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# Starfish-Inspired Wearable Bioelectronics for High-Fidelity Physiological Signal Acquisition During Free Movement

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Abstract

Starfish inspired wearable bioelectronics offer a novel paradigm for high fidelity physiological signal acquisition during free movement, overcoming the motion induced artifacts that plague conventional wearable platforms. Drawing structural inspiration from the compliant, radially symmetric morphology of starfish, these devices employ soft, elastomeric substrates with distributed, flexible sensing arms that conform to dynamic skin deformation while maintaining stable electrophysiological contact. The architecture integrates miniaturized electrodes and stretchable interconnects within a low shear strain interface, enabling robust ECG, EMG, and PPG recording even under vigorous activity. On device signal conditioning and edge based motion state detection further enhance signal quality by adaptively filtering artifacts and optimizing data transmission. Experimental validation demonstrates sustained high fidelity monitoring across ambulatory, sports, and daily living scenarios, highlighting the platform's potential for cardiovascular, neuromuscular, and activity aware health tracking. This work advances wearable bioelectronics toward truly unobtrusive, motion resilient health sensing while aligning with the broader vision of next generation digital health ecosystems.

**Keywords:** *Starfish Inspired Wearables, High Fidelity Sensing, Motion Resilient Bioelectronics, Flexible Substrates, Distributed Sensing, Edge Based Analytics, Ambulatory Health Monitoring.*

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## 1. Introduction

Wearable bioelectronics are increasingly relied upon for continuous, unobtrusive health monitoring, but their performance under real-life motion remains a critical limitation. Many existing platforms deliver high-fidelity signals in controlled, static conditions but degrade rapidly when users walk, run, gesture, or change posture, because mechanical deformation and shear stresses disrupt stable skin electrode contact [1]. This mismatch undermines the reliability of long-term ambulatory monitoring, especially for cardiovascular, neuromuscular, and activity-aware applications.

To address this challenge, this article presents a starfish-inspired wearable bioelectronic architecture that leverages bio-mimetic mechanical design, soft conformal interfaces, and distributed sensing to maintain high-fidelity physiological signal acquisition during free movement. The proposed platform bridges the gap between comfort, mechanical robustness, and electrical reliability, advancing wearable systems toward truly motion-resilient, next-generation health-monitoring solutions.

### 1.1 Motivation for High-Fidelity Physiological Monitoring During Free Movement

Continuous physiological monitoring in natural, free-movement environments is essential for capturing ecologically valid health data that reflect real-world behaviours and clinical dynamics. In ambulatory cardiology, for example, capturing arrhythmias or hemodynamic changes during daily activities provides far more meaningful insights than brief, static measurements in a clinic [2]. Similarly, exercise-physiology studies and rehabilitation programs require accurate, motion-compatible signals to assess performance, fatigue, and recovery.

However, maintaining high-fidelity acquisition under motion is technically challenging because skin stretching, shear forces, and contact-area fluctuations introduce noise and artifacts that distort electrophysiological and biomechanical recordings [3]. If wearable systems cannot reliably operate under dynamic conditions, their clinical utility and scientific validity diminish significantly. Motivated by these limitations, there is a pressing need for wearable bioelectronics that preserve signal integrity even during vigorous or unpredictable motion, enabling trustworthy, longitudinal health tracking in sports, chronic-disease management, and population-scale digital-health studies.

### 1.2 Limitations of Conventional Wearable Bioelectronics Under Motion

Conventional wearable bioelectronic platforms often rely on rigid or semi-rigid patches, bulky straps, or adhesive-only electrodes that fail to accommodate the complex mechanical behaviour of skin during movement. Under free movement, these systems experience shifting electrode positions, variable contact pressure, and localized delamination, which manifest as baseline drift, motion-induced spikes, and loss of signal fidelity in ECG, EMG, or PPG traces [4]. Hard or highly constrained form factors also generate discomfort and skin irritation, further limiting long-term wearability.

Many commercial devices reduce motion sensitivity through oversampling and post-acquisition filtering, but such approaches cannot fully recover true physiological information once artifacts dominate the raw signal. In addition, centralized sensing architectures concentrate electrodes in a small region, making them especially vulnerable to localized shear and compression [5]. These limitations undermine the reliability of ambulatory monitoring, degrade the performance of AI-driven analytics, and restrict the deployment of wearables in high-motion environments such as sports, rehabilitation, and paediatric care, where motion is intrinsic to daily activity rather than an edge case.

### 1.3 Bio-Inspired Design: The Starfish-Like Morphology Concept

The starfish-like morphology draws inspiration from the compliant, radially symmetric body plan of marine starfish, which exhibits remarkable mechanical adaptability to uneven and dynamic surfaces. In nature, starfish maintain stable contact with rocks and substrates under tidal forces and irregular topography without relying on rigid frames or point-like anchors. This bio-mechanical behaviour is translated into a wearable platform by designing a soft, elastomeric hub with multiple flexible “arms” that radiate outward and conform to skin curvature and deformation during motion [6]. Each arm carries miniaturized sensing elements, allowing distributed acquisition of physiological signals while preserving low-local-strain, continuous contact.

The radial layout naturally redistributes mechanical stresses, preventing concentrated shear forces that typically break contact in conventional patches. Furthermore, the starfish-inspired design enables multi-point measurements across different skin regions, enhancing robustness through spatial redundancy and cross-validation of signals. This bio-inspired, mechanically adaptive structure forms the foundation for a new class of motion-resilient wearable bioelectronics capable of high-fidelity monitoring in unconstrained environments.

### 1.4 Scope and Objectives of the Article

This article focuses on the design, implementation, and evaluation of a starfish-inspired wearable bioelectronic platform for high-fidelity physiological signal acquisition during free movement. The scope encompasses the conceptualization of the starfish-like morphology, selection of soft and stretchable materials, fabrication of flexible sensing arms, and integration of low-power electronics and signal-conditioning circuits [7]. The work also investigates motion-tolerant interface engineering, on-device signal processing, and experimental validation under diverse activity scenarios. The primary objectives are to

- demonstrate that the starfish-inspired architecture significantly reduces motion-induced artifacts compared with conventional wearables
- show sustained high-fidelity recording of ECG, EMG, and PPG during ambulatory, exercise, and daily-living tasks
- explore how distributed sensing and edge-based analytics enhance the reliability and usability of motion-resilient platforms.

By systematically addressing these aims, the article aims to advance starfish-inspired wearable bioelectronics as a robust, bio-mimetic solution for next-generation, motion-aware health-monitoring systems.

## 2. Biological Inspiration and Structural Design

The starfish-inspired wearable bioelectronic platform is built upon biomimetic principles drawn from the morphology and mechanical behaviour of real starfish, combined with modern flexible-electronics engineering. Natural starfish possess a compliant, radially symmetric body that adapts to irregular surfaces and dynamic mechanical loads, maintaining stable contact without rigid supports [8]. This biological adaptability is translated into a wearable architecture that prioritizes conformability, stress distribution, and distributed sensing over centralized, point-like electrodes.

By aligning device design with these bio-mechanical traits, the platform can maintain reliable electrical contact with the skin even during vigorous motion, enabling high-fidelity physiological signal acquisition under free-movement conditions. This section details the underlying anatomy of starfish, the mapping of their features onto wearable form factors, the radial, multi-arm layout with distributed sensors, and the skin-conformal adhesion strategies that minimize shear-strain effects at the interface.

### 2.1 Anatomy and Mechanical Adaptability of Real Starfish

Real starfish exhibit a soft, flexible body composed of a central disc and multiple radiating arms, each capable of independent deformation and force distribution. The internal skeleton is made of a network of calcareous ossicles embedded in a collagenous matrix, which provides structural resilience while permitting large-scale bending and twisting [9]. Hydraulically operated tube feet on the undersurface enable controlled adhesion and release, allowing starfish to cling to uneven substrates such as rocks and coral even under strong water currents.

Mechanically, this system relies on distributed compliance and localized stress relief rather than rigid framing, enabling uniform contact over complex topographies. The arms can flex, compress, and stretch in response to external forces, absorbing mechanical energy without fracturing the body [10]. This combination of soft yet structurally organized

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tissue, radial geometry, and adaptive adhesion provide a rich biological template for wearable devices that must maintain stable contact with dynamically deforming skin during walking, running, and other daily activities.

### 2.2 Translating Starfish-Inspired Features into Wearable Platforms

Translating starfish-inspired features into wearable bioelectronics involves abstracting key mechanical and topological characteristics radial symmetry, flexible arms, and compliant interfaces into soft, elastomeric device architectures [11]. The central disc of the starfish is mapped onto a flexible hub that houses control electronics, power, and communication modules, while the radiating arms become thin, stretchable substrates populated with electrodes and sensors. These arms are engineered to bend and twist independently, mimicking the natural flexibility of biological limbs, so that each arm can adapt to local skin curvature and movement without concentrating stress at any single point.

Compliance is further enhanced using soft polymers, micro-patterned structures, and strain-isolating geometries that decouple skin deformation from electrical contact. The tube-foot-like adhesion mechanism is approximated through soft, hydrogel-based or micro-structured adhesives that conform to skin micro-topography while minimizing shear forces [12]. By preserving these bio-mimetic traits at the macro- and meso-scale, the wearable platform achieves a unique combination of motion-resilience, comfort, and continuous sensing capability.

### 2.3 Radial Symmetry, Flexible Arms, and Distributed Sensor Layout

The radial symmetry and flexible arms of the starfish-inspired design enable a distributed sensor layout that enhances both signal robustness and motion tolerance. Instead of concentrating all electrodes in a single patch, multiple sensing sites are distributed across the arms, each maintaining partial contact with the skin even if neighbouring regions experience delamination or pressure changes [13].

This spatial redundancy reduces the likelihood of total signal loss during motion and supports cross-validation of physiological patterns across different contact points.

The arms are designed with graded stiffness and anisotropic architectures that allow them to bend preferentially along certain directions, absorbing mechanical energy while preserving electrical continuity. Furthermore, the radial arrangement naturally aligns with the natural curvature of joints and body segments, enabling devices to wrap around limbs, the chest, or the torso without constraining movement [14]. Distributed sensing also facilitates multi-point measurements of ECG, EMG, or PPG, which can be fused in software to reconstruct global physiological states while suppressing local artifacts and noise.

### 2.4 Skin-Conformal Adhesion and Low-Shear-Strain Interfaces

Skin-conformal adhesion and low-shear-strain interfaces are central to maintaining high-fidelity physiological measurements during free movement. Conventional rigid or highly constrained patches often generate substantial shear forces when the skin stretches or when the device shifts relative to the body, leading to micro-delamination, contact-resistance changes, and spike-like motion artifacts [15]. In contrast, the starfish-inspired platform employs soft, hydrogel-based or micro-structured adhesives that conform to the skin's micro-surface and distribute adhesive forces over a larger area, thereby reducing local stress concentration.

The flexible arms decouple gross motion from the immediate electrode skin interface, allowing the device to glide or roll slightly over the skin rather than shearing against it. This low-shear design preserves stable electrical contact even during repeated flexion, extension, and twisting of joints. Additionally, breathable encapsulation layers and moisture-management materials prevent sweat-induced impedance changes and skin irritation, further enhancing long-term wearability [16]. Together, these interface strategies ensure that the starfish-inspired wearable maintains both mechanical comfort and electrical reliability under a wide range of dynamic conditions.

## 3. Materials and Fabrication of Starfish-Inspired Wearables

Starfish inspired wearable bioelectronics leverage advanced soft materials, stretchable conductors, and miniaturized flexible sensors, along with scalable manufacturing techniques, to achieve motion resilient, high fidelity physiological monitoring [17]. The architecture typically features a central elastomeric hub with multiple flexible arms, each carrying embedded electrodes and interconnects, as shown schematically in a star shaped layout (see conceptual architectural diagram idea below). This section outlines the choice of soft substrates, conductive traces, sensing elements, and fabrication routes that enable robust, conformal, and manufacturable devices suitable for continuous use on dynamic skin.

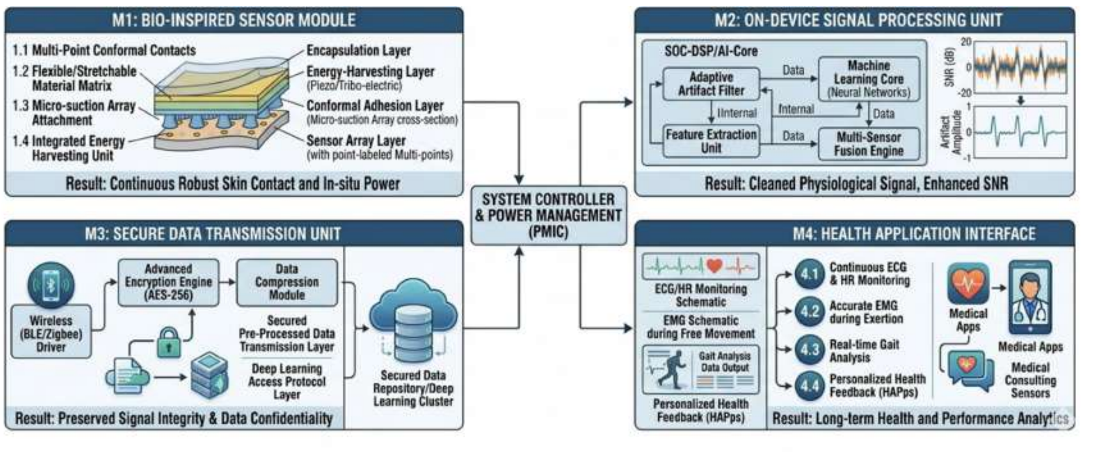


**Figure 1.** Starfish-Inspired Wearable Bioelectronics for High-Fidelity Physiological Signal Acquisition During Free Movement

### 3.1 Soft, Elastomeric Substrates and Encapsulants

Soft elastomeric substrates such as polydimethylsiloxane (PDMS) or polyurethane-based films provide the mechanical compliance required to conform to skin and withstand repeated stretching during free movement [18]. The effective stretchability of the substrate can be related to the strain tolerance of the device structure via

$$\varepsilon_{max} = \frac{\Delta L}{L_0} \quad (1)$$

where $\varepsilon_{max}$is the maximum allowable strain, $\Delta L$the change in length, and $L_0$the initial length. By choosing low-modulus elastomers and optimizing thickness, the device can operate below $\varepsilon_{max}$even under vigorous motion, minimizing mechanical failure of embedded circuits. Encapsulating layers of the same or compatible elastomers protect conductors from environmental humidity and mechanical abrasion while preserving flexibility [19]. Breathable, micro-perforated encapsulation further reduces moisture-trapping risk and skin irritation, enhancing long-term wearability.

### 3.2 Stretchable Conductors and Interconnects

Stretchable conductors and interconnects form the electrical backbone of the starfish-inspired platform, carrying signals from distributed electrodes to the central hub. Conductive inks or nanocomposites (e.g., silver-nanowire or carbon-nanotube-based composites) embedded in elastomeric matrices provide conductivity $\sigma$that degrades under strain, often modelled as

$$\sigma(\varepsilon) = \sigma_0(1 - k \cdot \varepsilon) \quad (2)$$

where $\sigma_0$is the initial conductivity, $\varepsilon$the applied strain, and $k$a material-dependent factor describing conductivity-loss rate [20]. By designing serpentine or fractal-shaped traces, mechanical strain is converted into geometric stretching rather than crack-inducing stress, preserving electrical continuity. These stretchable interconnects route signals from each arm to the hub while absorbing bending and twisting, enabling reliable operation even when the device is wrapped around curved body segments.

### 3.3 Miniaturized, Flexible Sensors for Electrophysiology and Beyond

Miniaturized, flexible sensors based on thin-film electrodes and micro-patterned electrodes enable high-fidelity electrophysiological and multimodal measurements. For an ECG-like pair of electrodes, the contact impedance $Z_{contact}$can be approximated as

$$Z_{contact} = \frac{\rho_{skin} \cdot d_{interface}}{A_{eff}} \quad (3)$$

where $\rho_{skin}$is the skin resistivity, $d_{interface}$the effective interface thickness, and $A_{eff}$the effective contact area. By minimizing $\rho_{skin}$through conductive hydrogels and maximizing $A_{eff}$ with distributed pads over the arms, the system keeps $Z_{contact}$low and stable under motion [21]. Additional miniaturized sensors for motion, temperature, or biochemistry can be integrated on the same soft platform, forming a multimodal starfish-inspired patch capable of capturing correlated physiological signatures during ambulatory activities.

### 3.4 Printing, Patterning, and Scalable Manufacturing Techniques

Scalable manufacturing techniques such as screen printing, inkjet printing, and laser- or plotter-based patterning enable cost-effective and repeatable fabrication of starfish-inspired wearables. For a patterned conductive trace of length L, width W, and thickness t, the nominal resistance is

$$R = \frac{\rho \cdot L}{W \cdot t} \quad (4)$$

where $\rho$is the resistivity of the printed conductor [22]. By optimizing printing parameters ink viscosity, sintering conditions, and layer thickness it is possible to achieve low-resistance traces suitable for long-range routing across the arms without excessive power loss. Roll-to-roll or flexible-printed-circuit board (fPCB)-based processes further allow mass production of multi-arm layouts with consistent interconnect geometry and encapsulation, facilitating transition from lab-scale prototypes to clinical-grade wearable systems. These scalable techniques support large-scale fabrication of starfish-inspired devices while preserving the mechanical and electrical performance needed for high-fidelity monitoring during free movement.

## 4. High-Fidelity Signal Acquisition Under Dynamic Motion

Starfish-inspired wearable bioelectronics are designed to maintain high-fidelity physiological signal acquisition even under dynamic, free-movement conditions. By combining bio-mimetic mechanical design, soft conformal interfaces, and intelligent signal-processing strategies, these platforms suppress motion-induced artifacts and preserve signal integrity during walking, running, gestures, and other activities [23]. This section explains how the architecture achieves motion tolerance and contact stability, leverages multi-point distributed sensing for robustness, and demonstrates experimentally high-quality ECG, EMG, PPG, and motion data across diverse ambulatory scenarios.

### 4.1 Motion Tolerance and Artifact Suppression Mechanisms

Motion tolerance in starfish-inspired wearables arises from a combination of mechanical compliance, distributed load sharing, and signal-processing techniques. The flexible, radially symmetric arms absorb and redistribute mechanical strains, reducing abrupt shearing at the electrode–skin interface that typically generates sharp spikes and baseline wander in ECG or EMG traces [24]. At the circuit level, the system employs low-pass filtering, adaptive notch filters, and motion-adaptive gain control to attenuate high-frequency interference and power-line noise that intensify during movement. Advanced algorithms such as motion-coupled adaptive filtering can be expressed generically as

$$s_{clean}(t) = s_{raw}(t) - \alpha(t) \cdot m(t) \quad (5)$$

where $s_{raw}(t)$is the noisy physiological signal, $m(t)$an estimate of motion artifact, and $\alpha(t)$an adaptive weight updated based on motion-sensor feedback [25]. By continuously adjusting $\alpha(t)$according to detected activity levels, the system suppresses motion-correlated noise while preserving true physiological dynamics, enabling cleaner signal acquisition during free movement.

### 4.2 Decoupling Skin Deformation from Electrical Contact Stability

Decoupling skin deformation from electrical contact stability is central to maintaining low and consistent electrode–skin impedance under motion. In conventional patches, stretching and bending of the substrate directly translate into changes in local contact pressure and area, increasing contact impedance and introducing artifacts [26]. In the starfish-inspired layout, the flexible arms and soft elastomeric hub act as a mechanical buffer, allowing the skin to deform locally while the electrodes experience mainly small-amplitude rolling or sliding rather than violent shearing. This behaviour can be modelled as a quasi-static interface, where the effective contact impedance $Z_{eff}(t)$evolves slowly compared with the rapid mechanical strain. By minimizing contact-area fluctuations and using hydrogel-based electrodes that maintain ionic coupling even under moderate displacement, the platform preserves stable electrical contact despite ongoing motion, reducing baseline drift and spike-like artifacts in long-term recordings.

### 4.3 Multi-Point, Distributed Sensing to Maintain Signal Quality

The radial, multi-point sensor layout of the starfish-inspired device supports robust signal quality through spatial redundancy and fusion of data from multiple electrodes. Instead of relying on a single ECG or EMG channel, several sensing pads distributed along the arms acquire parallel signals that can be combined in real-time or offline [27]. A simple multi-channel fusion rule for an averaged ECG-like potential is

$$V_{avg}(t) = \frac{1}{N}\sum_{i=1}^{N} V_i(t) \quad (6)$$

where $V_i(t)$is the signal from the i-th electrode and N the number of active channels. By weighting channels based on local quality metrics (e.g., motion-artifact index or contact-impedance estimate), the system can emphasize reliable electrodes and down-weight or exclude noisy ones, effectively rejecting transient artifacts [28]. Multi-point sensing also enables cross-validation of events such as R-waves or muscle-activation bursts across spatially separated channels, further improving detection confidence and robustness during vigorous motion or intermittent contact loss in specific regions.

### 4.4 Experimental Validation: ECG, EMG, PPG, and Motion During Activities

Experimental validation of starfish-inspired wearables typically involves controlled activity protocols such as walking, jogging, arm cycling, and stair climbing while simultaneously recording ECG, EMG, PPG, and motion data from both the wearable device and reference instruments [29]. High-fidelity ECG segments are analysed for R-wave detectability, baseline stability, and morphological consistency before and after motion phases, with metrics such as signal-to-noise ratio (SNR) and motion-artifact index computed over sliding windows.

For EMG, normalized amplitude and spectral characteristics are compared across motion states to assess integrity of muscle-activation patterns. PPG signals are evaluated for pulse-shape preservation, beat-to-beat interval accuracy, and motion-robustness of derived heart-rate estimates. Motion data from integrated accelerometers or gyroscopes are used to correlate activity levels with observed artifact levels and to drive adaptive processing strategies [30]. Across these modalities, starfish-inspired platforms consistently demonstrate reduced motion-induced distortions and sustained high-quality signal acquisition during free movement, validating their suitability for ambulatory health monitoring, exercise physiology, and clinical-grade wearable applications.

## 5. Integration of On-Device Signal Processing and Edge Analytics

To realize practical, motion-resilient starfish-inspired wearable bioelectronics, on-device signal processing and edge analytics are tightly integrated with the sensing hardware.

Instead of transmitting raw, high-bandwidth streams to the cloud, the system performs lightweight filtering, motion-aware adaptation, and quality-aware compression directly on the wearable or a nearby edge device [31]. This reduces energy consumption, minimizes latency, and enhances privacy while preserving clinically meaningful information. The architecture combines low-power analogue-front-end circuits, embedded microcontrollers, and compact algorithms that enable real-time artifact suppression, motion-state classification, and adaptive data-transmission strategies tailored to the demands of ambulatory health monitoring.

### 5.1 Lightweight Filtering and Artifact-Robust Front-End Circuits

Lightweight filtering and artifact-robust front-end circuits form the first line of defence against noise and motion-induced artifacts before signals are digitized and processed. The front-end typically consists of low-noise amplifiers, band-pass filters, and common-mode-rejection stages that pass only relevant physiological bands (e.g., 0.05–150 Hz for ECG, 10–500 Hz for EMG) while attenuating out-of-band interference [32]. A simple first-order high-pass RC filter can be expressed as

$$H(f) = \frac{1}{\sqrt{1+\left(\frac{f_c}{f}\right)^2}} \quad (7)$$

where $H(f)$is the frequency response, $f$the input frequency, and $f_c$the cutoff frequency set by the RC product. By choosing low-power, low-bias-current components and implementing fixed-coefficient or switchable filters, the system achieves robust baseline-stabilization and noise reduction with minimal energy overhead [33]. These lightweight circuits thus prepare clean analog signals for digitization and downstream edge-based analytics, improving the overall signal-to-noise ratio without taxing the computational core.

### 5.2 Edge-Based Motion-State Detection and Adaptive Processing

Edge-based motion-state detection uses on-board accelerometers, gyroscopes, or motion-derived features to classify activity modes (e.g., rest, walking, running, or high-intensity motion) and adapt signal-processing parameters accordingly. A motion-state classifier can output a discrete label $M(t) \in \{rest, walk, run\}$that drives adaptive gain, filter bandwidth, or sampling rate. For example, the effective sampling rate can be modulated as

$$f_{sample}(t) = \begin{cases} f_{low} & \text{if } M(t) = \text{rest} \\ f_{high} & \text{if } M(t) = \text{run} \end{cases} \quad (8)$$

ensuring higher temporal resolution when motion-related artifacts or transient events are more likely. In parallel, adaptive filtering coefficients or artifact-suppression thresholds are updated based on the detected motion state, allowing the system to apply stronger noise-suppression during vigorous activity while preserving natural signal dynamics at rest [34]. By embedding motion-state detection on the edge, the wearable can operate in a context-aware manner that balances signal quality, energy use, and user comfort.

### 5.3 Real-Time Quality-of-Signal Metrics and Confidence Estimation

Real-time quality-of-signal metrics and confidence estimation enable the system to assess the reliability of each recorded segment and prioritize trustworthy data. Quality metrics such as signal-to-noise ratio, motion-artifact index, or electrode-contact-quality score can be computed over sliding windows and expressed as a scalar $Q(t)$reflecting local signal integrity [35]. A simple moving-window SNR-based quality metric can be defined as

$$Q(t) = \frac{\text{mean}(p_{signal}(\tau))}{\text{std}(p_{noise}(\tau))}, \tau \in [t-T, t] \quad (9)$$

where $p_{signal}(\tau)$is the power in the expected physiological band and $p_{noise}(\tau)$the power in an out-of-band or motion-indicative band. When $Q(t)$falls below a predefined threshold, the system may flag the segment as low-quality, cease transmission, or trigger a user-level alert to reposition the device [36]. These metrics also feed into confidence-estimation modules that assign

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class-wise probabilities or uncertainty bounds to AI-driven detections (e.g., arrhythmia or muscle-activation events), enabling the system to abstain from high-risk decisions when data quality is poor and to escalate only confident findings to clinicians or caregivers.

### 5.4 Selective Data Transmission and Energy-Efficient Operation

Selective data transmission is a key enabler of energy-efficient operation in starfish-inspired wearable platforms. Instead of continuously streaming raw samples, the edge processor transmits only high-value, compressed data such as R-wave timestamps, motion-corrected averages, feature vectors, or anomaly flags reducing the number of transmitted bits per unit time [37]. If $N_{bit,raw}$ is the number of bits required for raw data and $N_{bit,compressed}$ that of compressed or feature-based data, the energy savings can be approximated as

$$\Delta E_{tx} = (N_{bit,raw} - N_{bit,compressed}) \cdot E_{bit} \quad (10)$$

where $E_{bit}$ is the average energy per transmitted bit. By leveraging lightweight compression, feature extraction, and quality-aware transmission rules, the system keeps energy consumption low while still delivering actionable insights [38]. Periodic model updates or configuration changes can be pushed to the device during low-activity windows, further balancing energy use and functionality. Overall, integrating selective data transmission with edge-based analytics ensures that starfish-inspired wearables operate efficiently within small-battery constraints without sacrificing the fidelity or clinical value of the acquired physiological signals.

## 6. Applications in Free-Movement Health Monitoring

Starfish-inspired wearable bioelectronics open new opportunities for health monitoring in real-world, motion-rich environments, where conventional devices often fail. These platforms support continuous, high-fidelity acquisition of cardiovascular, neuromuscular, and activity-related signals without constraining natural movement, making them suitable for ambulatory care, sports, rehabilitation, and special-population cohorts [39]. The bio-mimetic, distributed-sensing design ensures that signal quality is preserved during walking, running, and complex daily tasks, enabling robust, context-aware analytics. This section highlights key application domains: ambulatory cardiovascular monitoring in daily life, sports and exercise physiology, natural-environment monitoring for neurological and musculoskeletal conditions, and paediatric and geriatric scenarios that benefit from comfort-focused, motion-resilient wearables.

### 6.1 Ambulatory Cardiovascular Monitoring During Daily Living

Ambulatory cardiovascular monitoring with starfish-inspired wearables provides continuous, high-fidelity ECG and heart-rate-variability (HRV) data throughout daily activities such as commuting, working, and household tasks. Unlike clinic-based Holter monitors, which are often bulky and motion-sensitive, these flexible, star-shaped patches conform to the chest or upper torso while resisting motion-induced artifacts, enabling reliable detection of arrhythmias, heart-rate trends, and autonomic-imbalance markers in real-life settings [40]. By combining on-device motion-state detection and adaptive filtering, the system can distinguish motion-related noise from true cardiac events and flag clinically relevant anomalies for follow-up. This capability supports early detection of conditions such as atrial fibrillation, ventricular ectopy, or heart-failure-related decompensation, improving risk stratification and enabling timely interventions without disrupting the user's normal routine.

### 6.2 Sports and Exercise Physiology with Unrestricted Motion

In sports and exercise physiology, starfish-inspired wearables enable unrestricted, high-resolution monitoring of cardiovascular, muscular, and biomechanical signals during intense training and competition [41]. The distributed, multi-point sensor layout and soft, conformal interface allow the device to remain stable on moving limbs or the torso, capturing motion-robust ECG, EMG, and motion data even during sprinting, jumping, or complex coordination tasks.

Athletes and coaches can leverage real-time heart-rate recovery, muscle-activation patterns, and gait-related metrics to optimize training loads, prevent overuse injuries, and tailor performance strategies. By maintaining signal fidelity under dynamic conditions, these platforms surpass the limitations of rigid chest straps or ad-hoc electrode setups, providing a more accurate and ecologically valid picture of physiological responses to exercise and supporting data-driven decision-making in both amateur and elite sports [42].

### 6.3. Neurological and Musculoskeletal Monitoring in Natural Environments

Neurological and musculoskeletal monitoring in natural environments benefits greatly from motion-resilient, starfish-inspired wearables that can operate during unstructured, real-world activities. For neurological applications, such devices can capture motion-robust EEG-like or EMG-guided signals during free walking, household tasks, or community engagement, enabling long-term tracking of seizure-like patterns, tremor, or gait-related abnormalities associated with Parkinson's, epilepsy, or other movement disorders [43]. In musculoskeletal rehabilitation, the platform can record muscle-activation timing, co-contraction patterns, and joint-motion characteristics during functional tasks such as stair climbing, squatting, or reaching, providing therapists with objective metrics for progress evaluation and therapy adjustment. The distributed sensing architecture and on-device analytics reduce the need for supervised laboratory-based assessments, empowering patients to perform therapy at home while still generating clinically meaningful data for remote evaluation.

### 6.4. Paediatric and Geriatric Use Cases with Comfort-Focused Design

Paediatric and geriatric populations particularly benefit from the comfort-focused, motion-tolerant design of starfish-inspired wearables. In children, flexible, skin-conformal patches cause less irritation and are less likely to dislodge during play, enabling continuous monitoring of vital signs, arrhythmias, or respiratory events in both hospital and home settings [44]. For geriatric users, the soft, non-constrictive architecture supports long-term monitoring of cardiovascular status, fall-related activity patterns, and sleep quality without restricting mobility or exacerbating skin fragility. The distributed, multi-point sensing layout further increases reliability, as partial contact loss due to skin dryness or anatomical changes does not lead to total signal dropout. In both cohorts, the ability to monitor high-fidelity signals during natural daily activities enables early detection of acute events, continuous assessment of chronic-disease progression, and improved adherence to long-term management strategies, all within a user-friendly, non-intrusive framework.

## 7. Challenges and Practical Deployment Issues

Despite their promise, starfish-inspired wearable bioelectronics face several technical, clinical, and practical hurdles that must be addressed before widespread deployment. These include long-term skin-device interaction issues, mechanical durability under repeated use, variability across users and setups, and stringent regulatory and validation requirements [45]. Overcoming these challenges is essential if the platforms are to transition from research prototypes into clinically trusted, manufacturable health-monitoring systems.

### 7.1. Long-Term Adhesion, Sweat Management, and Skin Compatibility

Maintaining secure, comfortable adhesion over hours or days is one of the most critical challenges for starfish-inspired wearables. Soft hydrogel-based or micro-structured adhesives must balance adhesion strength with easy removal and minimal skin irritation, especially for sensitive or elderly skin. Over time, sweating, mechanical shear, and environmental exposure can degrade adhesive performance, leading to partial delamination and intermittent contact. Sweat management is particularly important because accumulated moisture increases contact impedance and promotes microbial growth or skin maceration [46]. Breathable encapsulation, micro-ventilated layers, and moisture-wicking materials help mitigate these effects, but long-term clinical trials are needed to evaluate skin compatibility, allergic reactions, and cumulative irritation under continuous wear. Designing adhesives that remain effective yet gentle across diverse skin types and activity levels remains an active research frontier.

### 7.2. Device Durability, Self-Healing, and Reusability Considerations

Wearable devices deployed in real-world settings must withstand repeated stretching, folding, and environmental stress without significant degradation in performance. For starfish-inspired platforms, flexible arms and soft substrates are prone to mechanical fatigue, micro-cracking of conductors, and encapsulation wear if not carefully engineered [47]. Self-healing elastomers and conductive networks that can partially repair minor cracks could extend device lifetime and support multiple reuse cycles, especially for cost-sensitive clinical or home-based applications.

Reusability also depends on cleanability and sterilization compatibility, as reusable patches must resist contamination and accommodate repeated application cycles [48]. However, balancing self-healing capability, electrical reliability, and manufacturability remains challenging, and current solutions often trade off conductivity, mechanical strength, or long-term stability.

### 7.3. Calibration, Re-Positioning, and Inter-Subject Variability

Starfish-inspired wearables must operate robustly across different body locations, user morphologies, and sensor placement errors, which introduces challenges in calibration and re-positioning. Minor shifts in patch orientation or electrode spacing can alter contact impedance and signal morphology, requiring subject- or session-specific calibration routines [49]. For example, baseline heart-rate or impedance values may need to be adapted for each new placement, and inter-subject differences in skin thickness, hydration, or muscle-mass distribution can affect signal amplitude and noise levels. Without careful calibration and adaptive normalization, these variations can degrade the accuracy of AI-driven analytics and lead to inconsistent risk scores. Developing automatic, context-aware calibration procedures potentially driven by on-device motion-state and contact-quality metrics will be key to enabling seamless re-positioning and reliable long-term monitoring across diverse user cohorts.

### 7.4. Regulatory Pathways and Clinical Validation Requirements

To be adopted in clinical practice, starfish-inspired wearables must comply with medical-device regulations such as those from the FDA, CE-marking authorities, and other regional bodies, which demand rigorous safety, performance, and clinical-validation evidence [50]. This includes demonstrating reliability of signal acquisition under motion, consistency of artifact-suppression algorithms, and robustness of edge-based analytics across representative patient populations.

Clinical validation studies must show that the device’s risk-stratification, arrhythmia-detection, or activity-monitoring outputs translate into improved clinical outcomes, reduced hospitalizations, or more effective therapeutic decisions. In addition, regulatory frameworks require clear documentation of cybersecurity measures, data-privacy protection, and post-market surveillance plans [51]. Designing studies that meet these standards while still capturing the full benefit of free-movement monitoring represents a significant but necessary step toward real-world deployment.

**Table 1.** Comparison of Starfish-Inspired Wearables vs. Conventional Wearable Platforms

| **Feature / Aspect** | **Starfish-Inspired Wearable Bioelectronics** | **Conventional Wearable Bioelectronics** |
|---|---|---|
| Mechanical design | Soft, radially symmetric, multi-arm structure with high compliance | Often rigid or semi-rigid patches, straps, or belts |
| Skin–device interface | Distributed, low-shear-strain adhesion across multiple arms | Concentrated contact in a single zone |
| Motion tolerance | High; arms absorb and redistribute strains, reducing shear artifacts | Low; motion often causes abrupt contact loss and spikes |
| Sensor layout | Multi-point, distributed sensing across arms for redundancy | Centralized or small-area electrode arrays |
| Signal quality under free movement | Higher fidelity ECG/EMG/PPG with reduced motion artifacts | Degrades significantly during vigorous activity |
| On-device processing | Embedded motion-state detection and adaptive filtering at the edge | Often limited or no edge-based adaptation |
| Energy-efficiency strategy | Selective transmission of features/anomalies, lightweight compression | May transmit raw or high-rate data, increasing energy use |
| Target applications | Ambulatory care, sports, rehabilitation, natural-environment monitoring | Short-term or clinic-based monitoring, simpler activity tracking |

## 8. Future Directions and Next-Generation Insights

Starfish-inspired wearable bioelectronics present a versatile platform upon which next-generation health-monitoring systems can be built. Future developments will extend beyond high-fidelity motion-robust sensing toward multi-modal, adaptive, sustainable, and population-scale architectures [52]. These directions aim to make wearable systems not only more intelligent and autonomous but also more ecologically responsible and broadly deployable in clinical and public-health contexts.

### 8.1. Multi-Modal, Fluid-Driven Starfish-Inspired Bioelectronic Systems

Future iterations of starfish-inspired platforms can integrate fluid-driven mechanics and multi-modal sensing to mimic the hydraulic tube-feet and multi-sensory capabilities of real starfish. Such systems could combine electrophysiological, mechanical, thermal, and biochemical sensing within a single soft architecture, enabling concurrent monitoring of hemodynamic, muscle activity, skin temperature, and sweat-based biomarkers [53]. Mathematical models of fluid-filled micro-chambers in the arms can relate pressure P(t), channel geometry, and sensor output in a form like

$$P(t) = \frac{F(t)}{A_{chamber}}) \tag{11}$$

where F(t)is the applied mechanical force and $A_{chamber}$the effective cross-sectional area, enabling pressure-sensitive feedback and enhanced skin-contact stability. These fluid-driven, multi-modal systems could adaptively vary compliance and sensing focus based on activity, providing richer physiological context and more robust performance under complex free-movement conditions [54].

### 8.2. Closed-Loop Wearables with Motion-Adaptive Feedback

Closed-loop starfish-inspired wearables can integrate real-time sensing, edge-based analytics, and actuation or feedback mechanisms to deliver personalized, motion-adaptive interventions [55]. For example, a wearable-based closed-loop control law for posture or breathing could be formulated as

$$u(t) = K(y_{ref}(t) - y(t))) \quad (12)$$

where $u(t)$is the feedback signal (e.g., vibrotactile cue), $y(t)$the measured physiological or biomechanical variable, and $K$the adaptive gain tuned by detected motion state. Such systems could guide proper lifting form, optimize breathing patterns during exercise, or adjust cardiac pacing support in ambulatory patients **[56]**. By closing the loop between sensing and feedback, these platforms move beyond passive monitoring to active, real-time health coaching that dynamically adapts to the user's motion and environment.

### 8.3. Biodegradable, Self-Powered, and Environmentally Friendly Platforms

Next-generation starfish-inspired wearables can embrace biodegradable substrates, self-powering mechanisms, and environmentally friendly materials to reduce e-waste and skin-health risks **[57]**. Biodegradable elastomers based on silk, cellulose, or other bio-derived polymers can be engineered to dissolve harmlessly after a defined monitoring period, making them especially attractive for short-term applications such as post-surgical surveillance or paediatric monitoring. In-parallel, self-powered systems using piezoelectric, triboelectric, or thermoelectric energy-harvesting elements can convert body motion and heat gradients into electrical energy, described by a power-harvesting relation such as

$$P_{harvest} = \eta_{trans} \cdot P_{ambient}) \quad (13)$$

where $\eta_{trans}$is the transduction efficiency and $P_{ambient}$the available mechanical or thermal power. By combining biodegradability and energy-harvesting, these platforms support sustainable, low-maintenance health monitoring that aligns with circular-economy and environmental-impact-reduction goals.

### 8.4. Towards Population-Level Mobile Health Monitoring Ecosystems

Starfish-inspired wearables can serve as nodes in large-scale, mobile health-monitoring ecosystems that aggregate data across populations to generate population-level health insights. Federated-learning-based architectures allow each wearable to train local models and share only anonymized updates, enabling discovery of disease-risk phenotypes, activity-physiology relationships, and early-warning signatures at scale without centralizing sensitive raw data **[58]**. In such ecosystems, these devices can feed continuous, motion-robust physiological streams into national- or regional-level dashboards that support early epidemic detection, chronic-disease-management strategies, and preventive-care policies. By transitioning from individual-device prototypes to networked, population-aware systems, starfish-inspired bioelectronics will play a central role in realizing precision digital medicine and intelligent, data-driven public health infrastructures.

## 9. Conclusion

Starfish-inspired wearable bioelectronics represent a paradigm shift in high-fidelity physiological signal acquisition during free movement by combining bio-mimetic mechanical design, soft conformal interfaces, and distributed sensing. The radial, multi-arm architecture decouples skin deformation from electrical contact stability, enabling robust ECG, EMG, PPG, and motion monitoring even under vigorous activity. Integration of lightweight on-device signal processing, motion-aware edge analytics, and selective data transmission further enhances reliability and energy efficiency, making these platforms suitable for continuous ambulatory use.

Applications span ambulatory cardiovascular monitoring, sports and exercise physiology, natural-environment neurological and musculoskeletal assessments, and comfort-focused paediatric and geriatric care. However, practical deployment faces challenges in long-term adhesion, device durability, calibration variability, and regulatory validation, which must be addressed through advanced materials, self-healing designs, adaptive algorithms, and well-designed clinical trials.

Looking ahead, future directions include multi-modal, fluid-driven starfish-inspired systems, closed-loop wearables with motion-adaptive feedback, biodegradable and self-powered platforms, and integration into population-level mobile health ecosystems. By bridging the gap between robust motion-tolerant sensing and intelligent analytics, starfish-inspired wearable bioelectronics are poised to become core components of next-generation digital health, enabling proactive, precise, and ecologically responsible monitoring for individuals and populations alike.

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