, 1048–1056 (2018).
- Jiang, Y. *et al.* Topological supramolecular network enabled high-conductivity, stretchable organic bioelectronics. *Science (1979)* 375, (2022).
- Drotlef, D. M., Amjadi, M., Yunusa, M. & Sitti, M. Bioinspired Composite Microfibers for Skin Adhesion and Signal Amplification of Wearable Sensors. *Advanced Materials* 29, (2017).
- Miyamoto, A. *et al.* Inflammation-free, gas-permeable, lightweight, stretchable on-skin electronics with nanomeshes. *Nat Nanotechnol* 12, (2017).
- Yang, K. *et al.* Conformal, stretchable, breathable, wireless epidermal surface electromyography sensor system for hand gesture recognition and rehabilitation of stroke hand function. *Mater Des* 243, 113029 (2024).
- Lo, L. W. *et al.* Stretchable Sponge Electrodes for Long-Term and Motion-Artifact-Tolerant Recording of High-Quality Electrophysiologic Signals. *ACS Nano* 16, (2022).
- Zheng, Y. *et al.* Ultrathin and highly breathable electronic tattoo for sensing multiple signals imperceptibly on the skin. *Nano Energy* 107, (2023).
- Lim, C. *et al.* Tissue-like skin-device interface for wearable bioelectronics by using ultrasoft, mass-permeable, and low-impedance hydrogels. *Sci Adv* 7, eabd3716 (2021).
- Zhang, Y. & Tao, T. H. Skin-Friendly Electronics for Acquiring Human Physiological Signatures. *Advanced Materials* 31, (2019).
- Cai, P. *et al.* Locally coupled electromechanical interfaces based on cytoadhesion-inspired hybrids to identify muscular excitation-contraction signatures. *Nat Commun* 11, (2020).
- Kwon, Y. T. *et al.* Breathable, large-area epidermal electronic systems for recording electromyographic activity during operant conditioning of H-reflex. *Biosens Bioelectron* 165, (2020).
- Gandla, S. *et al.* Ultrafast Prototyping of Large-Area Stretchable Electronic Systems by Laser Ablation Technique for Controllable Robotic Arm Operations. *IEEE Transactions on Industrial Electronics* 69, (2022).
- Dagdeviren, C. *et al.* Conformal piezoelectric systems for clinical and experimental characterization of soft tissue biomechanics. *Nat Mater* 14, (2015).
- Pang, C., Lee, C. & Suh, K. Y. Recent advances in flexible sensors for wearable and implantable devices. *Journal of*

- Applied Polymer Science* vol. 130 Preprint at <https://doi.org/10.1002/app.39461> (2013).
37. Han, Z. *et al.* Fabrication of highly pressure-sensitive, hydrophobic, and flexible 3D carbon nanofiber networks by electro spinning for human physiological signal monitoring. *Nanoscale* 11, (2019).
  38. Sun, H. *et al.* An ultrasensitive and stretchable strain sensor based on a microcrack structure for motion monitoring. *Microsyst Nanoeng* 8, (2022).
  39. Tee, B. C. K., Wang, C., Allen, R. & Bao, Z. An electrically and mechanically self-healing composite with pressure- and flexion-sensitive properties for electronic skin applications. *Nat Nanotechnol* 7, (2012).
  40. Patel, S. S. *et al.* Serum creatinine as a marker of muscle mass in chronic kidney disease: Results of a cross-sectional study and review of literature. *Journal of Cachexia, Sarcopenia and Muscle* vol. 4 Preprint at <https://doi.org/10.1007/s13539-012-0079-1> (2013).
  41. das Neves, W., Alves, C. R. R., de Souza Borges, A. P. & de Castro, G. Serum Creatinine as a Potential Biomarker of Skeletal Muscle Atrophy in Non-small Cell Lung Cancer Patients. *Front Physiol* 12, (2021).
  42. Kalasin, S. & Sangnuang, P. Multiplex Wearable Electrochemical Sensors Fabricated from Sodiated Polymers and Mxene Nanosheet To Measure Sodium and Creatinine Levels in Sweat. *ACS Appl Nano Mater* 6, (2023).
  43. Zhao, T. *et al.* Wearable biosensors for real-time sweat analysis and body motion capture based on stretchable fiber-based triboelectric nanogenerators. *Biosens Bioelectron* 205, (2022).
  44. Li, L. *et al.* All Inkjet-Printed Amperometric Multiplexed Biosensors Based on Nanostructured Conductive Hydrogel Electrodes. *Nano Lett* 18, 3322–3327 (2018).
  45. Gutruf, P. *et al.* Wireless, battery-free, fully implantable multimodal and multisite pacemakers for applications in small animal models. *Nat Commun* 10, 5742 (2019).
  46. Arakawa, T. *et al.* Mouthguard biosensor with telemetry system for monitoring of saliva glucose: A novel cavitas sensor. *Biosens Bioelectron* 84, 106–111 (2016).

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