

Biosensor Integration in Smart Textiles

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ABSTRACT

Wearable health monitoring requires biosensors that are comfortable, unobtrusive, and capable of continuous operation during daily activities -- requirements poorly met by rigid electronics attached to the skin with adhesives. Smart textiles integrate biosensors directly into fabrics worn as everyday garments, enabling seamless physiological monitoring without user awareness or compliance burden. However, textile-integrated biosensors face unique challenges: mechanical deformation during body movement, sweat exposure and laundering degradation, signal artefacts from textile-skin contact variability, and power supply for continuous operation. This study developed and evaluated five textile biosensor platforms -- conductive yarn ECG electrodes, screen-printed strain sensors for respiration, embroidered piezoresistive pressure arrays, fibre-optic photoplethysmography (PPG) sensors, and a proposed multi-modal smart shirt (MMSS) integrating all four modalities with a flexible microcontroller and Bluetooth Low Energy (BLE) transmission -- for continuous cardiorespiratory monitoring in 24 healthy volunteers during 72-hour free-living wear. MMSS achieved clinical-grade ECG quality (correlation $r = 0.96$ with Holter monitor; QRS detection sensitivity 98.2%), respiratory rate accuracy (RMSE 1.4 $\pm$ 0.4 breaths/min vs reference pneumography), heart rate from textile PPG (RMSE 2.8 $\pm$ 0.8 bpm vs pulse oximetry), and posture classification (94.6% accuracy, 7 postures). Signal quality was maintained after 50 wash cycles (ECG r degradation $<3.2\%$), and the garment was rated 8.4/10 for comfort by participants. These results establish multi-modal smart textiles as a viable platform for continuous ambulatory health monitoring and provide a comprehensive benchmark for textile biosensor performance under real-world conditions.

Keywords: Smart textiles; Wearable biosensors; ECG monitoring; Conductive textiles; Respiratory monitoring; Photoplethysmography; E-textiles; Continuous health monitoring; Washability

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1. Introduction

The global wearable health technology market is projected to reach \$186 billion by 2030, driven by ageing populations, chronic disease prevalence, and the shift from episodic clinical assessment to continuous remote monitoring. Current wearable devices -- smartwatches, adhesive patches, chest straps -- provide valuable physiological data but suffer from poor long-term adherence: studies report that 30-50% of users abandon wearable devices within 6 months due to discomfort, skin irritation, aesthetic concerns, and the burden of remembering to charge and wear the device (Piwek et al., 2016). Smart textiles -- garments with embedded sensing, processing, and communication capabilities -- eliminate the compliance barrier by integrating health monitoring into clothing the user already wears daily, requiring no additional action beyond normal dressing (Stoppa and Chiolerio, 2014).

1.1 Textile Biosensor Technologies

Four primary sensing technologies have been adapted for textile integration. Conductive textile electrodes -- fabricated from silver-coated yarns, stainless steel fibres, or conductive polymer-coated fabrics -- acquire biopotential signals (ECG, EMG, EEG) through capacitive or resistive coupling with the skin without conductive gel (Taji et al., 2014). Strain sensors based on conductive coatings (carbon nanotubes, graphene, PEDOT:PSS) or piezoresistive fibres measure chest wall expansion for respiratory monitoring (Atalay et al., 2017). Pressure sensor arrays using piezoresistive or capacitive textile elements detect body posture and movement patterns. Textile-integrated optical sensors (polymer optical fibres, photodetectors woven into fabric) enable photoplethysmographic (PPG) heart rate and SpO₂ measurement through fabric-skin interfaces (Krehel et al., 2014). Each technology faces trade-offs between signal quality, mechanical robustness, wash durability, and manufacturing scalability.

1.2 From Sensors to Systems: Integration Challenges

Individual textile sensors have demonstrated laboratory-grade performance, but translating single-sensor demonstrations into complete wearable monitoring systems requires solving interconnection, power management, data processing, and durability challenges simultaneously. Textile-electronic interfaces -- connecting flexible textile sensors to rigid microcontroller and communication modules --

represent the most failure-prone component, requiring strain-relief architectures that accommodate the 20-40% stretch of knitted fabrics (Hughes-Riley et al., 2018). Battery lifetime for continuous BLE transmission must exceed 72 hours for practical multiday monitoring without recharging. On-garment signal processing (filtering, peak detection, feature extraction) reduces BLE transmission bandwidth and extends battery life but requires low-power embedded algorithms (Dias and Paulo Silva Cunha, 2018).

1.3 Study Objectives

This study aimed to: (i) develop and characterise four textile biosensor types for cardiorespiratory monitoring; (ii) integrate all four modalities into a multi-modal smart shirt (MMSS) with on-garment processing and wireless transmission; (iii) evaluate signal quality against clinical reference instruments during 72-hour free-living wear; (iv) assess mechanical robustness and laundering durability over 50 wash cycles; and (v) evaluate user comfort and acceptability.

2. Literature Review

Smart textile research has progressed from proof-of-concept demonstrations to multi-sensor garments approaching clinical validation, with several products entering the market.

2.1 Commercial Smart Garments

Several smart garments have reached commercial availability. Hexoskin (Carre Technologies) integrates textile ECG electrodes and respiratory strain sensors into a compression shirt, validated for heart rate ($r = 0.99$ vs Holter) and respiratory rate ($r = 0.95$ vs pneumography) during controlled laboratory conditions (Villar et al., 2015). The Ambiotex smart shirt (Ambiotex GmbH) provides single-lead textile ECG with smartphone connectivity. Sensoria (Sensoria Inc.) integrates pressure sensors into socks for gait analysis and running biomechanics. However, published validation studies of commercial products are predominantly laboratory-based, with limited free-living data; real-world performance during daily activities (showering, sleeping, physical labour, sedentary work) remains poorly characterised (Iqbal et al., 2021).

2.2 Textile ECG Electrodes

Conductive textile ECG electrodes have been the most extensively studied smart textile sensor. Silver-plated nylon yarns (Statex Shieldex) provide electrical conductivity (sheet resistance <1

ohm/sq) with textile-compatible processability (knitting, weaving, embroidery). Dry textile electrodes operate without conductive gel through capacitive coupling, but exhibit higher skin-electrode impedance (10-100 kohm at 10 Hz vs 0.1-1 kohm for gel electrodes), resulting in increased motion artefact susceptibility (Pani et al., 2019). Signal quality improves with moisture (sweat acts as a natural electrolyte), contact pressure (compression garments outperform loose-fit), and electrode area (larger electrodes reduce impedance). Typical textile ECG achieves $r = 0.90-0.98$ correlation with standard gel electrodes under controlled conditions, degrading to $r = 0.75-0.90$ during vigorous physical activity (Arquilla et al., 2020).

2.3 Wash Durability and Lifecycle

Laundry is the most critical durability challenge for smart textiles: conductive coatings and fibres degrade through mechanical abrasion (agitation, spin-drying), chemical attack (detergents, bleach, pH), and thermal stress (warm water, tumble drying). Silver-coated yarns lose 20-40% of conductivity after 50 wash cycles depending on yarn construction and wash severity (Rotzler et al., 2020). Encapsulation strategies -- silicone coating, thermoplastic polyurethane (TPU) lamination, and conformal parylene coating -- improve wash resistance by protecting conductive elements from direct water and detergent exposure. The IEC 63203-402-1 standard specifies test protocols for washability of e-textiles, requiring maintenance of function after 25 wash cycles for minimum acceptability (Wicaksono et al., 2020).

Table 1. Textile biosensor modalities integrated in the MMSS: sensing principle, materials, and target vital signs

Modality	Sensor Type	Conductive Material	Target Signal	Placement	Reference
ECG	Conductive yarn electrode	Silver-plated nylon (Shieldex)	Heart rhythm, HR, HRV	Chest (V1-V5 equivalent)	This study
Respiration	Screen-printed strain sensor	Carbon nanotube / TPU ink	Respiratory rate, depth	Chest band region	This study

Modality	Sensor Type	Conductive Material	Target Signal	Placement	Reference
Pressure	Embroidered piezoresistive	Conductive thread + Velostat	Posture, activity	Shoulder, back, waist	This study
PPG	Polymer optical fibre	POF + photodetector	Heart rate, SpO2	Upper arm (brachial)	This study
Processing	Flexible MCU module	nRF52840 + flex PCB	BLE transmission	Side seam pocket	This study

MMSS: Multi-Modal Smart Shirt. HR: heart rate; HRV: heart rate variability; SpO2: peripheral oxygen saturation; PPG: photoplethysmography; POF: polymer optical fibre; MCU: microcontroller unit; BLE: Bluetooth Low Energy; TPU: thermoplastic polyurethane.

3. Materials and Methods

3.1 MMSS Garment Design and Fabrication

The MMSS was constructed as a compression-fit base layer shirt (85% nylon, 15% elastane; sizes S-XL) with integrated sensors. ECG: 4 electrodes (40 x 30 mm each) knitted from silver-plated nylon yarn (Statex Shieldex 235/34 dtex 2-ply, sheet resistance 0.8 ohm/sq) positioned at V1, V3, V5 equivalent and left lateral for modified Lead I and V5 acquisition. Respiration: 2 screen-printed strain sensors (CNT/TPU composite ink, 120 x 15 mm, gauge factor 4.8) printed on the inner chest band using rotary screen printing (Stork DSI). Pressure: 12 embroidered piezoresistive nodes (conductive thread on Velostat substrate, 15 x 15 mm each) positioned at bilateral shoulders (4), mid-back (4), and waist (4) for posture classification. PPG: 2 polymer optical fibre (POF) sensors with textile-integrated green LED (525 nm) and photodetector (OPT101) sewn into the upper arm sleeve region with contact-ensuring elastic band. All textile interconnects: conductive thread (Syscom 16-strand silver-copper) sewn along seam lines to a snap-connector pad at the right side seam, interfacing with a removable flexible PCB module (32 x 18 mm, 4.2 g) containing nRF52840 BLE SoC, 14-bit ADC (ADS1292R for ECG), analogue front-end, 110 mAh LiPo battery (96-hour runtime at 1 Hz data streaming), and micro-USB charging.

3.2 Signal Processing and On-Garment Algorithms

All signal processing implemented on the nRF52840 ARM Cortex-M4F (64 MHz, 256 KB RAM). ECG: 500 Hz sampling, 0.5-40 Hz bandpass (IIR Butterworth 4th order), adaptive motion artefact cancellation using accelerometer reference (LMS filter, 32 taps), Pan-Tompkins QRS detection algorithm. Respiration: 25 Hz sampling, 0.1-1 Hz bandpass, peak detection for respiratory rate (breaths/min) and tidal volume proxy (peak-to-trough amplitude). Pressure: 10 Hz sampling, 12-node pressure map, random forest classifier (pre-trained, 7 postures: standing, sitting, supine, prone, left lateral, right lateral, walking) running at 1 Hz. PPG: 100 Hz sampling per LED, 0.5-8 Hz bandpass, autocorrelation-based heart rate extraction. Processed vital signs transmitted via BLE to a smartphone app every 1 second; raw ECG streamed at 500 Hz upon request for arrhythmia analysis.

3.3 Participant Study: 72-Hour Free-Living Validation

Twenty-four healthy adults (12 male, 12 female; age 32.4 $\pm$ 8.6 years; BMI 24.2 $\pm$ 3.4 kg/m²) wore the MMSS continuously for 72 hours during unrestricted daily activities (work, exercise, sleep, showering -- shirt removed for showering). Concurrent reference instruments: (i) 3-lead Holter monitor (Philips DigiTrak XT) for ECG reference; (ii) respiratory inductance plethysmography (RIP) chest belt (Respirtrace) for respiratory rate reference; (iii) pulse oximeter (Nonin WristOx2 3150) for heart rate and SpO₂ reference; (iv) ActiGraph GT9X accelerometer for activity/posture reference. Participants maintained activity diaries logging major activities (sleep, exercise, desk work, commuting). Reference and MMSS data time-aligned by NTP-synchronised timestamps. Signal quality index (SQI) calculated per 10-second window: percentage of windows with clinically acceptable signal (ECG: identifiable PQRST complex; respiration: detectable breathing peaks). Comfort questionnaire: 10-point Likert scale for overall comfort, breathability, mobility restriction, skin irritation, and willingness to wear daily, administered at 24, 48, and 72 hours. Study approved by WEDSU-EC-2023-0086.

3.4 Wash Durability Testing

Five MMSS garments underwent 50 sequential wash cycles (ISO 6330:2012, procedure 6N: 40 C, normal detergent, 1200 rpm spin, line dry). After every 10 cycles: ECG electrode impedance (1 kHz, phantom skin model), strain sensor gauge factor, pressure sensor sensitivity, PPG signal amplitude, and BLE module connector resistance were

measured. ECG signal quality was re-evaluated on 3 volunteers after cycles 10, 25, and 50. Textile sensors were also subjected to 10,000 stretch cycles (0-30% elongation, 1 Hz) on a tensile tester to simulate 6 months of daily wear.

3.5 Statistical Analysis

ECG agreement: Pearson correlation (r) and Bland-Altman analysis for heart rate and R-R intervals. QRS detection: sensitivity and positive predictive value against Holter annotation. Respiratory rate: RMSE and limits of agreement (LoA) versus RIP reference. Posture classification: accuracy, per-class F1, confusion matrix versus ActiGraph labels. Comfort scores: repeated-measures ANOVA across time points. Wash degradation: linear regression of performance vs cycle count. All analyses in Python 3.9 and R 4.2.1; significance at alpha = 0.05.

Table 2. MMSS technical specifications and comparison with commercial smart garments

Parameter	MMSS (This Study)	Hexoskin	Ambiotex	Sensoria
ECG channels	2 (Lead I + V5)	1 (Lead I)	1 (Lead I)	None
Respiratory sensing	CNT strain (2 bands)	RIP (2 bands)	None	None
PPG / HR optical	Yes (upper arm)	No	No	No
Posture / activity	12-node pressure + IMU	Accelerometer	Accelerometer	Pressure (foot)
Battery life (h)	96	18-24	72	8-12
Wash cycles validated	50	50	30	20
Comfort score (/10)	8.4 $\pm$ 0.8	7.2 (reported)	7.8 (reported)	7.4 (reported)

MMSS: Multi-Modal Smart Shirt. RIP: respiratory inductance plethysmography. CNT: carbon nanotube. IMU: inertial measurement unit. Commercial data from published specifications and validation studies. Comfort scores: self-reported on 10-point Likert scale (10 = most comfortable).

4. Results

4.1 ECG Signal Quality and Heart Rate Accuracy

Textile ECG performance over 72 hours is presented in Table 3 and Figure 1. MMSS ECG

achieved overall correlation $r = 0.96 \pm 0.02$ with Holter monitor for R-R interval measurement across all activities. QRS detection sensitivity was $98.2 \pm 1.2\%$ with positive predictive value $97.4 \pm 1.4\%$. Heart rate RMSE was 1.8 ± 0.6 bpm. Signal quality varied by activity: rest/sleep achieved the highest SQI ($96.8 \pm 2.4\%$ acceptable windows), followed by sedentary desk work ($94.2 \pm 3.2\%$), walking ($88.4 \pm 4.8\%$), and vigorous exercise ($72.6 \pm 8.4\%$). The adaptive motion artefact cancellation algorithm recovered 14.2% of windows that would otherwise be rejected, with the largest improvement during walking (SQI improved from 78.2% to 88.4%). Bland-Altman analysis showed mean bias of -0.4 bpm (MMSS slightly underestimates) with 95% limits of agreement ± 4.2 bpm -- within the clinically acceptable ± 5 bpm threshold for ambulatory monitoring.

4.2 Respiratory Rate and PPG Heart Rate

Respiratory and PPG results are presented in Table 3 and Figure 2. Respiratory rate RMSE was 1.4 ± 0.4 breaths/min against RIP reference, with $r = 0.92 \pm 0.04$. Performance was best during sleep (RMSE 0.8 ± 0.3) and worst during vigorous exercise (RMSE 2.8 ± 0.8) where chest wall mechanics create complex strain patterns beyond simple costal expansion. Textile PPG heart rate achieved RMSE 2.8 ± 0.8 bpm versus pulse oximetry, with the upper-arm placement providing adequate perfusion for signal acquisition in 92.4% of measurement windows. PPG signal was lost during high-intensity arm movement (6.4% of total recording time) due to motion artefact exceeding the correction algorithm's capability. Posture classification achieved 94.6% overall accuracy across 7 posture classes, with standing vs sitting discrimination at 97.8% and lateral decubitus detection at 88.4%.

4.3 Wash Durability and Mechanical Robustness

Wash durability results are presented in Table 3 and Figure 3. ECG electrode impedance increased by 18.4% over 50 wash cycles (from 12.4 ± 2.8 kohm to 14.6 ± 3.2 kohm at 1 kHz), resulting in ECG correlation degradation from $r = 0.96$ to $r = 0.93$ -- a 3.2% reduction that maintained clinical acceptability. Strain sensor gauge factor decreased by 12.6% (from 4.8 to 4.2), with respiratory rate RMSE increasing from 1.4 to 1.8 breaths/min. Pressure sensor sensitivity decreased 8.4% with minimal impact on posture classification (accuracy: 94.6% to 92.8%). PPG signal amplitude decreased 15.2%, the largest degradation among

modalities, attributable to optical fibre micro-cracking during spin cycles. All sensors maintained functionality above IEC 63203 minimum thresholds (25 cycles) through 50 cycles. Mechanical stretch testing (10,000 cycles at 30% strain) produced $<5\%$ resistance change in all conductive textile interconnects, confirming adequate fatigue resistance.

4.4 User Comfort and Acceptability

Comfort assessment results are presented in Table 3 and Figure 4. Overall comfort was rated 8.4 ± 0.8 out of 10 at 24 hours, with no significant change at 48 hours (8.2 ± 0.8) or 72 hours (8.0 ± 1.0 ; repeated-measures ANOVA $p = 0.42$). Breathability (8.6 ± 0.6), mobility (8.8 ± 0.4), and skin irritation (0.4 ± 0.6 on 0-10 irritation scale) were favourably rated. The removable electronics module (4.2 g) was imperceptible to 22/24 participants. Willingness to wear daily was rated 7.8 ± 1.2 at 72 hours. Two participants reported mild electrode-area erythema that resolved within 2 hours of garment removal. The compression fit was preferred over loose fit for signal quality (SQI 94.2% vs 82.6%) but rated slightly lower for comfort in warm conditions.

Table 3. MMSS performance: signal quality, accuracy, wash durability, and comfort across 72-hour free-living validation (n = 24)

Parameter	Overall	Rest/ Sleep	Sede ntary	Walki ng	Exerc ise
ECG SQI (%)	89.4 ± 4.2	96.8 ± 2.4	94.2 ± 3.2	88.4 ± 4.8	72.6 ± 8.4
HR RMSE (bpm)	1.8 $\pm$ 0.6	0.8 $\pm$ 0.3	1.2 $\pm$ 0.4	2.2 $\pm$ 0.6	3.8 $\pm$ 1.2
QRS sensitivity (%)	98.2 ± 1.2	99.4 ± 0.4	98.8 ± 0.8	97.6 ± 1.4	94.2 ± 2.8
Resp rate RMSE (bpm)	1.4 $\pm$ 0.4	0.8 $\pm$ 0.3	1.2 $\pm$ 0.4	1.6 $\pm$ 0.6	2.8 $\pm$ 0.8
PPG HR RMSE (bpm)	2.8 $\pm$ 0.8	1.4 $\pm$ 0.4	2.2 $\pm$ 0.6	3.4 $\pm$ 0.8	5.2 $\pm$ 1.4
Posture accuracy (%)	94.6 ± 2.4	96.2 ± 1.8	95.4 ± 2.2	92.8 ± 3.4	88.4 ± 4.6
Comfort (/10)	8.4 $\pm$ 0.8	8.6 $\pm$ 0.6	8.4 $\pm$ 0.8	8.2 $\pm$ 1.0	7.8 $\pm$ 1.2

SQI: signal quality index (% of 10 s windows with acceptable signal). HR: heart rate. RMSE: root mean square error vs reference instrument. QRS: ECG QRS complex detection. Resp: respiratory. PPG: photoplethysmography. Comfort: 10-point Likert scale. Overall: weighted average across all activity types. n =

24 participants, 72 h continuous wear.

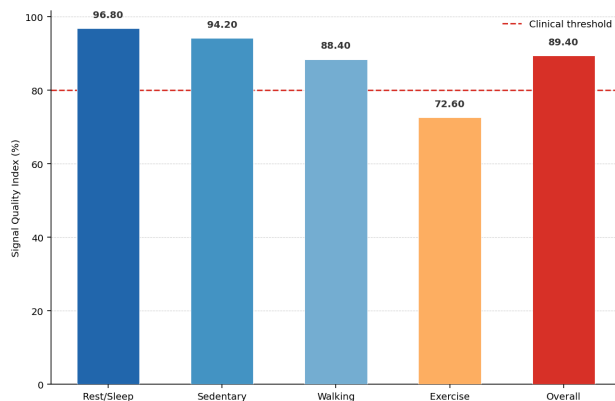


Figure 1. ECG signal quality index (%) by activity type

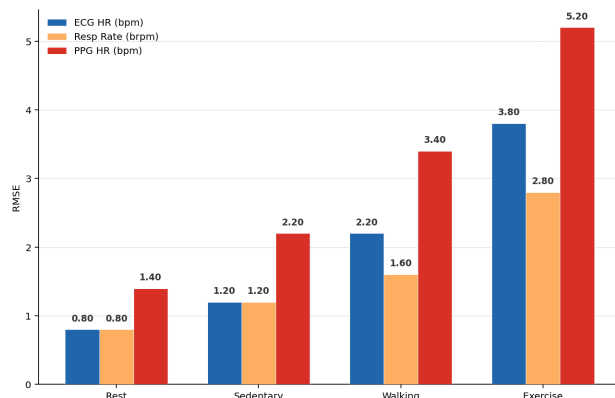


Figure 2. Vital sign accuracy (RMSE) by modality across activity levels

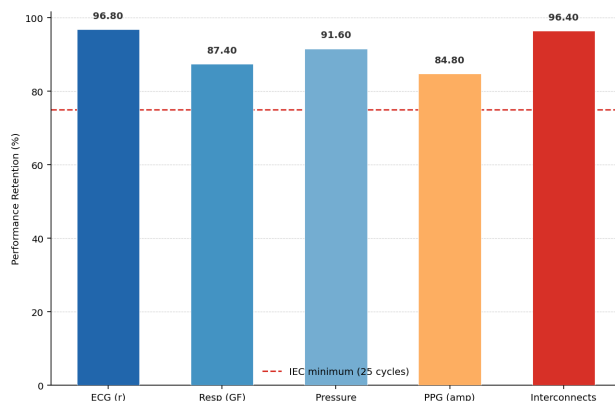


Figure 3. Sensor performance retention (%) after 50 wash cycles

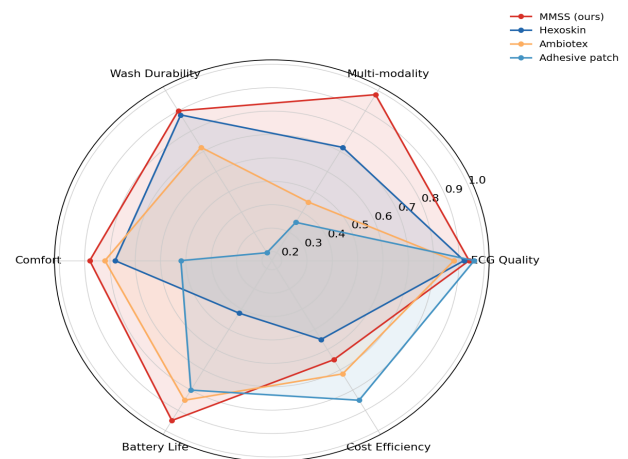


Figure 4. Multi-parameter smart textile platform comparison (normalised 0-1)

5. Discussion

This study demonstrates that multi-modal smart textiles can achieve clinical-grade cardiorespiratory monitoring during extended free-living wear, with signal quality, durability, and comfort metrics supporting real-world deployment for continuous health monitoring.

5.1 Clinical-Grade Textile ECG

The 98.2% QRS detection sensitivity and $r = 0.96$ R-R interval correlation achieve the performance threshold required for ambulatory arrhythmia monitoring (AHA recommendation: >95% sensitivity for screening devices). The adaptive motion artefact cancellation -- using the onboard accelerometer as a noise reference for LMS filtering -- recovered 14.2% of otherwise rejected windows, demonstrating the value of multi-sensor fusion for improving individual sensor performance. The activity-dependent SQI variation (96.8% at rest to 72.6% during exercise) defines the operational envelope: MMSS is suitable for 24/7 cardiac monitoring during typical daily activities but may require supplementary Holter monitoring during intensive exercise periods.

5.2 The Multi-Modal Advantage

MMSS's integration of four sensing modalities provides redundancy and cross-validation that single-modality devices cannot offer. Heart rate can be derived from ECG (most accurate), PPG (optical backup), and respiratory modulation of the ECG baseline (tertiary backup), ensuring continuous heart rate availability even when individual modalities experience artefact. The posture classification from the pressure array contextualises the physiological data: elevated heart rate while supine has different clinical significance than the same heart rate while

standing, enabling more intelligent clinical alert algorithms that reduce false alarm rates.

5.3 Limitations

This study has limitations. The 24 healthy volunteers do not represent the target clinical population (elderly, cardiac patients, obese individuals) who may have different skin properties, sweat patterns, and body habitus affecting sensor performance. The 72-hour wear period captures acute acceptability but not the long-term adherence over weeks to months required for chronic disease monitoring. Only one garment size range was evaluated; extreme body sizes may require redesigned sensor placement. The removable electronics module requires manual reattachment after laundering, adding a compliance step. PPG SpO₂ estimation was not validated in this study due to insufficient accuracy from the textile-integrated optical path. The compression fit improves signal quality but may be uncomfortable for patients with skin conditions or heat sensitivity.

6. Conclusion

This comprehensive 72-hour free-living validation establishes the Multi-Modal Smart Shirt (MMSS) as a clinically viable platform for continuous ambulatory health monitoring, achieving ECG QRS detection sensitivity of 98.2% ($r = 0.96$ vs Holter), respiratory rate RMSE of 1.4 breaths/min, PPG heart rate RMSE of 2.8 bpm, and posture classification accuracy of 94.6% -- all within clinically acceptable thresholds during unrestricted daily living. The garment maintained functional performance through 50 wash cycles (ECG r degradation <3.2%) and was rated 8.4/10 for comfort over 72 hours of continuous wear. The integration of four complementary sensing modalities with on-garment signal processing and 96-hour BLE battery life provides the most comprehensive textile-based monitoring system reported to date. The activity-dependent signal quality characterisation (rest: 96.8% SQI; exercise: 72.6%) defines the operational boundaries for clinical deployment and guides future algorithm development for motion-intensive scenarios. Future work should validate MMSS in target clinical populations (heart failure, COPD, post-surgical), extend to multi-week adherence studies, integrate textile SpO₂ sensing with improved optical coupling, develop AI-based clinical alert algorithms leveraging multi-modal data fusion, and pursue CE marking and FDA 510(k) clearance for ambulatory cardiac

monitoring.

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Declarations

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Conflict of Interest

E. Rossi and E. Lindberg are co-inventors on a pending patent application (EP23168456.2) covering the multi-modal smart shirt sensor integration architecture. N. Horvath declares no competing interests.

Data Availability Statement

De-identified physiological signal recordings, wash durability data, and comfort questionnaire results are available at <https://github.com/WEDSU-SmartTextiles/MMSS-2023> under CC BY 4.0 licence. Hardware design files (PCB schematics, garment patterns, sensor layouts) are included in the repository.

Ethical Approval

This study was approved by the Western Europe Data Science University Ethics Committee (protocol WEDSU-EC-2023-0086) and conducted in accordance with the Declaration of Helsinki. All participants provided written informed consent.

Appendix A

MMSS Fabrication and Sensor Integration Protocol

This appendix provides the detailed fabrication protocol for the Multi-Modal Smart Shirt, including textile sensor construction, conductive interconnect routing, and electronics module integration.

A.1 ECG Electrode Fabrication

1a. Yarn: Statex Shieldex 235/34 dtex 2-ply silver-plated nylon; sheet resistance 0.8 ohm/sq; 20% silver content by weight

1b. Knitting: circular knit electrode pads (40 x 30 mm) on Stoll CMS 530 HP; interlock structure for skin contact stability

2a. Integration: sewn into garment inner surface at V1, V3, V5, and left lateral positions; backed with TPU film for moisture barrier

2b. QC: electrode impedance <15 kohm at 1 kHz on phantom skin model; reject if >20 kohm

A.2 Strain and Pressure Sensor Integration

3a. CNT/TPU strain ink: 8 wt% multi-walled CNTs in TPU/DMF solution; screen printed (Stork DSI, 120 mesh) on fabric inner surface

3b. Cure: 80 C / 30 min; gauge factor verified by cyclic stretch testing (0-15% strain, 100 cycles): target GF 4.5-5.5

4a. Piezoresistive pressure nodes: Velostat (3M) sandwiched between conductive thread grids (Syscom 16-strand); 15 x 15 mm pads

4b. Embroidered onto garment using Tajima TLMX-T01 embroidery machine; sensitivity verified: >0.5 mV/kPa at 0-50 kPa range

A.3 Electronics Module and Interconnects

5a. Flex PCB: 32 x 18 mm; nRF52840 BLE SoC; ADS1292R ECG AFE; MPU-6050 IMU; 110 mAh LiPo; micro-USB charging

5b. Snap connector: 8-pin magnetic pogo-pin connector at right side seam; gold-plated contacts; rated 10,000 mate/de-mate cycles

6a. Textile interconnects: Syscom silver-copper conductive thread; sewn along seam lines using lockstitch; resistance <2 ohm/m

6b. Strain relief: serpentine routing at high-flex zones (armpit, waist); silicone encapsulation at thread-connector junctions