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Anatomical Placement Issues and Technological Solutions for Biosensor Integration in Smart Clothing

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Abstract: Smart clothing represents a promising technological platform for continuous and non-invasive monitoring of physiological parameters in modern healthcare, sports medicine, and remote monitoring systems. This study investigates anatomical placement challenges and technological solutions for biosensor integration in smart T-shirts. A BioSmartClothes prototype was designed and experimentally evaluated under both laboratory and on-body conditions.

The system incorporates a digital temperature sensor for body temperature monitoring, a single-channel electrocardiographic module for cardiac activity assessment, and a photoplethysmographic sensor for heart rate estimation. Biosensors were positioned based on physiological relevance and signal quality criteria, and integrated into the textile structure using conductive threads, flexible printed circuits, and printed conductive layers. Experimental results demonstrated stable and continuous acquisition of temperature, electrocardiographic, and photoplethysmographic signals for monitoring sessions of up to 60 minutes.

The findings indicate that the axillary region provides the highest stability for body temperature measurement, while electrode placement around the sternum significantly improves electrocardiographic signal quality. For photoplethysmographic measurements, mechanical fixation and optical shielding were identified as critical factors influencing signal stability. Comparative analysis of textile integration techniques revealed that hybrid integration strategies offer superior performance in terms of signal quality, mechanical robustness, and wash durability.

Overall, the proposed approach establishes a comprehensive framework for the effective integration of biosensors into smart T-shirts. The results provide a solid scientific and technological basis for the deployment of smart garments in practical health monitoring and sports performance applications.

Keywords: smart clothing, biosensors, smart T-shirt, anatomical placement, textile integration, physiological monitoring.

INTRODUCTION

Smart clothing (smart textiles) has rapidly emerged as a promising technological platform in modern healthcare, sports medicine, rehabilitation, and remote physiological monitoring systems. Unlike conventional portable or wearable devices, smart clothing enables continuous, non-invasive, and user-friendly monitoring of physiological parameters while seamlessly integrating into the user's daily life (1). In particular, smart T-shirts represent an effective and practical platform for biosignal monitoring due to their ability to cover a large body surface area, combined with high elasticity and ergonomic comfort.

Biosensors constitute the core functional components of smart T-shirts. These sensors are responsible for acquiring, processing, and transmitting critical physiological parameters such as heart rate, electrocardiogram (ECG), body temperature, photoplethysmography (PPG), and pressure signals (2). However, the overall performance of a biosensor system depends not only on the intrinsic technical specifications of the sensors but also significantly on their anatomical placement on the human body and the technologies used for integration into textile structures.

Anatomically optimal placement of biosensors plays a decisive role in ensuring signal quality and measurement stability. For instance, ECG signal acquisition is commonly performed around the sternum, where muscle activity is relatively low, resulting in an improved signal-to-noise ratio, while axillary or central chest regions provide body temperature measurements closest to core temperature values (3). Improper sensor placement may lead to motion artifacts, reduced signal amplitude, and increased measurement errors.

The integration of biosensors into smart T-shirts involves multiple, sometimes conflicting requirements, including measurement accuracy, user comfort, mechanical robustness, washability, and energy efficiency (4). Factors such as the mechanical contact between the sensor and skin, the reliability of electrical interconnections, and environmental influences including humidity, temperature variations, and repeated bending can significantly affect biosignal quality. Consequently, the design of biosensor systems for smart clothing requires a comprehensive, multi-criteria engineering approach.

Energy consumption of biosensor modules is another critical factor determining the long-term and autonomous operation of smart clothing systems. Experimental studies indicate that the power consumption of biosensors used in smart garments typically ranges from several microwatts to a few milliwatts (5). The application of duty cycling, event-triggered sensing strategies, and energy-efficient microcontrollers can substantially optimize the overall energy balance of the system. In addition, washability and resistance to mechanical deformation are essential to ensure reliable operation under real-life usage conditions.

Recent research has demonstrated that ECG, PPG, temperature, and pressure sensors are among the most commonly employed biosensors in smart clothing applications (6–8). At the same time, various textile integration technologies such as conductive threads, flexible printed circuits (FPC), and printed conductive coatings have been extensively investigated (9–11). Despite these advances, achieving simultaneous high measurement accuracy, energy efficiency, wash durability, and user comfort in smart T-shirts remains a significant challenge (12).

Therefore, this paper systematically analyzes the challenges associated with anatomical placement of biosensors in smart clothing, examines existing technological solutions for textile integration, and discusses the advantages and limitations of current approaches.

METHODOLOGY

In this study, a systematic methodology was applied to evaluate biosensor placement and textile integration in smart clothing. The methodology includes biosensor selection, anatomical placement design, textile integration techniques, and experimental testing stages.

Biosensors were selected based on measurement accuracy, power consumption, and suitability for flexible textile integration. A digital DS18B20 sensor was used for body temperature monitoring, a single-channel ECG module based on the AD8232 analog front-end was employed for cardiac activity monitoring, and an optical MAX3010x sensor was utilized for PPG-based heart rate measurement. An ESP32 microcontroller with Bluetooth Low Energy (BLE) capability was selected for central control and data transmission.

Sensor placement on the body was determined according to physiological relevance and signal quality. The temperature sensor was positioned in the axillary region or central chest area, ECG electrodes were placed around the sternum with an inter-electrode distance of 8–12 cm, and the

PPG sensor was located in the upper left chest region or inner collar area. Contact pressure between the sensor and skin was maintained within the range of 10–20 mmHg.

Three technological approaches were used for integrating biosensors into the smart T-shirt: conductive threads, flexible printed circuits (FPC) with an elastomer intermediate layer, and printed conductive coatings. Conductive threads were stitched into the fabric, FPC modules were laminated using a hot-press process, and printed conductive layers based on PEDOT:PSS or metallic nanostructures were applied and reinforced with a protective coating.

Temperature signals were acquired at approximately 1 Hz, ECG signals at 250–500 Hz, and PPG signals at 50–100 Hz. Appropriate digital filtering techniques were applied to reduce noise, and initial signal processing was performed on the ESP32 platform.

To improve energy efficiency, duty cycling and low-power operating modes were implemented. Mechanical robustness and wash durability were evaluated through repeated bending tests and multiple washing cycles at 40 °C.

RESULTS.

The BioSmartClothes smart garment prototype demonstrated stable operation during both laboratory and on-body testing. Continuous monitoring sessions of up to **60 minutes** were conducted without signal interruption across the temperature, ECG, and PPG channels. Data transmission via the ESP32–BLE communication link achieved a packet delivery success rate exceeding **98.6%** within a 5 m indoor range. No reconnection events were observed during the measurement cycles, indicating reliable electrical interconnections and stable module contacts within the garment.

The DS18B20 digital temperature sensor was evaluated at the axillary region and, as an alternative, at the central chest location. Axillary placement exhibited higher measurement stability due to reduced exposure to ambient airflow. The sensor operated at a sampling rate of **≈1 Hz**, and the application of temporal averaging over a **5–10 s** window effectively reduced short-term fluctuations. Compared with a calibrated medical digital thermometer, the mean deviation was approximately **±0.32 °C**, while the standard deviation under static conditions remained **≤0.15 °C**. During mild movement (arm lifting, turning, slow walking), temperature drift remained within **±0.4 °C**, confirming the practical effectiveness of the pocket-based mounting and TPU thermal padding.

A single-channel ECG module based on the AD8232 front-end was tested using electrodes positioned around the sternum (inter-electrode spacing **8–12 cm**, diameter **25–35 mm**). Maintaining a contact pressure of **10–20 mmHg** reduced contact impedance and enhanced QRS complex definition. The applied filtering chain (HPF **0.5 Hz**, LPF **40 Hz**, and **50/60 Hz** notch) significantly attenuated baseline wander and power-line interference. At rest, ECG signal-to-noise ratio (SNR) values ranged from **16.8 to 19.5 dB**, decreasing slightly to **14.2–16.0 dB** during mild motion. R-peak detection accuracy exceeded **97%**, with false detections below **3%**. Contact pressures below **10 mmHg** increased baseline drift and artifacts, while excessive pressure negatively affected wearer comfort, confirming **10–20 mmHg** as the optimal operating range.

The optical PPG sensor from the MAX3010x family was evaluated at the upper-left chest region and inner collar location. Given the sensitivity of PPG signals to mechanical fixation and optical conditions, the effect of a dark TPU light-shield ring was assessed. The presence of the light-shield reduced baseline fluctuations by approximately **35–40%** and improved waveform stability. When ECG-derived heart rate values were used as the reference, the mean absolute error of PPG-derived heart rate was **±2.1 bpm** at rest and **±3.8 bpm** during mild motion. Band-pass filtering within the **0.5–5 Hz** range effectively isolated the pulsatile components while suppressing high-frequency noise and low-frequency drift.

Electrical stability was compared across three integration approaches: conductive threads, FPC combined with an elastomer layer, and printed conductive coatings with and without protective overcoat. Conductive threads exhibited linear resistances in the range of **12–18 Ω/m**, with zig-zag stitching improving continuity under deformation by distributing mechanical stress. FPC–elastomer modules showed the highest stability, with minimal resistance drift after bending and washing. Printed conductive traces without overcoat experienced significant degradation after washing, whereas overcoated traces maintained resistance drift within acceptable limits. These results confirm that a hybrid integration strategy conductive threads for routing, FPC modules for electronic islands, and printed traces for localized interconnects provides the most robust solution.

Under continuous operation, the average system power consumption was approximately **3.2 mW**. By implementing duty cycling and low-power modes of the ESP32 microcontroller, the average power demand was reduced to **0.9–1.2 mW**, corresponding to an energy reduction of approximately **65%**. This performance supports extended operation using supercapacitors or rechargeable power sources and provides a foundation for future integration with energy-harvesting modules.

Mechanical durability and washability tests conducted at **40 °C** revealed integration-dependent behavior. Conductive threads exhibited resistance changes of **<8%** after **50 bending cycles** and **≤12%** after **100 washing cycles**. FPC–elastomer modules maintained resistance drift below **3%** under comparable conditions. Printed traces without protective coating showed resistance increases exceeding **25%**, while overcoated traces limited drift to **≤10%**. The most failure-prone regions were identified at stitching terminations and snap-connector zones, where the application of strain-relief and encapsulation layers significantly improved long-term stability.

Table 1. Textile integration technologies: performance comparison

Technology	Electrical performance	Mechanical/wash durability	Practical notes	Recommended use
Conductive Threads (Ag-nylon, Cu-PET)	12–18 Ω/m; stable under stretch routing	ΔR <8% (50 bending); ≤12% (100 wash @40°C)	Stitch terminals need strain-relief	Sports/daily garments, routing lines
FPC + Elastomer (TPU/PDMS)	Lowest drift; stable interconnect	ΔR <3% after bending/wash	Best for electronics "islands"	Medical/high-accuracy monitoring
Printed Coatings (PEDOT:PSS/AgNW/CNT) – no overcoat	Initial ok, degrades in wash	ΔR >25% after wash	Not recommended without protection	Early prototyping only
Printed Coatings + Overcoat	Stable after protection	ΔR ≤10% after wash	Needs encapsulation layer	Local dense interconnects

Table 2. Biosensor placement and acquisition parameters

Sensor	Anatomical location	Contact/Design	Sampling	Signal conditioning
Temperature (DS18B20)	Axilla / Central chest	Pocket + TPU pad; insulation	≈1 Hz	5–10 s averaging
ECG (AD8232, 1-ch)	Sternum region; 8–12 cm spacing	10–20 mmHg contact pressure	250–500 Hz	HPF 0.5 Hz; LPF 40 Hz; Notch 50/60 Hz
PPG (MAX3010x)	Upper-left chest / Inner collar	Dark TPU light-shield ring	50–100 Hz	Band-pass 0.5–5 Hz

Figure 1. BioSmartClothes prototype (front and rear views)

Front and rear views of the BioSmartClothes smart garment prototype, illustrating the overall design, front-side service zone for sensor/electronics modules, and the back-side smart textile structure used during biosignal monitoring experiments.

DISCUSSION

he obtained results demonstrate that anatomically optimized sensor placement and appropriate textile integration are critical factors for achieving high signal quality and system stability in smart garments. In particular, the superior performance of axillary temperature measurements can be attributed to reduced exposure to ambient airflow and closer correlation with core body temperature.

For electrocardiographic monitoring, electrode spacing and contact pressure were shown to strongly influence signal quality. Maintaining a pressure range of **10–20 mmHg** provided an effective balance between electrical contact stability and wearer comfort. These findings indicate that mechanical contact conditions in smart garments are not merely structural considerations but also play a key metrological role.

In photoplethysmographic measurements, optical shielding and mechanical fixation emerged as dominant factors affecting signal stability. The substantial reduction in baseline fluctuations achieved by light-shielding confirms the sensitivity of optical biosignals to ambient illumination. The increased heart rate estimation error observed during movement further highlights the susceptibility of photoplethysmography to motion artifacts and suggests that future designs should incorporate improved fixation strategies and artifact compensation methods.

The comparison of textile integration techniques confirms the advantages of hybrid integration approaches. Conductive threads provide flexibility and preserve garment comfort, whereas flexible printed circuits combined with elastomer layers offer superior mechanical protection for electronic modules. Printed conductive traces require protective encapsulation to achieve acceptable wash durability, underscoring the importance of multilayer integration strategies.

Energy consumption analysis emphasizes the importance of power management in smart clothing systems. The significant reduction in power demand achieved through low-power operating modes enables extended operation using compact energy storage devices and supports future integration with energy-harvesting technologies.

Overall, the results indicate that the successful deployment of biosensor-integrated smart T-shirts depends on the combined optimization of anatomical placement, sensor–skin contact conditions, and textile integration technologies. This integrated approach enhances signal quality, mechanical reliability, and energy efficiency, supporting the practical application of smart garments in health monitoring and sports performance systems.

CONCLUSIONS

This study demonstrates that the effective implementation of biosensors in smart T-shirts requires a coordinated approach that integrates anatomically optimized sensor placement, stable sensor–skin contact, and appropriate textile integration technologies. Experimental evaluation of the BioSmartClothes prototype confirmed the feasibility of continuous and stable acquisition of temperature, electrocardiographic, and photoplethysmographic signals under real wearing conditions.

The results indicate that the axillary region is the most suitable anatomical location for body temperature monitoring, while electrode placement around the sternum provides high-quality electrocardiographic signals. For photoplethysmographic measurements, mechanical fixation and optical shielding were shown to be critical factors for signal stability. Maintaining sensor–skin contact pressure within an optimal range was essential to achieving a balance between signal quality and wearer comfort.

The comparison of textile integration techniques revealed that hybrid integration strategies outperform single-method approaches. Conductive threads are well suited for flexible signal routing, whereas flexible printed circuits combined with elastomer layers provide superior mechanical protection for electronic modules. Printed conductive traces require protective encapsulation to ensure sufficient wash durability and long-term reliability.

Energy consumption analysis showed that the application of low-power operating modes significantly extends system operating time, supporting the use of supercapacitors and energy-harvesting technologies for autonomous operation. This energy-efficient behavior enhances the practicality of smart garments for long-term monitoring applications.

Overall, this work provides a solid scientific and technological foundation for the deployment of biosensor-integrated smart T-shirts in health monitoring and sports performance systems. The obtained results position the BioSmartClothes platform as a practical, reliable, and scalable solution for next-generation wearable technologies.

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