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Current Opinion in
Biomedical Engineering

Soft, skin-interfaced wearable systems for sports science and analytics

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Abstract

Connected wearable biosensors are a critical part of athletic performance analysis, injury and recovery time assessment, and hydration analytics, enabling elite athletes, trainers, and coaches to characterize the daily demands of sports. However, existing classes of wearable biosensors are constrained to a few body locations and tend to limit mobility due to their bulky size and weight. Recent advances in soft and stretchable skin-interfaced wearable sensors capable of real-time physiological monitoring and in situ sweat collection provide capabilities for real-time continuous motion, physiology, and biochemical analysis in an imperceptible mode from any location on the body. This review presents an overview of the latest developments in skin-interfaced wearable sensor technologies with an emphasis on soft materials and stretchable designs most suitable in sports. We conclude with a summary of unresolved challenges, opportunities, and future directions facing the field of sports science and analytics.

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Current Opinion in Biomedical Engineering 2019, **9**:47–56

This review comes from a themed issue on **Future of BME: Digital Heath and BME**

Edited by **George Truskey**

https://doi.org/10.1016/j.cobme.2019.01.003

Keywords

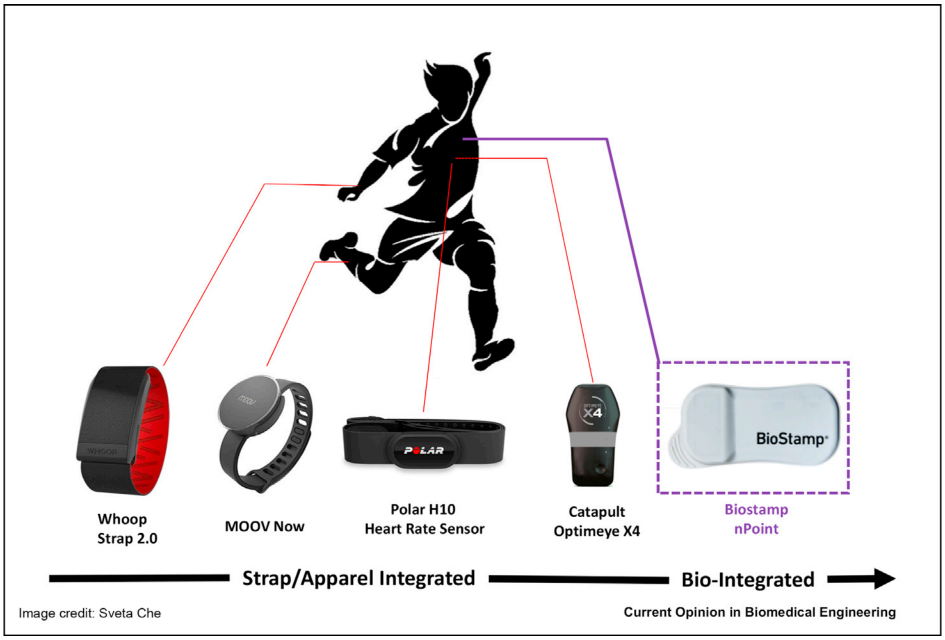
Wearable biosensors, Physiological monitoring, Sweat analysis, Sports science, Quantified athlete, Sweat sensing.

Introduction

Connected wearable technologies have enabled continuous monitoring of physiology, biomechanics, and movements during our daily activities and living. In sports, these biosignals have found broad utility in quantifying the performance and physical demands of athletes. Existing classes of wearable devices support continuous monitoring of athletes by leveraging recent advances in miniaturized microelectronics [1], wireless communication [2], rechargeable batteries, and multi-modal inertial and impedance-based biosensors [3], which are embedded in wrist bands, adhesives, athletic apparel, and chest straps for tight attachment to the body [4] (Figure 1). Although broadly deployed in sports, these wearable technologies lack the real-time metabolic and biochemical sensing capabilities required for quantifying electrolyte balance and hydration levels and, in some instances, impede athlete mobility due to physical characteristics of the device (e.g. form factor and weight), leading to poor signal quality and discomfort [5].

Recent advances in flexible/stretchable bioelectronics, biochemical sensors, soft microfluidics, and elastic bio-encapsulating materials have created new classes of skin-interfaced wearable systems that are compelling for use during intense sporting activities and in demanding environments. The soft physical design and ultrathin packaging of these skin-interfaced systems are essential properties that overcome many of the key challenges identified for conventional wearables. The Biostamp nPoint (MC10 Inc, Figure 1), a recently commercialized physiological monitoring device, embodies critical soft/stretchable mechanics features needed for intimate coupling with multiple locations on the human body, thus paving the way for entirely new skin-interfaced wearable systems.

Figure 1



Representative commercial devices for athletic performance monitoring. Typical commercial embodiments exploit straps (Whoop Strap 2.0, MOOV Now, Polar H10) or integrate with apparel (Catapult Optimeye X4) to interface with the skin for monitoring athletic performance. The BioStamp nPoint (MC10 Inc.), harnessing recent advances in stretchable electronics, represents the first truly biointegrated commercially available platform for wireless athletic performance monitoring.

This review focuses on the latest innovations in soft, stretchable wearable systems that enable a multitude of sensing capabilities including motion, physiological, and biochemical monitoring. These systems operate in a mode that is significantly advanced in functionality while exerting a minimal mechanical load on athletes to offer real-time understanding of sports performance and recovery. Beginning with an overview of key technologies underpinning skin-integrated devices, this review highlights representative examples of wearable skin-interfaced devices deployed in field studies and sports outside of laboratory settings. This review concludes with a discussion of the remaining technical challenges and opportunities for commercialization and broad-scale adoption in sports.

Enabling technologies for skin-interfaced wearables

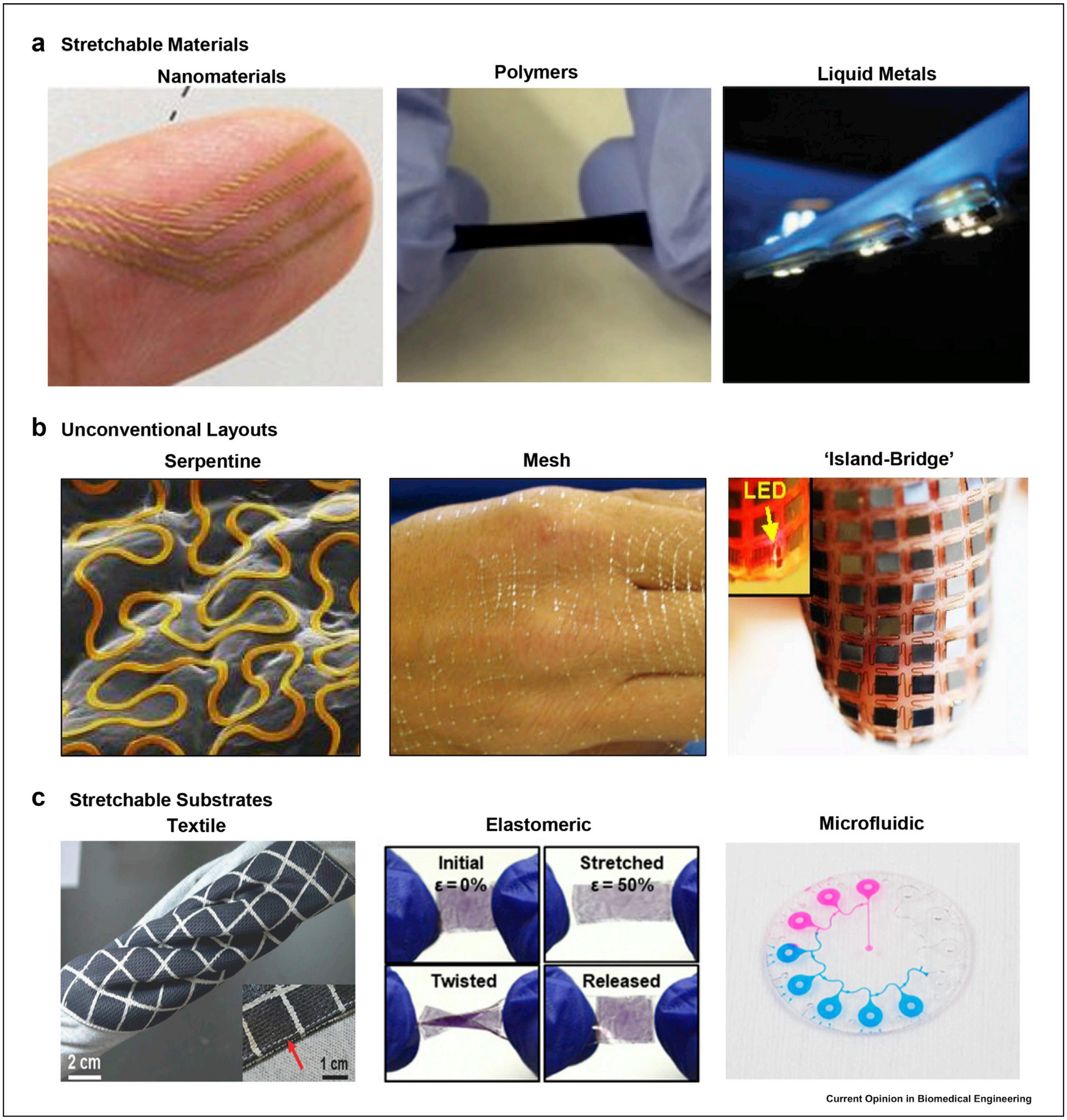
The direct integration of biosensors with the soft, curvilinear surface of the human body necessitates careful design to ensure seamless wear and reliable data capture during strenuous endurance training and sports activities. The most established classes of wearable sensors rely on stiff, brittle inorganic materials (e.g. silicon) well suited for rigid, planar devices [6]. However, such embodiments lack the requisite soft, stretchable physical properties for establishing an intimate, nonirritating interface with biological tissues, including the skin, necessary for long-duration monitoring of athletes.

Broad research efforts have sought to develop novel classes of electronics and underlying materials that overcome the physical design constraints inherent in traditional planar electronics without sacrificing function or performance [7]. Flexible electronics with submicrometer thicknesses have been shown to integrate with, to a large extent, the curvilinear contours of the human body, however not without random wrinkles, folds, and other nonideal features [8]. Stretchability is a critical characteristic for a robust and conformal interface with biological tissues without movement-induced device failure or loss in performance.

The strategies for achieving stretchable electronics utilize either inherently stretchable materials [9–13], unconventional layouts [14–16], or a combination thereof (Figure 2A and B). Replacing traditional electronic materials with those that are intrinsically stretchable, using either organic or inorganic chemistries, or by utilizing engineered composites that combine ultra-thin, typically nanoscale wires, membranes, ribbons or platelets of established, high-performance materials (e.g. silicon, metals) with soft substrates/superstrates, yields systems that can bend, stretch, and flex [17].

Soft encapsulating substrates are of considerable importance in defining robust interfaces with the body. These substrates (Figure 2C) are typically comprised of textiles or soft elastomeric materials [18] that have been

Figure 2



Enabling technologies for skin-interfaced wearable devices. **(a)** Representative examples of stretchable materials including stretchable nanocomposites [12] (left), inherently stretchable organic polymers [13] (center), and composites with liquid metals [9] (right). **(b)** Representative examples of unconventional layouts for enabling stretchability including serpentine device interconnects [14] (left), open mesh designs [15] (center), and 'island–bridge' layouts [16] (right). **(c)** Representative examples of stretchable substrates including textiles [10] (left), elastomeric materials [18] (center), and elastomeric materials with embedded microfluidic channels [11] (right).

shown to support bending, flexure, and dynamic multidimensional deformations. In addition to stretchability, moisture-resistant barrier layers, coatings, and embedded microfluidic channels help limit failure modes caused by sweat excretion and fluid exposure [5]. Although most wearable devices primarily interface with the skin, alternative surfaces such as the fingernails, outer ear lobe, inner mouth cavity, and surface of the eye represent other areas of interest for sports applications, where soft, biocompatible encapsulating materials, moisture barriers, and mechanical ruggedness are crucial features.

Soft wearables for athletic performance monitoring

Interest in wearable device technologies stems from the need for quantifying the physiological health state of athletes during activity (e.g., sporting event or training), recovery, and rest. Biometric parameters of interest such as movement (both geospatial and biomechanical), electrophysiological (heart rate), and hydration state (sweat loss) must be readily accessed either in real time or upon the event completion [7]. Although biochemical signals offer important physiological insights, few commercial solutions exist for in situ biomarker monitoring (e.g., electrolytes and metabolites). Soft wearable devices, owing to the previously described conformal, seamless interfacing with the body, offer new integrated platforms for continuous monitoring of both biophysical and biochemical signals of interest. The sections that follow highlight emerging wearable devices for capturing these signals and the potential insights offered for athletic performance.

Inertial and motion tracking

Complex multidimensional motion and kinematic measurement tools monitor sport-specific movements to assess motion quality and biomechanics for energy expenditure characterization and injury prediction [19]. Commercially available systems such as STATSports and Catapult Sports measure body weight, motion, distance traveled, and body position using inertial sensors and global positioning system modules [20]. These apparel integrated systems track body movements from the torso, requiring directly coupled sensors to achieve localized motion tracking of core and limb movements. In contrast, skin-interfaced wearable devices in flexible/stretchable formats can intimately couple with various body locations, offering highly localized motion capture capabilities from conformal multimodal sensors. Figure 3A shows a representative example [21] in which encapsulated commercial accelerometers, in a stretchable island–bridge configuration (e.g. Figure 2C), capture various body motions in a series of on-body tests. Other sensor embodiments exploit [22] high gauge-factor strain sensors for detecting human motions. Integrating a network of this class of stretchable sensors on the body would greatly expand the range of measurable full-body movements, such as gait, balance, and joint specific motions, in previously inaccessible areas (such as the knee or ankle) during athletic activities [23].

Physiological monitoring

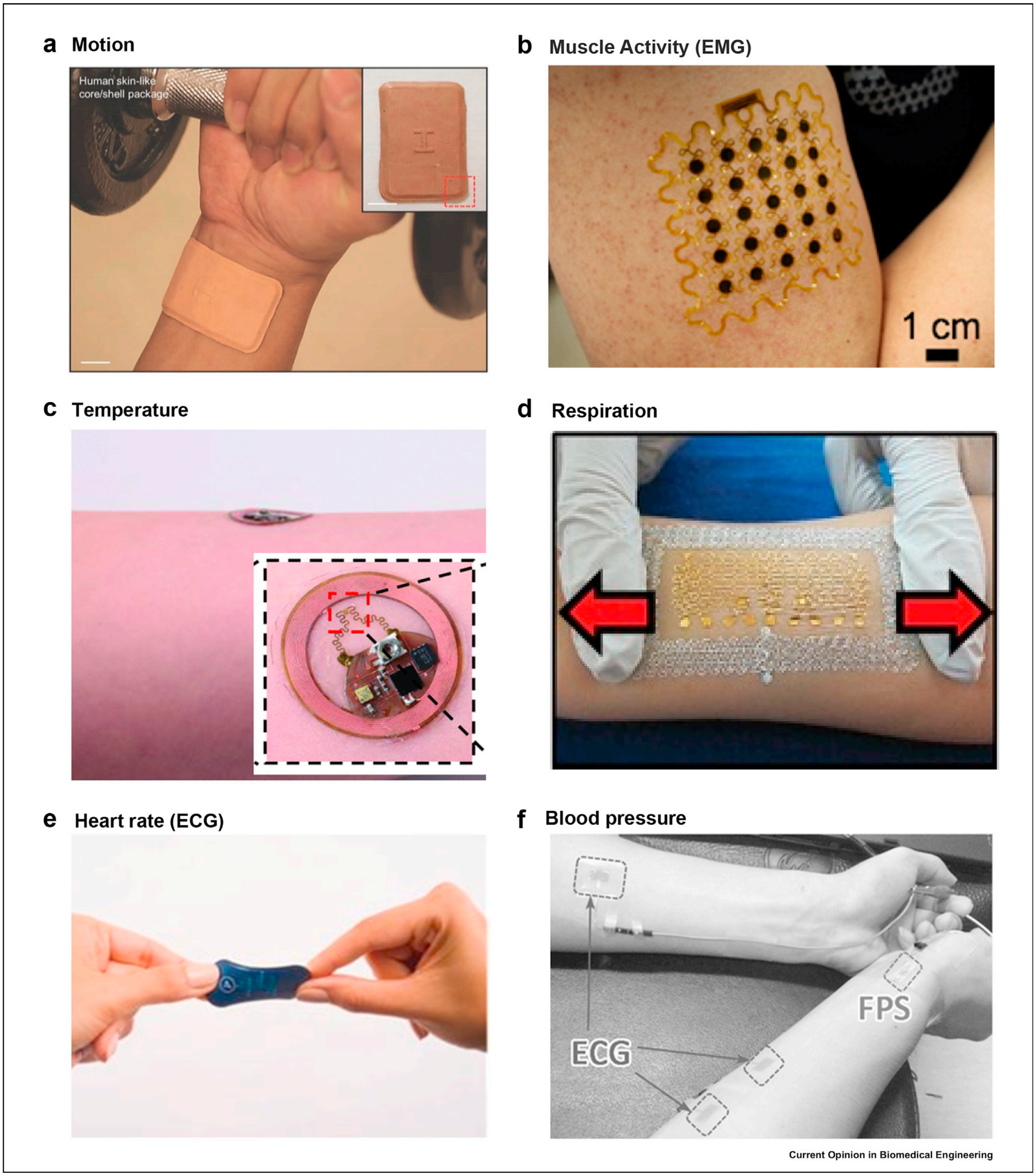
Beyond location- and position-based tracking, biophysical parameters such as muscle activity (Electromyography [EMG]), body temperature, respiration, heart rate, and blood pressure provide deep insights into both the physiological health state of an athlete before, during, and after physical activity, and the efficiency of different training regimes [24]. Recent advances in epidermal sensors provide significantly enhanced capabilities for continuously monitoring these parameters during athletic events.

EMG measurements by soft, stretchable electrode arrays conformally interfaced to the skin record the electrical signal associated with muscle activation. As the recorded signal proportionally increases to the force of muscle contractions, EMG measurements can quantitatively assess muscle utilization and overall muscle health. A recent study [25] (Figure 3B) shows that multichannel, large-area EMG sensors can measure multiple muscles by utilizing various levels of stiffness. EMG sensors, when attached to the forearm and leg, can simultaneously record the signals from both muscle groups correlating different muscle activation states to different bulk-body motions.

Body temperature during exercise represents another key component for both understanding metabolic activity to optimize performance and for maintaining overall health (e.g. prevent heat stroke). Recent work [26] introduces a highly sensitive, wireless, and stretchable temperature sensor that conformally and robustly integrates to the skin (Figure 3C). This intimate interfacing enables measurement of skin hydration state due to changes in skin thermal properties. Other work [27] exploits similar principles to monitor temperature changes resulting from muscle activity during a workout. In an on-body demonstration, the sensor, worn on the bicep, recorded a 0.9 °C temperature increase (from 31.7 °C to 32.6 °C) during a workout. This class of soft, stretchable temperature sensors enables highly accurate temperature measurements comparable to infrared (IR) thermal imaging [28], offering the possibility for garnering deeper insight into thermoregulatory processes during exercise in a real-time, continuous manner.

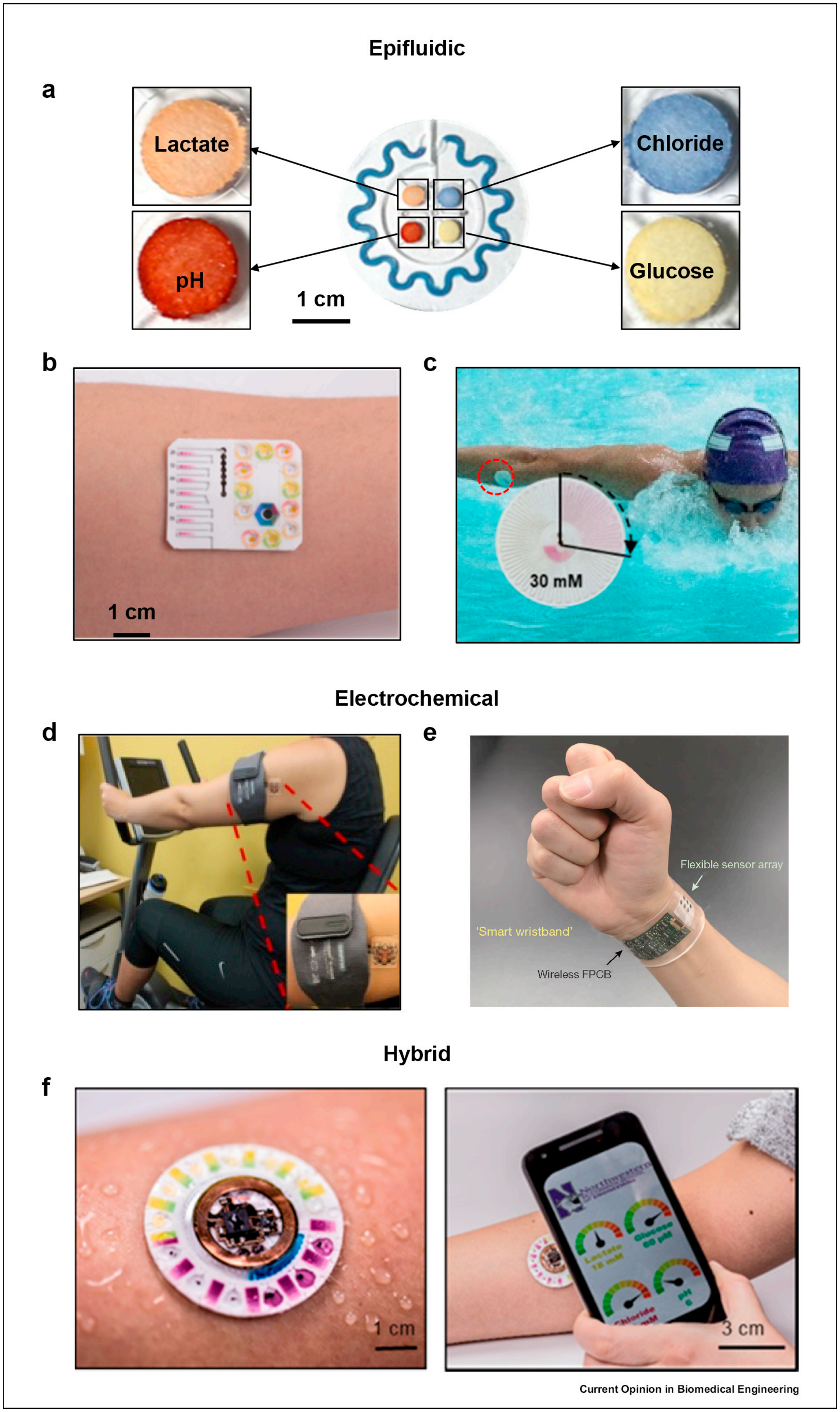
Respiration rate, when coupled with these aforementioned measurements, offers additional insights about exercise-induced fatigue critical for maintaining peak performance [29]. As with motion measurements,

Figure 3



Skin-interfaced wearable devices for physiological monitoring. **(a)** Optical image of an integrated strain sensor for capturing various body motions [21]. **(b)** Optical image of a wearable device for recording EMG signals for quantitatively assessing muscle activation [25]. **(c)** Representative example of a soft, flexible temperature sensor for monitoring muscle activity [26]. **(d)** Integrated device for measuring respiration rate [31]. **(e)** Representative example of an ECG sensor for monitoring heart rate during exercise [32]. **(f)** Optical images of a skin-interfaced wearable device for blood pressure monitoring [34]. ECG, electrocardiogram; EMG, electromyography.

Figure 4


Epifluidic
a
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Wireless FPCB
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Current Opinion in Biomedical Engineering

respiration rate monitoring typically utilizes highly sensitive strain sensors, which in turn, enable facile integration into multimodal sensing platforms [30]. One example [31] utilizes a simple benchtop fabrication approach for low-cost, high-throughput manufacture of skin-interfaced sensors capable of measuring EMG, temperature, and respiration rates. As Figure 3D shows, the device comprises a series of metallic sensors connected by gold-on-polyethylene terephthalate serpentine ribbons. This results in a robust sensing platform suitable for exercise monitoring, which, as validated through on-body testing, demonstrates clear differentiation between normal and deep breaths.

Athletic performance relies not only on kinematics, biomechanics, and motion control but also on the cardiovascular output of the athlete. Of primary interest are heart rate, heart rate variability, and heart rate recovery, which track physical exertion and the body's autonomic response when the body has an elevated need for oxygenated blood and nutrients. Heart rate, heart rate variability, and heart rate recovery represent important biometrics for evaluating an individual's overall physiological health state and are thus topics of intense academic interest in sports science and performance [5]. Although many sensor embodiments exist, few exhibit sufficient durability for athletic environments. A recent embodiment [32] (Figure 3E) exploits thin, soft, and stretchable construction with skin-safe adhesive to robustly interface to the skin and perform wireless electrocardiogram (ECG) measurements. On-body testing during daily activity demonstrates the accurate wireless recording of ECG waveforms in real time with minimal motion artifacts and reduced noise due to conformal skin interfacing.

Blood pressure (BP) represents another cardiovascular signal of great significance. Physical exercises induce an increase in cardiac output related with increase in both systolic BP and diastolic BP. Although typically measured by a BP cuff, a skin-interfaced sensor is critical for monitoring BP during sports activities. Using ECG measurements, such sensors can measure an athlete's BP via the established pulse transit time method [33]. An advanced device embodiment [34] (Figure 3F) combines three epidermal ECG electrodes with a fabric-based flexible piezoresistive sensor to measure the pulse from the wrist. By comparing the signals from before and after exercise, the flexible piezoresistive sensor provides signals that reflect respiration and enables tracing the missing pulse features, an indicator of blood vessel expansion.

Biochemical and hydration monitoring

Although biophysical signals offer a critical window into the physiological health state of athletes, understanding the biochemical basis of athletes is essential for maximizing performance and preventing injuries due to overtraining [35]. Traditional biochemical measurement tools are ill-suited for in situ performance tracking due to their reliance on blood draws and subsequent analysis either off-field or in centralized laboratory facilities [36]. Biofluids such as sweat, saliva, and tears contain vital biochemical information and as such offer attractive noninvasive alternatives to blood, with sweat being the most viable one for athletic performance monitoring [37]. In this section, we highlight two emerging and promising wearable, sweat-based biochemical analytical platforms classified as epidermal microfluidic devices ('epifluidics') and wearable electrochemical sensors.

Epidermal microfluidic devices comprising skin-interfaced sensors formed from soft, stretchable elastomeric substrates with embedded microfluidic channels leverage simple colorimetric assays for the capture, storage, and quantitative analysis of sweat [38]. Although sweat contains many metabolite and electrolyte targets of interest, most work focuses on detecting chloride and lactate. A recent example [38] integrates the colorimetric analysis of sweat glucose, lactate, chloride, and pH with sweat rate measurements (Figure 4A). Sweat enters the device from the natural pressure generated by the sweat glands and continues to enter separate chambers via embedded microfluidic channels. Each chamber contains a commercially available colorimetric assay for an analyte of interest such that sweat components interact with the colorimetric reagents and develop distinct colors quantitatively linked to analyte concentration. Using a smartphone to capture an image of the device, application-based color analysis of each assay chamber provides a simple analytical pathway. Incorporation of advanced microfluidic channel geometries (Figure 4B) enables time- (or volume-) sequenced capture and analysis of sweat by routing sweat such that the chambers fill in a sequential manner [39]. With geometries designed to prevent bidirectional fluid flow (i.e. entering from the outlet), epifluidic devices can capture and analyze sweat from athletes in a variety of environments, including aquatic or transitional environments (as in triathlons) (Figure 4C) [40].

Skin-interfaced wearable devices for biochemical and hydration monitoring. **(a)** Photographs of multiparameter colorimetric sweat sensors [38]. **(b)** Photograph of integrated epidermal microfluidic device with time-sequenced multiparameter analysis [39]. **(c)** Photograph of epidermal microfluidic device worn during swimming [40]. **(d)** Image of a patch worn on the arm of a subject while cycling to record real-time concentration changes in sweat chloride [45]. **(e)** Wireless electrochemical sensor for wireless multimodal sweat analysis [46]. **(f)** Integrated device for the wireless electrochemical and colorimetric analysis of biomarkers [47].

Because the concentrations of constituents in sweat can dynamically vary depending on physiological status, the real-time monitoring of some sweat biomarkers is critical. Skin-interfaced electrochemical sensors provide continuous monitoring of specific analyte targets by leveraging amperometric or potentiometric measurement techniques to generate an electrical signal proportional to the quantity of the analyte in the sample [41]. This results in highly sensitive and selective measurements with low power requirements suitable for miniaturization into a wearable format [42]. High sensitivity is required for detecting most analytes of interest, which typically appear in low concentrations in noninvasively sampled biofluids [43]. Intimate, conformal device interfaces are essential for high-fidelity capture of biofluids in a way that avoids irritation and sample contamination [44]. Advanced sensing systems [45,46] incorporate multiple chemical sensors onto a single platform and utilize epidermal electronic designs with integrated wireless communication capabilities, as highlighted in Figure 4D and E. These devices transmit real-time data wirelessly to a smartphone for the user to analyze sweat composition and correlate well with samples analyzed by conventional techniques.

Recent efforts have led to the integration of both of these biochemical sensing approaches into a single analytical platform for the wireless, battery-free analysis of chloride, pH, lactate, and glucose [47] (Figure 4F). This approach leverages the facile nature of the colorimetric assays to monitor pH and chloride levels while exploiting the high sensitivity of the electrochemical sensors for capturing glucose and lactate in a time-evolved setting. This capability enables multiday monitoring of both sweat glucose and lactate, demonstrating significant promise for long-term continuous deployment for tracking changes during training and rest cycles.

Opportunities and outlook

Emerging classes of soft, stretchable wearable devices represent a transformative advance in body integration with utility for athletic performance and recovery monitoring. By achieving intimate, conformal interfaces with the body, such devices offer significant improvements in both measurement accuracy and multifunctional analysis compared with existing commercial platforms. Such systems enable an expansion of both the type and quantity of biosignal measurements possible and do so without impeding athletic performance. This seamless interfacing offers opportunities to better understand complex physical motions from a biomechanical standpoint (e.g. human gait and baseball pitch) while monitoring the stresses on muscles and joints to prevent injuries (e.g. anterior cruciate ligament [ACL] tears). However, these multifunctional capabilities require not only further refinement and enhancement of sensor accuracy and performance but also an understanding of the complexities that arise from the power management of sensors and electronics modules [48]. The power draw of many sensor modalities for long-term, continuous monitoring typically necessitate the integration of large onboard batteries, which increase the bulk of the device, thereby limiting the ability to conformally interface with the body. Emerging physiological, environmental, and biochemical sensors that exploit energy harvesting and the human body's natural sweat excretion mechanisms are physically imperceptible to athletes and poised to eliminate potential barriers to adoption.

The breadth of physiological targets and locations for body interfacing dictate variable operational life spans for this class of wearable devices. Recent devices, such as the MC10 BioStamp [49], are reusable (with a disposable skin adhesive layer) and designed for continuous physiological monitoring, whereas others, such as L'Oreal's My UV Patch [50], are single-use devices. Utilization of industry-standard materials, including medical-grade skin adhesives (e.g. 3M Inc.), communication electronics (e.g., NFC and Bluetooth modules), and manufacturing processes (e.g., flexible hybrid and roll-to-roll manufacturing) help to minimize fabrication costs at volume, thereby achieving price points necessary for single-use (\$1−\$5) and reusable wearable products (\$50−\$500) in consumer health and medical markets. As this field matures, the environmental impact of disposable, single-use or limited-use devices with onboard batteries must be considered. Early-stage efforts currently focus on utilization of sustainable, environmentally friendly materials, and energy-harvesting strategies [17].

With an increase in sensor ubiquity, the volume of collected data will necessitate new algorithms and approaches to understanding physiological relevance. Data analytics tools will provide ways to quickly assess large physiological data sets to communicate actionable information back to coaches and trainers. Recent studies [51] have found that commercial platforms are beginning to provide insights to improve athletic performance and recovery. These data analytics and feedback considerations, when taken together, provide a roadmap to fully realize the potential of skin-interfaced wearable biosensors to transform the current state of athletic performance monitoring.

Acknowledgments

This work was supported by the Northwestern University Center for Bio-Integrated Electronics and the Simpson Querrey Institute for BioNanotechnology.

Conflict of interest statement

SPL, AJA, RG and JAR are cofounders of Epicore Biosystems, Inc. which pursues commercialization of skin-like microfluidic systems in sports applications.

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