Textile & Leather Review

ISSN 2623-6281| www.tlr-journal.com | 10.31881/TLR

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How to cite: Chen K, Xiao L. Design and Prototype Implementation of a Smart Garment for Badminton Performance Monitoring: A Methodological Case Study. Textile & Leather Review. 2025; 8:813-826. https://doi.org/10.31881/TLR.2025.813

How to link: https://doi.org/10.31881/TLR.2025.813

Published: 24 November 2025

Design and Prototype Implementation of a Smart Garment for Badminton Performance Monitoring: A Methodological Case Study

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Article

https://doi.org/10.31881/TLR.2025.813

Received 4 June 2025; Accepted 28 July 2025; Published 24 November 2025

ABSTRACT

This study aims to design and validate a prototype smart garment for monitoring badminton-specific movements. The research captures and analyzes body deformation signals during various technical movements performed at different intensities, by integrating flexible textile sensors into key areas of the sportswear (namely, the chest, back, and sides of the waist) and employing a multi-channel synchronous data acquisition system.Results demonstrate that: (1) the prototype system operates with stable functionality and can effectively acquire motion-related signals; (2) for specific technical movements, optimal monitoring zones exist; for instance, the sensor placed on the back achieves the highest signal-to-noise ratio when monitoring a high clear shot; (3) the amplitude of sensor signals exhibits a significant correlation with the intensity of exertion, indicating the system's potential for quantifying training loads. This study confirms the feasibility of the proposed technological approach and provides methodological groundwork and empirical evidence for the development of intelligent sportswear capable of high-precision movement recognition and exertion analysis.

KEYWORDS

smart textiles, flexible sensors, motion monitoring, wearable technology, textile technology

INTRODUCTION

In an era marked by rapid technological advancement, the deepening integration of information technology across various industries drives unprecedented transformation and innovation—sports being no exception. With the swift progress of cutting-edge technologies—such as sensor systems, wireless communication, and artificial intelligence—wearable smart devices have emerged and rapidly gained traction, becoming a prominent new frontier in the development of the sports industry. Smart wearable garments for athletic monitoring incorporate various advanced sensors and intelligent technologies, enabling the real-time and accurate tracking of physiological metrics (such as heart rate) and activity-related data (such as step count and speed). These data are transmitted to smart devices or cloud platforms for further analysis and processing [1–3]. Educators can gain a comprehensive understanding of each student's physical condition and activity levels by leveraging this data, thereby enabling the design of personalized instruction and training programs tailored to individual needs [4,5]. Compared with traditional metal sensors, flexible sensors offer notable advantages such as softness and stretchability, rendering them more suitable for seamless integration with textiles [6]. However, mature products that incorporate flexible sensors into garments remain scarce, and relevant research is still in its nascent stages. Within the textile field, considerable attention has been provided to the fabrication and performance of flexible fabric sensors. For instance, some studies have developed flexible sensors by combining silver-coated conductive nylon filaments with yarns, applying them to assess pressure distribution in seamless underwear [7]. Other research has used conductive fibers to produce flexible sensors capable of monitoring human respiration, with results indicating a certain degree of reliability and stability [8,9]. Nevertheless, studies on the performance of flexible fabric sensors in real-world applications—particularly in high-humidity environments typical of athletic activity—remain limited.

The present study builds upon existing research to design and fabricate a wearable smart garment for athletic monitoring to explore the application of this emerging technology in specific sports contexts. This research seeks to validate the feasibility of using such a system to capture motion-related signals specific to badminton and to examine its potential for distinguishing between various technical actions by strategically placing flexible sensors in different regions of a form-fitting badminton outfit. The full design and development process of the smart garment are presented as a methodological case study, offering practical insights and identifying critical challenges to inform the future development of functionally advanced intelligent sportswear.

WEARABLE SMART SPORTSWEAR DESIGN

Structural Composition

The wearable smart sportswear architecture consists of a hardware system and a software system. The hardware combination mainly includes sensor modules, battery modules, printed circuit board (PCB) circuit modules, signal transmitters, receivers, and terminal displays, whereas the software involves regional sensor network systems, wireless data processing systems, and communication systems, as shown in Figure 1.

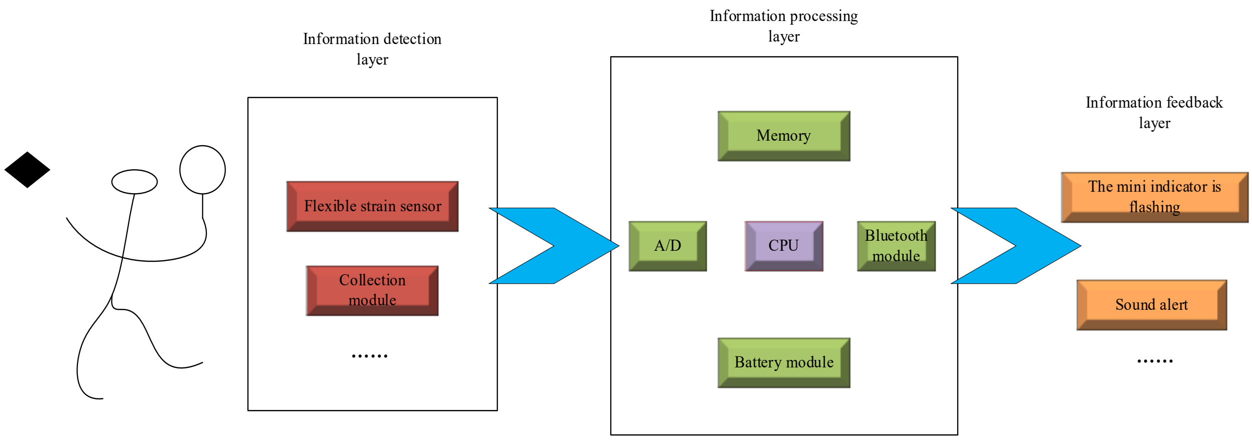


Figure 1. Overall structure of wearable smart sportswear

Monitoring Principle of Flexible Fabric Strain Sensor

The flexible fabric strain sensors were primarily supplied by Zhuhai Anrunpu Technology Co., Ltd. These sensors incorporate advanced nanomaterial technology and processes. Nanomaterials offer numerous superior properties, including a high specific surface area, unique electronic structures, and exceptional physical and chemical characteristics. These features enable the sensors to exhibit remarkable sensitivity, allowing them to accurately capture extremely subtle deformations in fabrics, thereby more precisely reflecting human physiological and movement information. The fabric is based on elastic knitted material and coated with carbon-based conductive materials. This combination maximizes the fabric's flexibility and stretchability, as well as the conductive properties of the carbon-based materials. During fabric stretching and compression, the resistance of the conductive material changes systematically with the fabric deformation. The sensors can accurately collect information on human breathing, heart rate, and movement by precisely measuring these resistance changes, as illustrated in Figure 2.

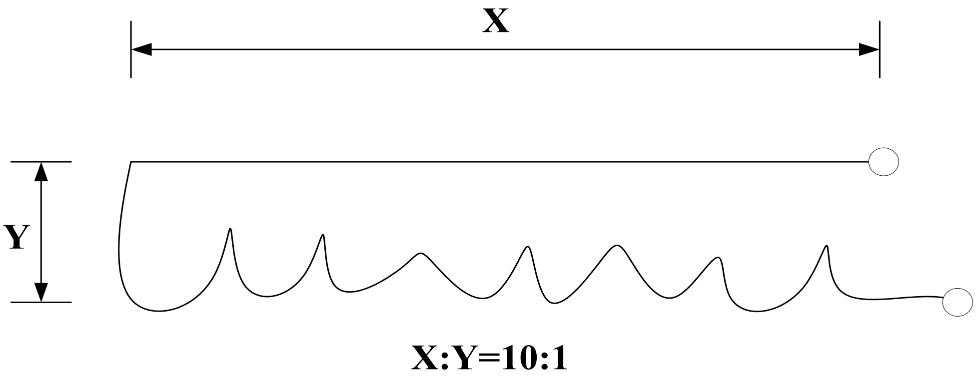


Figure 2. Equivalent schematic of flexible fabric strain sensor

Figure 2 illustrates that when the fabric is stressed at both ends, the fabric length gradually increases and the cross-section of the sensitive layer gradually decreases. Combined with formula (1), the resistance value gradually increases. In other words, during fabric stretching, the corresponding index can be obtained through the change in the resistance value.

$$R = \rho \frac{L}{S} \tag{1}$$

In formula (1), ρ represents resistivity; L refers to length; S indicates the cross-sectional area.

When using this sensor to monitor the intensity of badminton sports, it mainly stretches the fabric sensor through body movement, thereby varying the corresponding resistance value. Moreover, the sports intensity is analyzed based on the change pattern of the resistance value.

Smart Sportswear Sewing Process

In the production of smart sportswear, sensors are integrated with clothing mainly through sewing. Different sewing processes will affect the tensile performance of sensors. Therefore, the sewing process must be determined.

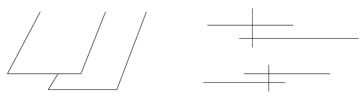
(1) Selection of sewing stitches

At present, commonly used sewing machines are mainly categorized into several types, such as interlock sewing machines, overlock sewing machines, and chain stitch machines. In the sewing process, the stretchability of various stitches must be considered, as well as the tensile strength of the stitches. Based on the existing experimental conditions, two sewing stitches are determined, namely, 600-level covering stitch and 404 herringbone stitch. At the same time, JUKI MF-7800 sewing machine and JUKI LZ-2280N sewing machine are selected, and 605 three-needle five-thread interlock stitch is used uniformly.

(2) Determination of sewing details

At present, popular sportswear brands on the market include Li-Ning, Kaisheng, and Under Armour. The materials used in these sportswear products are primarily polyester fiber and spandex. In this study, Li-Ning's quick-drying badminton sportswear series (88% polyester fiber, 12% spandex) was selected as the carrier. To ensure that the sensor maintains the same elasticity as the garment after splicing, the sewing thread, tension, and stitch length must be adjusted during the sewing process. In this study, for the JUKI MF-7800 sewing machine, two types of sewing thread were selected, namely, polyester sewing thread and nylon high elastic (DTY) colored silk, used as decorative thread and ground thread, respectively. For the JUKI LZ-2280N sewing machine, the sewing thread used is the same as the first type of sewing thread of the interlock sewing machine. The seam type, stitch, and stitch length used for splicing samples during the experiment are shown in Table 1.

Table 1. Seam type, stitch, and stitch length used for stitching samples

serial number	Seam Type Number	Seam type diagram	Stitch	Needle distance
1	2.01		Three needles and five threads	5.00 mm
2			Herringbone stitch	2.50 mm
3			Herringbone stitch	1.50 mm

In this study, a herringbone stitch with a stitch length of 1.5 mm was determined as the sewing method for fabricating the sensor specimens.

Sensor Sample Sewing Experiment

(1) Flexible sensor placement method

At present, common sensor samples mainly include non-welded sensors and sensors connected to PCB, which are more widely used in actual applications. However, non-welded sensors are prone to tearing during use, resulting in signal interruption. Considering the effect of fabric thickness on comfort, the method of wrapping the flexible sensor with a double-layer fabric and sewing it to insert the sensor is adopted.

(2) Sewing of flexible sensor samples

Prior to sewing, the initial resistance value of the flexible sensor was measured with a multimeter, and the average initial resistance value was 83.89 kΩ. After sewing, the sensor was stretched to a certain extent, slightly increasing the resistance value compared with the initial value, with the measured resistance value was 92.53 kΩ.

PROOF-OF-CONCEPT SYSTEM VALIDATION

Experimental Setup

Test Subjects

This exploratory technological case study aims to detail the full process of developing and validating a system prototype. To ensure relatively consistent and standardized motion input for the system, two male badminton enthusiasts (labeled A1 and A2) from a university badminton club were invited to participate in the testing. Both subjects have over three years of playing experience and exhibit technically sound movements, rendering them suitable for assessing the system's signal capture capabilities. Basic information about the participants is provided in Table 2.

Table 2. Basic Information of Test Subjects

Subject ID	Gender	Age	Height, cm	Weight, kg	Dominant Hand
A1	Male	22	178	70	Right
A2	Male	23	181	75	Right

Experimental Garment and Apparatus

The experimental garment used in this study was a size-L Li-Ning quick-dry badminton shirt (88% polyester, 12% spandex), selected for its elasticity. Rectangular flexible sensors (10 cm × 1 cm) were stitched into three key monitoring positions using a double-layer fabric wrapping technique: horizontally across the chest, horizontally across the back, and vertically along the side waist. The signal acquisition module (80 mm × 45 mm) supported multi-channel synchronous data collection, ensuring that signals from all three positions were recorded simultaneously with a unified time reference. The module was secured to the garment using hook-and-loop fasteners (Velcro), allowing for easy adjustment and reliable attachment.

Test Protocol

The test protocol included four representative badminton movements: net shot, high clear, forehand lift, and backhand lift. Prior to each test, participants were instructed to hold a standard badminton ready position for 60 seconds to establish a resting baseline reference. Each movement was performed in two sets to preliminarily assess the system's sensitivity to movement intensity: one at 50% of the participant's perceived exertion level (rate of perceived exertion, RPE) and the other at 90%.

Data Acquisition Procedure

A standardized synchronous acquisition process was followed to ensure data quality.

Preparation Phase

Upon arrival, participants rested for 10 minutes while researchers prepared the equipment. The experimental procedures and relevant precautions were reviewed with the participants to ensure full understanding.

Data Collection Phase

Participants performed each predefined movement 10 times per intensity level according to the test sequence. The multi-channel acquisition system recorded real-time, synchronized resistance signals from the sensors located on the chest, back, and waist. One technician was responsible for monitoring data storage and performing a preliminary inspection of the waveform graphs generated by the software, whereas another technician recorded the entire session on video to facilitate subsequent synchronization between exact movement timestamps and corresponding signal waveforms.

Signal Feature Extraction and Analysis Method

The data analysis combined waveform visualization with the extraction of key performance indicators. All analyses were conducted using Matlab (R2022b). Initially, raw synchronized signals were visualized to inspect their continuity and overall quality. For objective evaluation and comparison, the following quantitative metrics were extracted from the synchronized signals of each sensor location for every movement:

(1) Baseline value: the mean and standard deviation (SD) of resistance values while the subject maintained a resting posture; used to assess the sensor's initial state and stability.

(2) Peak value: the average and standard deviation of signal peaks recorded during movement execution, reflecting the amplitude of the sensor response.

(3) Coefficient of variation (CV): calculated as (standard deviation / mean) × 100% for the peak values across 10 repeated movements. This metric quantifies waveform reproducibility. Lower CV values indicate improved consistency.

(4) Signal-to-noise ratio (SNR): SNR was defined as the ratio between the net signal amplitude (the difference between the peak resistance during motion and the mean baseline resistance at rest) and the standard deviation of the baseline resistance during the resting state; this metric provides an initial measure of signal clarity.

Most importantly, a core component of the analysis involved direct comparisons between sensor locations because the data were collected synchronously. For each movement type, the study evaluated which sensor placement yielded the highest SNR and lowest CV, thereby identifying the most reliable signal source for recognizing specific actions. In addition, comparisons were made between signal peaks under 50% and 90% exertion levels to assess the system's potential for quantifying physical intensity.

RESULTS

System Functionality and Structural Stability

Throughout all testing phases, the smart garment prototype—integrated with flexible sensors—demonstrated robust structural stability. Even during the high-speed, large-amplitude arm swings, and torso rotation characteristic of badminton, no tearing or damage occurred at the sensor-to-fabric seams. The signal acquisition module, secured using Velcro fasteners, remained firmly in place without detachment. More importantly, the upgraded multi-channel synchronous acquisition system demonstrated reliable performance across all trials, successfully and continuously capturing resistance variations induced by body movements in the chest, back, and waist regions. These results confirm the system's functional stability and overall feasibility. The initial resistance value of the sewn-in sensors was approximately 92.53 kΩ, providing a stable baseline for subsequent signal analysis.

Comparative Signal Analysis of Different Technical Actions

Synchronized data acquisition enabled direct performance comparisons among the sensors in response to targeted movements. As an illustrative example, the "high clear" shot—characterized by substantial torso rotation and power generation, was performed by subject A1 in three consecutive executions. Figure 3 illustrates the corresponding waveform responses from the three sensors. Quantitative results presented in Table 3 further validate these visual observations. During the high clear movement, the back sensor exhibited the highest SNR and the lowest coefficient of variation (CV), indicating that for full-body actions involving extensive trunk extension and rotation, the back is the most effective location for capturing movement-defining signals.

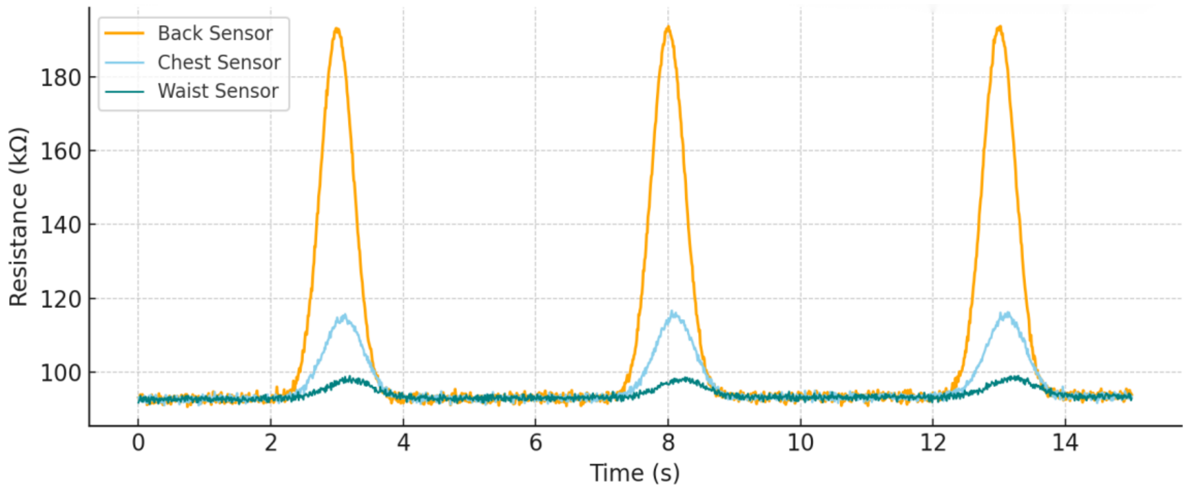


Figure 3. Synchronized signal waveforms from the back, chest, and waist sensors of subject A1 during three consecutive high clear shots

Table 3. Performance Comparison of Sensor Positions During the High Clear Movement

Sensor Position	Average Peak Value (kΩ)	Signal-to-Noise Ratio (SNR)	Coefficient of Variation (CV)
Back	195.2	122	7.50%
Chest	115.8	48.2	15.30%
Waist	98.1	5.6	28.10%

Signal Response to Movement Intensity

The system proved effective in distinguishing between varying levels of exertion. For example, Figure 4 illustrates a comparison of the chest sensor signal responses of subject A2 during the “backhand lift” movement performed at 50% and 90% of perceived exertion. The results show a markedly higher average peak value at 90% intensity (106.5 kΩ) than 50% intensity (99.5 kΩ), representing an increase of nearly 7%. This finding may indicate a correlation between signal amplitude and the intensity of physical effort, providing empirical support for the system’s potential in quantitatively monitoring training load.

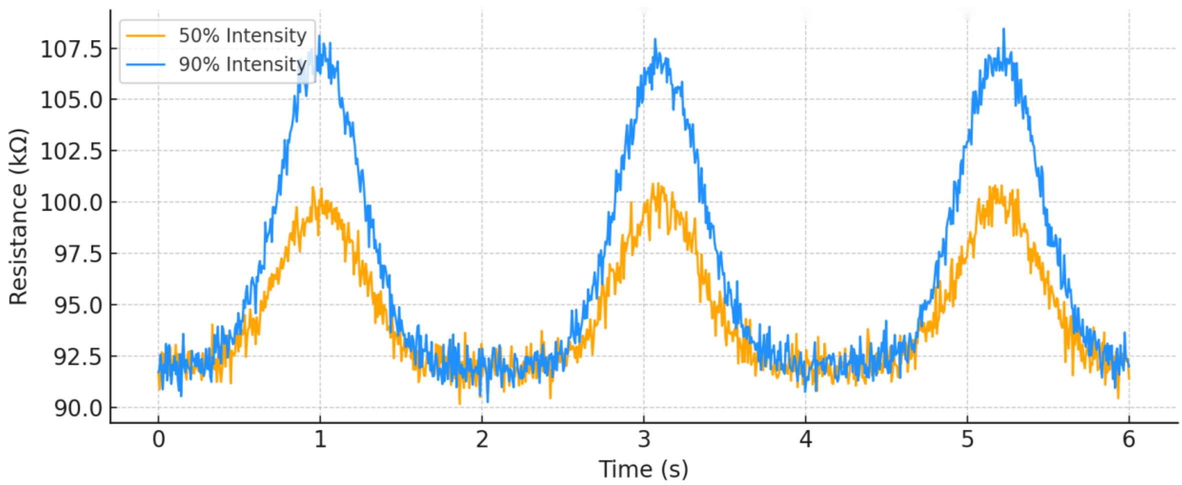


Figure 4. Comparison of signal responses from the chest sensor of subject A2 during backhand lift executed at 50% and 90% intensity levels

DISCUSSION

This study successfully validated the monitoring capabilities of a smart badminton garment prototype through a refined and scientifically structured research process. Findings revealed that optimal sensor placement varies depending on technical movements. For example, the back sensor demonstrated the highest sensitivity in detecting the “high clear” shot, a motion heavily reliant on back musculature and trunk rotation—aligning well with the biomechanical demands of the technique [10,11]. This insight provides a critical reference for future sensor placement strategies in smart garments aimed at high-precision movement recognition. One of the most significant findings of this study is the system’s ability to differentiate between varying levels of physical exertion. The strong correlation observed between signal amplitude and effort intensity [12,13] suggests that the system transcends basic binary detection (i.e., movement present or absent), demonstrating potential for assessing movement quality and training load. This capability holds substantial value for designing individualized training programs and enabling real-time monitoring of athletic condition.

Methodologically, the greatest strength of this research lies in the successful construction and validation of a comprehensive pipeline—from multi-channel synchronous data acquisition to comparative signal analysis. This approach effectively addresses a longstanding challenge in prior studies, where hardware limitations hindered direct comparison of signals across multiple sensor locations [14,15]. The established workflow serves as a robust methodological foundation for future investigations in this domain. Despite its methodological rigor, the principal limitation of this study is the small sample size (N = 2). Therefore, conclusions such as the superiority of the back sensor during the serve, or the correlation between signal amplitude and exertion, should be interpreted as preliminary findings validated only in two technically proficient subjects. These observations lack statistical generalizability and warrant further verification through larger-scale studies. Building on validated prototype and research methodology established here, future efforts will focus on three key directions: first, expanding the sample size is a top priority. Recruiting a more diverse group of participants, across varying skill levels and genders, will be crucial for validating the generalizability of the preliminary patterns observed. Second, leveraging the high-quality synchronized data collected, we aim to develop machine learning algorithms that can automatically recognize different badminton techniques and potentially assess the quality of movement execution. Finally, we plan to conduct synchronized testing with biomechanical “gold standard” systems such as motion capture or electromyography to establish quantitative models linking our sensor signals to validated biomechanical indicators. This approach will enable deeper, data-driven analyses of athletic performance.

CONCLUSION

This study successfully validated a prototype smart garment for badminton performance monitoring. The results demonstrate that optimizing sensor placement (e.g., positioning on the back for serve monitoring) effectively identifies specific technical movements. Moreover, the strong correlation between signal amplitude and exertion intensity confirms the system’s potential for quantifying training load. This research lays a solid methodological foundation for the development of next-generation intelligent sportswear.

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

Ke Chen and Long Xiao designed the study; all authors conducted the study; Ke Chen and Long Xiao collected and analyzed the data. Long Xiao and Ke Chen 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 Tsinghua University] (QH-1-51). 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.

Acknowledgments

Not applicable.

Funding

This work received no funding.

Conflict of Interest

The authors declare no conflict of interest.

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