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Design and Evaluation of Smart Textile Systems for Sports Monitoring and Health Assessment

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ABSTRACT

Smart textiles have attracted growing attention in wearable sports monitoring due to their flexibility, comfort, and sensing capability. This study designs and evaluates a smart textile system for physiological and motion-related monitoring in sports scenarios. The proposed system integrates conductive yarn-based sensing elements, a signal acquisition unit, and a wireless transmission module into an elastic textile platform. Its sensing mechanism is based on resistance variation caused by fabric deformation during body movement and physiological activity. Controlled experiments were conducted with 15 participants under resting, moderate-intensity, and high-intensity conditions. A commercial wearable device was used as the reference system to compare pulse-related trend estimates indirectly derived from textile resistance signals, rather than direct heart-rate measurement. The acquired signals were processed using low-pass filtering and smoothing, and system performance was evaluated using MAE, RMSE, standard deviation, and the coefficient of determination (R^2). The results showed that the indirectly estimated pulse-related trends had MAE values of 1.4, 2.1, and 3.5 BPM under the three activity levels when compared with the reference device, with an overall R^2 of 0.94. The system also captured respiratory-related variations and motion-response characteristics. These findings indicate that the proposed smart textile system has practical potential for wearable sports monitoring by providing cardiac-related trend information under controlled conditions, although it does not directly measure heart rate using ECG- or PPG-based methods.

KEYWORDS

smart textiles, wearable sensing, sports monitoring, health-related monitoring, conductive yarn, physiological signal acquisition

INTRODUCTION

In recent years, smart textiles have emerged as a promising branch of wearable technology, offering new possibilities for continuous physiological monitoring and motion-related assessment in sports applications

[1-3]. By integrating sensing elements directly into textile structures, smart textiles provide a more natural and unobtrusive interface between the human body and electronic systems. Compared with conventional wearable devices such as wristbands or chest straps, textile-based systems exhibit superior comfort, flexibility, and long-term wearability [4,5].

The demand for real-time monitoring in sports training and health-related applications has increased significantly. Accurate observation of physiological parameters, including pulse-related signals, respiration, and movement patterns, plays an important role in exercise monitoring and injury prevention [6,7]. Although various commercial wearable devices have been developed for these purposes, they often suffer from limitations such as poor skin conformity, motion-induced signal artifacts, and limited integration with clothing systems [8,9]. These limitations reduce both the accuracy and usability of existing solutions, particularly during high-intensity or long-duration activities.

Smart textile systems aim to address these challenges by embedding conductive materials and flexible sensors within fabric structures. Previous studies have demonstrated the feasibility of textile-based sensing through conductive yarn integration, knitted strain sensors, and embroidered electrodes [10-12]. These systems can detect mechanical deformation and physiological signals via changes in electrical resistance or signal transmission characteristics. In addition, sensing fabrics have been successfully applied to monitor biomechanical and physiological variables in wearable systems [13].

Despite these advances, several limitations remain. First, many existing studies focus on single sensing functions rather than integrated systems capable of physiological and motion-related monitoring. Second, system-level design considerations, including sensor placement, textile structure, and signal stability, are often insufficiently addressed [14,15]. Third, quantitative validation under realistic sports conditions is still limited, and only a few studies provide systematic comparisons with standard measurement devices or evaluate repeatability and robustness through statistical analysis [16,17].

To address the above gaps, this study proposes a smart textile system for sports monitoring and health-related applications. The system integrates conductive textile sensors, a compact data acquisition module, and wireless communication components within a wearable fabric platform. The sensing mechanism is based on resistance variation induced by fabric deformation and physiological activity, enabling the monitoring of respiratory-related signals, motion response, and pulse-related trend estimates.

A series of controlled experiments were conducted to evaluate the performance of the proposed system. Multiple participants were recruited to perform different types of physical activities, including resting, moderate exercise, and high-intensity movement. The measurements obtained from the smart textile system were compared with those from a reference device to assess pulse-related trend estimation performance. Statistical metrics, including mean absolute error (MAE), root mean square error (RMSE), standard deviation, and the coefficient of determination (R^2), were used to quantify system performance and repeatability.

The main contributions of this study can be summarized as follows:

- (1) A smart textile system integrating sensing, data acquisition, and communication functions is designed and implemented;
- (2) A sensing approach based on textile deformation is applied for physiological and motion-related monitoring;
- (3) The effectiveness of the proposed system is validated through controlled experiments and quantitative statistical analysis.

MATERIALS AND METHODS

System Design and Fabrication

A smart textile system was designed to enable continuous monitoring of selected physiological and motion-related signals during sports activities. The system consisted of four main components: a textile sensing layer, a signal acquisition unit, a data transmission module, and a data analysis interface. The overall architecture of the proposed system is illustrated in Figure 1.

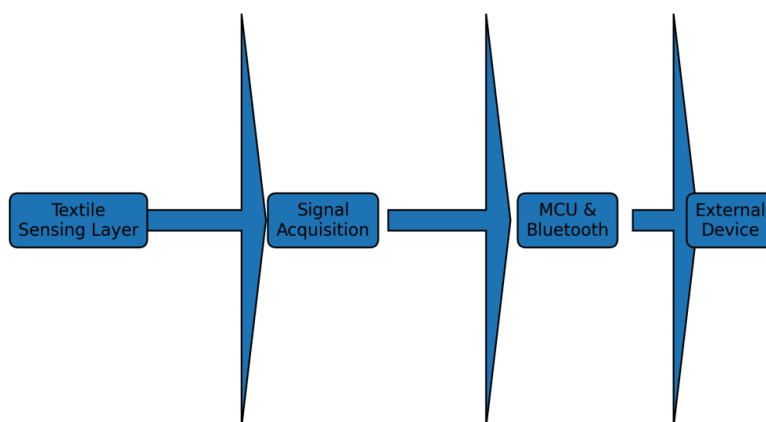


Figure 1. Architecture of the proposed smart textile system.

The textile sensing layer was constructed on an elastic knitted fabric substrate to provide flexibility, breathability, and conformity to body movement. Knitted structures are widely used in smart textile applications because of their stretchability and suitability for integrating conductive elements into wearable garments [5,10]. In the present study, conductive yarns were incorporated into the fabric through a combination of knitting and local embroidery, forming sensing zones in body regions sensitive to physiological deformation, particularly the chest area. This configuration was selected to improve the stability of fabric–body contact during motion while maintaining wearer comfort.

The electronic acquisition unit was connected to the textile sensing layer through conductive interfaces. The acquired analog signals were conditioned by a front-end circuit and converted into digital signals for further processing. A compact embedded control unit was used for data collection and temporary storage, and the processed signals were transmitted wirelessly to an external terminal for visualization and analysis. The overall system was designed to remain lightweight and wearable during both moderate- and high-intensity physical activities.

Sensing Principle

The sensing mechanism of the proposed smart textile system was based on resistance variation in conductive yarns under mechanical deformation. When the textile structure was stretched or compressed due to body motion or physiological activity, the conductive path underwent a change in geometry, resulting in measurable electrical resistance variation. Similar strain-responsive mechanisms have been widely reported in textile-based sensing systems [11].

The electrical resistance of the conductive path can be expressed as

$$R = \rho \frac{L}{A} \quad (1)$$

where R is the resistance, ρ is the resistivity of the conductive material, L is the conductive path length, and A is the cross-sectional area.

Under deformation, the relative change in resistance can be described as

$$\frac{\Delta R}{R_0} = k\varepsilon \quad (2)$$

where ΔR is the resistance change, R_0 is the initial resistance, k is the gauge factor, and ε is the applied strain.

Based on this principle, periodic chest expansion and contraction during breathing generated low-frequency resistance fluctuations, while body motion during exercise produced additional dynamic signal changes. It should be noted that the proposed textile system does not directly measure cardiac electrical activity or optical blood-volume changes. Instead, pulse-related information was indirectly estimated from subtle chest-wall micro-vibration components superimposed on the textile resistance signal after filtering and peak analysis. Therefore, the output of the proposed system should be interpreted as pulse-related trend estimation rather than direct heart-rate measurement. Compared with ECG- or PPG-based devices, this indirect approach is more susceptible to motion artifacts, garment fit, contact pressure, and individual body-shape differences. Therefore, the textile system was primarily intended to capture respiratory-related variations, motion response, and pulse-related trends within an integrated wearable monitoring framework.

Experimental Protocol

Controlled experiments were conducted to evaluate the monitoring performance of the proposed smart textile system under different activity conditions. A total of 15 healthy adult participants aged between 20 and 35 years were recruited for the study. The participant group included both male and female subjects, and basic characteristics such as body mass index (BMI) and chest circumference were recorded to account for potential effects of body shape and garment–skin contact on sensing performance. Participants were instructed to avoid vigorous exercise for 24 hours prior to testing and to maintain similar pre-test routines to partially control for baseline fitness variability. Although no formal fitness assessments (e.g., VO_2 max or physical activity questionnaires) were conducted, these measures were intended to reduce extreme variability in moderate- and high-intensity responses across participants. Future work should include standardized fitness assessments to ensure more consistent task execution across participants. All participants were informed of the experimental procedure before testing and provided consent prior to participation.

The experimental tasks included three activity levels: resting, moderate-intensity exercise, and high-intensity exercise. During the resting condition, participants remained seated in a relaxed posture for baseline data acquisition. During the moderate-intensity condition, participants performed walking or light jogging at a controlled speed of approximately 4–6 km/h. During the high-intensity condition, participants performed running at speeds above 8 km/h or repeated jumping under standardized instructions to generate stronger

physiological and motion responses. All participants followed the same test duration and standardized instructions to reduce inter-subject variability.

Each participant wore the developed smart textile system throughout the test. The garment size was selected according to individual body dimensions, and elastic adjustment was applied to maintain stable but comfortable contact between the sensing area and the chest. The sensor placement was standardized across participants under researcher guidance. At the same time, a Polar H10 chest strap heart-rate sensor (Polar Electro Oy, Kempele, Finland) was used as the reference device. While this device has been validated for general consumer use, it does not constitute a clinical gold standard. Therefore, the MAE and RMSE values reported in this study reflect agreement with a validated consumer device rather than direct clinical heart-rate measurements. Future work should incorporate clinical ECG or PPG sensors to provide a more authoritative benchmark for comparison. Each activity session lasted approximately 10 min, and the measurements under each condition were repeated three times to improve the reliability of the results. After each test, the textile garment was cleaned or disinfected according to a standardized procedure before being used by the next participant. To reduce interference from external factors, the experiments were conducted in a stable indoor environment with similar temperature and humidity conditions.

Signal Processing and Feature Extraction

The raw signals collected from the textile sensors contained both useful physiological information and unwanted noise caused by motion artifacts, transient contact variation, and environmental disturbance. Therefore, signal processing was performed before feature extraction. A fourth-order low-pass Butterworth filter, which is commonly applied in wearable physiological signal processing [7], was used to suppress high-frequency noise. The cutoff frequency was set to 5 Hz in order to preserve the dominant physiological components while removing rapid fluctuations unrelated to respiration and pulse-related trend estimates. Subsequently, a moving-average smoothing procedure with a short temporal window was applied to reduce short-term fluctuations and improve waveform readability.

After preprocessing, characteristic features were extracted from the filtered signal. Pulse-related information was estimated from relatively faster periodic fluctuations in the processed signal and converted into beats per minute through peak-interval analysis. Respiratory-related variations were obtained from slower cyclic resistance changes associated with chest motion. In addition, overall waveform amplitude variation and temporal regularity were used to describe motion response under different exercise intensities.

All signal processing steps were implemented using a consistent analysis workflow to ensure that the measurements from different participants and repeated trials were processed under the same conditions.

Performance Evaluation

The monitoring performance of the proposed smart textile system was evaluated primarily by comparing its indirectly estimated pulse-related trends with those obtained from the reference device. To quantify the trend-level deviation, the mean absolute error (MAE) and root mean square error (RMSE) were calculated. These indicators are commonly used for the evaluation of wearable sensing systems because they reflect average deviation and overall error magnitude, respectively [3]. It should be noted that the reference device is a consumer-grade chest strap (Polar H10, Polar Electro Oy, Finland) rather than a clinical gold-standard ECG or PPG device. Therefore, the MAE and RMSE values reflect agreement with a validated consumer device, not direct clinical heart-rate measurement accuracy. Since the textile sensor does not directly acquire ECG or PPG signals, the comparison was intended to evaluate consistency with the reference device rather than to claim clinical-grade heart-rate measurement accuracy.

The MAE and RMSE were calculated as follows:

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |y_i - \hat{y}_i| \quad (3)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (4)$$

where y_i is the reference value and \hat{y}_i is the corresponding value estimated by the proposed system.

In addition, the mean value and standard deviation were calculated for repeated measurements to assess result dispersion and repeatability. The coefficient of determination (R^2) was also used to evaluate the correlation between the developed smart textile system and the reference device. These statistical indicators provided a quantitative basis for assessing the practical performance and short-term repeatability of the proposed system in wearable sports monitoring scenarios.

Respiratory-related variations and motion response were evaluated mainly in terms of signal responsiveness, waveform regularity, and trend consistency under different activity conditions, rather than by direct comparison with a dedicated clinical reference instrument.

RESULTS AND DISCUSSION

Signal Quality Analysis

The raw signals acquired from the smart textile sensors exhibited noticeable fluctuations, particularly during moderate- and high-intensity activities. These fluctuations were mainly associated with motion artifacts and variations in fabric–skin contact conditions. After applying the fourth-order low-pass Butterworth filter and moving-average smoothing described in Section 2.4, the overall signal stability improved, although minor irregularities remained under dynamic conditions. A representative example of the raw and filtered signals is presented in Figure 2.

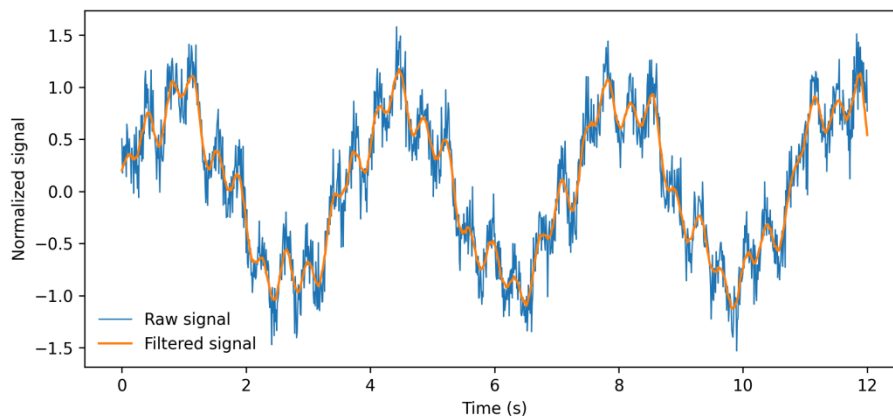


Figure 2. Comparison of raw and filtered signals under moderate activity.

During resting conditions, the signal waveform showed relatively stable periodic characteristics with a comparatively low noise level. In contrast, during moderate activity, intermittent disturbances were observed, resulting in slight waveform distortion. Under high-intensity conditions, the signal exhibited larger amplitude variation and more irregular peaks, reflecting the stronger influence of rapid body movement and transient contact instability.

Although filtering effectively reduced high-frequency noise, it did not completely eliminate motion-induced interference. These observations suggest that the adopted signal processing method improved waveform readability and feature extraction, whereas signal quality under intense activity was still affected by garment fit, body motion, and local sensor contact conditions.

Pulse-Related Trend Agreement Evaluation

The pulse-related trends indirectly estimated by the proposed system were compared with those from the reference device, and the results are summarized in Table 1.

Table 1. Agreement of pulse-related trend estimates with the reference device (Mean \pm SD).

Activity Level	Reference Device (BPM)	Proposed System (BPM)	MAE (BPM)	RMSE (BPM)
Resting	72.4 \pm 3.2	73.8 \pm 4.1	1.4	2.0
Moderate	108.7 \pm 5.6	110.8 \pm 6.9	2.1	2.9
High-intensity	146.2 \pm 7.8	150.3 \pm 9.7	3.5	4.4

The correlation between the reference device and the proposed system is further illustrated in Figure 3.

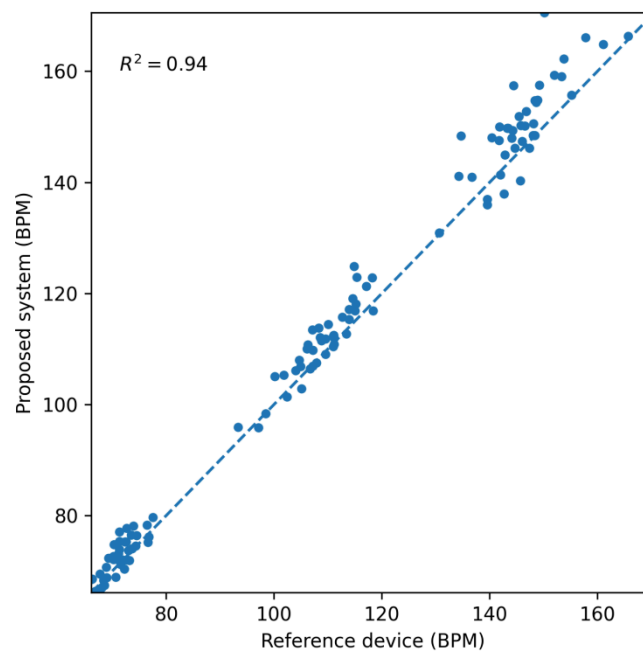


Figure 3. Correlation between the reference device and the proposed system for pulse-related trend estimates.

The results indicate that the indirectly estimated pulse-related trends show a generally consistent pattern with the reference device across different activity levels. Under resting conditions, the trend deviation remains relatively low, with an MAE of 1.4 BPM. As the activity intensity increases, the error gradually rises, reaching 3.5 BPM under high-intensity conditions.

3.5 BPM during high-intensity exercise. This trend can be attributed to the increased influence of motion artifacts, as well as variations in sensor–skin contact during dynamic movements. In addition, the standard

deviation of the measurements also increases with activity intensity, indicating reduced signal stability under more demanding conditions.

The coefficient of determination (R^2) between the two measurement systems was calculated to be 0.94, indicating a strong overall correlation. Although the absolute error increased under high-intensity conditions, the two systems still exhibited consistent trends across participants and activity levels, which contributed to the relatively high correlation coefficient.

These results suggest that the proposed system can provide pulse-related trend information under different activity conditions. However, since the signal is indirectly derived from textile resistance variations rather than direct ECG or PPG acquisition, the results should not be interpreted as direct heart-rate measurement.

Respiratory Signal and Motion Response

The smart textile system demonstrated the ability to capture respiratory-related signal variations through periodic resistance changes associated with chest expansion and contraction. Under resting conditions, the extracted respiration-related waveform corresponded to an average breathing rate of approximately 15.2 ± 2.4 breaths per minute, while under moderate activity the observed rate increased to 23.1 ± 3.8 breaths per minute. These values were within physiologically reasonable ranges for the corresponding activity conditions, although no dedicated respiratory reference device was used for direct accuracy validation.

During high-intensity exercise, the respiratory-related signal became less regular, with increased amplitude variation and occasional waveform distortion. In some cases, short-term fluctuations reduced the stability of peak detection, requiring additional smoothing to identify dominant breathing patterns. This indicates that the textile signal remained responsive to respiratory activity, but its reliability decreased under vigorous movement.

Representative signal patterns under different activity conditions are shown in Figure 4.

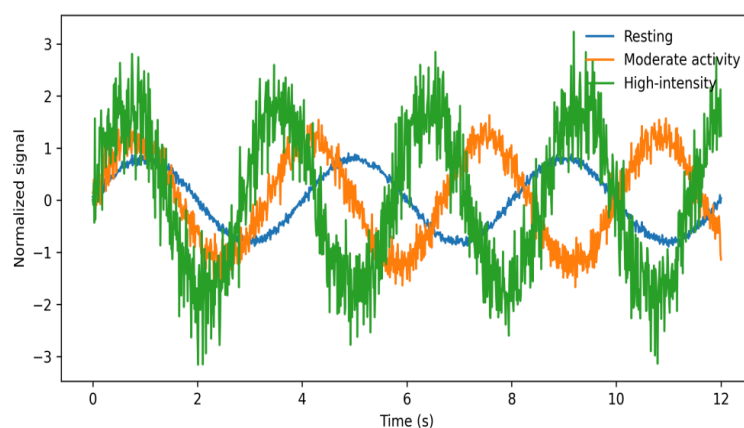


Figure 4. Representative signal patterns under different activity levels

In terms of motion response, the system exhibited distinguishable waveform characteristics across different activity levels. Walking and light jogging produced relatively regular oscillatory patterns, whereas running and jumping resulted in more irregular and larger-amplitude responses. However, partial overlap between waveform patterns was also observed in some cases, suggesting that activity differentiation based solely on raw signal features remains limited and may require further refinement through more advanced feature extraction or classification methods.

Wearability Evaluation

The wearability of the smart textile system was assessed through subjective feedback from participants. Overall, the system showed acceptable comfort and flexibility during the test, with minimal restriction on body movement.

The knitted fabric structure provided adequate elasticity, allowing the garment to conform to different body shapes. Most participants reported no obvious discomfort during resting and moderate activities. However, during prolonged high-intensity exercise, several participants noted slight tightness or localized pressure in areas where conductive yarns were densely integrated.

The average comfort rating based on a 5-point Likert scale was 4.1 ± 0.7 . This result indicates generally positive user acceptance, although the observed standard deviation suggests that wearer experience varied across participants, likely due to differences in body shape, garment fit, and local pressure distribution.

Reliability and Repeatability Analysis

To evaluate the repeatability and short-term reliability of the system, repeated measurements were conducted under identical conditions. The results showed that the proposed system maintained generally consistent performance across multiple trials, although minor variations were still observed.

Across repeated measurements, variability remained relatively low under resting conditions and increased under moderate- and high-intensity activities, consistent with the standard deviations reported in Table 1. This trend indicates that measurement stability decreased as body motion became more intense, mainly due to stronger motion artifacts and greater variability in local fabric–skin contact.

No obvious signal drift was observed during short-term measurements of less than 30 min. However, small differences between trials were noted, which may be attributed to slight changes in sensor positioning, garment fit, and user movement patterns.

These findings suggest that the system demonstrates reasonable repeatability for short-term wearable monitoring, although its performance is still influenced by practical factors related to sensor placement and user-specific conditions. Further optimization in textile design, sensor integration, and garment fit may help improve long-term stability and measurement consistency.

DISCUSSION

The experimental results demonstrate that the proposed smart textile system has practical potential for wearable sports monitoring. Compared with conventional wearable devices, the textile-based platform provides good comfort, flexibility, and continuous contact with the human body, which is beneficial for unobtrusive physiological and motion-related signal acquisition during exercise.

The results further indicate that the proposed system can provide reasonable pulse-related trend estimation under different activity conditions. The MAE increased from 1.4 BPM under resting conditions to 3.5 BPM during high-intensity activity, while the overall coefficient of determination (R^2) remained 0.94. This suggests that the system maintained a consistent trend relationship with the reference device, although its agreement performance was reduced under dynamic motion. The main sources of error were likely motion artifacts, transient changes in fabric–skin contact, and local deformation of the textile sensing region.

In addition to pulse-related trend estimation, the system was able to capture respiratory-related signal variations and distinguish general waveform differences across activity levels. However, respiratory monitoring was not directly validated against a dedicated reference device, and partial overlap between motion-response patterns was still observed. Therefore, the current system should be regarded as a feasible monitoring prototype rather than a fully validated multi-parameter sensing solution.

Several limitations remain. First, measurement stability decreased during vigorous activity, indicating that signal robustness under strong motion still requires improvement. Second, the current study focused on short-term experiments under controlled indoor conditions, and long-term durability, washing stability, and repeated use of conductive textiles were not evaluated. Third, the sample size was relatively limited, which may affect the generalizability of the findings. Although basic participant characteristics and garment-fitting procedures were recorded, body-shape-related differences, such as BMI, chest circumference, and gender-related fit variation, may still have influenced textile–skin contact stability. A limitation of this study is that baseline physical fitness was not formally assessed, which may have influenced individual responses to moderate- and high-intensity activities. Participants were instructed to maintain similar pre-test routines to partially

control for baseline variability, but future work should include standardized fitness assessments (e.g., $VO_2\max$ or activity questionnaires) to ensure more consistent task execution across participants. Another limitation is that the reference device used (Polar H10 chest strap) is a consumer-grade sensor rather than a clinical gold standard. Therefore, the MAE and RMSE values reflect agreement with a validated consumer device and do not represent clinical heart-rate measurement accuracy. Future studies should incorporate clinical-grade ECG or PPG sensors to provide a more authoritative benchmark. In addition, since cardiac-related information was indirectly derived from textile resistance variations rather than directly measured using ECG or PPG signals, the results should not be interpreted as clinical-grade heart-rate measurement. Future work should focus on improving sensor integration, optimizing garment fit, enhancing signal-processing strategies, expanding the participant sample, and conducting long-term durability and washability tests in real-world application scenarios.

Conclusion

This study designed and experimentally evaluated a smart textile system for sports monitoring and health-related applications. By integrating conductive yarn-based sensing elements into an elastic textile substrate, the proposed system was able to acquire physiological and motion-related signals in a wearable and relatively unobtrusive manner.

The experimental results showed that the system achieved reasonable performance under different activity conditions. For pulse-related trend estimation, the MAE values were 1.4 BPM, 2.1 BPM, and 3.5 BPM under resting, moderate-intensity, and high-intensity conditions, respectively, with an overall coefficient of determination (R^2) of 0.94 compared with the commercial reference device. These findings indicate that the proposed system was capable of providing consistent pulse-related trend estimation, although agreement with the reference device decreased under vigorous motion due to motion artifacts and variations in fabric-skin contact.

In addition, the system was able to capture respiratory-related signal variations and motion-response characteristics under different activity conditions. The wearable textile platform also exhibited acceptable user comfort, with an average comfort score of 4.1 ± 0.7 . These results suggest that the proposed system has practical potential for short-term wearable sports monitoring.

Nevertheless, several limitations remain. Respiratory-related monitoring was not directly validated using a dedicated reference device, the sample size was relatively limited, and long-term durability and washability

were not investigated. Future work should focus on improving sensor integration, enhancing signal robustness under dynamic motion, and evaluating long-term performance in real-world application scenarios.

Availability of Data and Materials

The datasets used and/or analysed during the current study were available from the corresponding author on reasonable request.

Author Contributions

Hao Deng and Pengfei Deng designed the study; all authors conducted the study; Pengfei Deng and Hao Deng collected and analyzed the data. Pengfei Deng and Hao Deng participated in drafting the manuscript, and all authors contributed to critical revision of the manuscript for important intellectual content. All authors gave final approval of the version to be published. All authors participated fully in the work, took public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or completeness of any part of the work were appropriately investigated and resolved.

Ethics Approval and Consent to Participate

This survey was conducted in compliance with Ethics Committee of Xi'an JiaoTong University City College. Participants were informed of the study's purpose and data usage prior to participation, and responses were collected anonymously. No personally identifiable information was stored.

Acknowledgment

Not applicable.

Conflict of Interest

The authors declare no conflict of interest.

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REFERENCES

- [1] Stoppa M, Chiolerio A. Wearable electronics and smart textiles: a critical review. *Sensors*. 2014; 14(7): 11957-11992. doi: 10.3390/s140711957
- [2] Heikenfeld J, Jajack A, Feldman B, et al. Accessing analytes in biofluids for peripheral biochemical monitoring. *Nature Biotechnology*. 2019; 37(4):407-419. doi: 10.1038/s41587-019-0040-3

- [3] Yetisen A K, Martinez-Hurtado J L, Ünal B, et al. Wearables in medicine. *Advanced Materials*. 2018; 30(33): 1706910. doi: 10.1002/adma.201706910
- [4] Cherenack K, van Pieterse L. Smart textiles: challenges and opportunities. *Journal of Applied Physics*. 2012; 112(9): 091301. doi: 10.1063/1.4742728
- [5] Castano LM, Flatau AB. Smart fabric sensors and e-textile technologies: a review. *Smart Materials and Structures*. 2014; 23(5):053001. doi: 10.1088/0964-1726/23/5/053001
- [6] Chen M, Ma Y, Song J, et al. Smart clothing: connecting human with clouds and big data for sustainable health monitoring. *Mobile Networks and Applications*. 2016; 21(5):825-845. doi: 10.1007/s11036-016-0745-1
- [7] Majumder S, Mondal T, Deen MJ. Wearable sensors for remote health monitoring. *Sensors*. 2017; 17(1):130. doi: 10.3390/s17010130
- [8] Axisa F, Schmitt PM, Gehin C, et al. Flexible technologies and smart clothing for citizen medicine. *IEEE Transactions on Information Technology in Biomedicine*. 2005; 9(3):325-336. doi: 10.1109/TITB.2005.854503
- [9] Liu Y, Pharr M, Salvatore GA. Lab-on-skin: a review of flexible and stretchable electronics for wearable health monitoring. *ACS Nano*. 2017; 11(10):9614-9635. doi: 10.1021/acsnano.7b04898
- [10] Atalay O, Kennon WR, Demirok E. Weft-knitted strain sensor for monitoring respiratory rate and heart activity. *Sensors*. 2015; 15(2):2947-2960. doi: 10.3390/s150202947
- [11] Mattmann C, Clemens F, Tröster G. Sensor for measuring strain in textile. *Sensors*. 2008; 8(6):3719-3732. doi: 10.3390/s8063719
- [12] Paradiso R, Loriga G, Taccini N. A wearable health care system based on knitted integrated sensors. *IEEE Transactions on Information Technology in Biomedicine*. 2005; 9(3):337-344. doi: 10.1109/TITB.2005.854512
- [13] Pacelli M, Loriga G, Taccini N, et al. Sensing fabrics for monitoring physiological and biomechanical variables. *IEEE Transactions on Information Technology in Biomedicine*. 2006; 10(3):521-528. doi: 10.1109/TITB.2005.863868
- [14] Tao X. *Handbook of Smart Textiles*. Singapore: Springer; 2015. doi: 10.1007/978-981-4451-45-1
- [15] Dias T. *Electronic textiles: smart fabrics and wearable technology*. Woodhead Publishing; 2015.
- [16] Yang K, Isaia B, Brown LJ, et al. E-textiles for healthy ageing: a systematic review. *Materials*. 2019; 12(3):446. doi: 10.3390/ma12030446
- [17] Ryu S, Kim P, Kim S, et al. Highly sensitive and flexible strain sensors based on conductive materials. *Advanced Functional Materials*. 2016; 26(36):6546-6553. doi: 10.1002/adfm.201601856