Indian Journal of Fibre & Textile Research
Vol. 49, December 2024, pp. 462-469
DOI: 10.56042/ijftr.v49i4.7099

Design and development of a textile sensor for synergetic muscle action measurement

S S Suresh[1], D Raja[1, a], R G Panneerselvam[2], A Arputharaj[3] & A Selvakumar[4]

[1]Department of Fashion Technology, Sona College of Technology, Salem 636 005, India

[2]Department of Fashion Technology, KCG College of Technology, Chennai 600 097, India

[3]ICAR-Central Institute for Research on Cotton Technology, Mumbai 400 019, India

[4]VIT Fashion Institute of Technology, Vellore Institute of Technology, Chennai 600 127, India

Received 4 December 2023; revised received and accepted 3 April 2024

This study presents a novel flexible textile sensor designed for measuring musculoskeletal joint movements, employing commonly available textiles and conductive yarns. To evaluate this sensor's accuracy, calibration and verification are conducted using a biomedical-based electronic sensor device as a reference standard. Performance of the textile sensor involves lower limb knee joint movements, with outputs from the textile sensor compared against those from a digital goniometer and a 3-axis electronic sensor device. Results demonstrate high correlation coefficients of 0.92 and 0.93 respectively, between the waveforms of the textile sensor and the reference devices. These findings strongly suggest that the proposed sensor accurately tracks synergistic muscle joint actions during diverse physical activities performed by humans.

Keywords: Conductive yarn, Knee joint movement, Muscle movement, Textile fabric, Textile sensor

1 Introduction

Continuous monitoring of human joint movements in natural settings is critical for applications in rehabilitation, sports medicine, and virtual training. Current state-of-the-art joint detection techniques primarily function within controlled laboratory settings, while portable devices are limited in availability. Previous research has explored flexible sensor-based devices with varying success. Yamada *et al.*[1] demonstrated the use of flexible sensors crafted from electrically conductive materials that offer exceptional comfort owing to their elastic properties. These sensors, such as stretchy strain sensors comprising polydimethylsiloxane filled with conductive carbon nanotubes, exemplify tracking capabilities for human activities. However, Son *et al.*[2,3] highlighted the delicacy of these sensors, often exhibiting considerable hysteresis due to the properties of the materials used. Ensuring both comfort and meeting standards for electrical security and mechanical reliability, especially under conditions of strain or compromise, remains a challenge. Some studies have attempted to address this by designing flexible and self-healing electronics; however, manufacturing such sensors involves intricate and time-consuming procedures. Bergmann *et al.*[4] observed that repeated deformation, relaxation, and fatigue can impact the conductivity of sensor materials, leading to hysteresis and decreased endurance.

Suresh *et al.*[5] designed and developed a wearable hand glove with a stretchable conductive textile-based sensor inside the gloves to operate an industrial sewing machine by detecting wrist and finger movements, converting them into electrical signals to operate the sewing motor. Bernardina *et al.*[6] noted that while optical motion capture systems stand as an industry standard for their precision in measuring human motion, they are not without errors due to image processing techniques and are relatively costly compared to other methods. Isabelle Poitras *et al.*[7] and Chiang *et al.*[8] demonstrated the advancements in wearable measurements by utilising triple-axis accelerometers, digital magnetometers, and gyroscope sensors fixed onto garments. However, the accuracy of obtained readings remains a challenge, necessitating further improvements in wearable sensor designs. Shyr *et al.*[9] highlighted the time-consuming nature of preliminary settings required for instruments and the human body's sensitivity to attached sensors for vital parameter measurements. Although instruments like goniometers deliver highly accurate measurements, their size and weight pose challenges for prolonged human wear and testing. Hwang *et al.*[10] and Li *et al.*[11]

[a]Corresponding author.
E-mail: rajaslm@gmail.com

endeavored to develop flexible sensors for human motion detection using silver nanowires and conductive elastomers, achieving higher performance outputs by integrating various materials into sensor designs. They adopted multiple stack layer concepts and assembled the sensor by integrating graphene and polyvinyl alcohol chemical composites as the conductive sheath and polyurethane yarn as the core. Totaro *et al.*[12] developed smart clothing equipped with textile-based kneepads and bands fitted with embedded sensors to detect lower limb movement, showcasing promising results with strain values of approximately 30%.

Suresh *et al.*[13] measured the longitudinal wicking of textile fabrics using electrical conductivity sensors. They employed a novel tribo-electric glass plate as the medium to measure the wicking, where electrostatic charges are distributed over the surface of the glass plate, attracting the textile fabric and facilitating wicking. This paper elucidated the fabric's attraction towards the electrostatic charge distributed over the glass medium which can be further studied by comparing it with the wicking action of human skin and sweat transfer. Raja *et al.*[14] conducted a study on the cyclic stress affecting the transverse wicking behavior of cotton/lycra knitted fabrics under different ranges of stretch. This study helped to analyze the effect of stretch on wicking behavior. The aforementioned previous research elucidates the complexity involved in developing textile-oriented sensors. In this study, a novel textile sensor using textile fabrics and conductive yarns captures knee joint movements and addresses flexibility, durability, and wearability challenges. This device underwent practical testing and assessment of its properties for tensile strength and musculoskeletal movements during daily activities, demonstrating the potential for practical, wearable monitoring solutions.

2 Materials and Methods

Figure 1 shows the novel textile sensor (TS) design. Constructed in a three-part structure, the sensor's top, middle and bottom parts were sewn sequentially (length-wise, one below the other). These sections used three distinct textile materials: the top and bottom parts were made from regular fabric, while the middle part comprised a conductive stretchable fabric as a core layer covered by stretchable non-conductive fabric. The stretchable conductive fabric served as the main conductive element measuring knee movement by tracking resistance during muscle stretch and restoring conditions. Silver conductive ink was applied onto the surface of the textile substrate (nylon double-knit elastic fabric) using the dip coating method. The silver conductive ink typically consists of silver nanoparticles dispersed in a solvent along with additives to improve adhesion and conductivity. A container filled with the silver conductive ink was well-mixed to ensure uniform coating. The textile substrate was carefully immersed into the ink bath, ensuring the entire surface to be coated was submerged fully in ink. The immersion time varied depending on fabric thickness and desired coating thickness. The stretchable non-conductive fabric was made from commercially available polyester lycra blend yarns. The non-stretchable normal fabric shown in Fig. 1 is a honeycomb-structured woven fabric developed using cotton blend yarn.

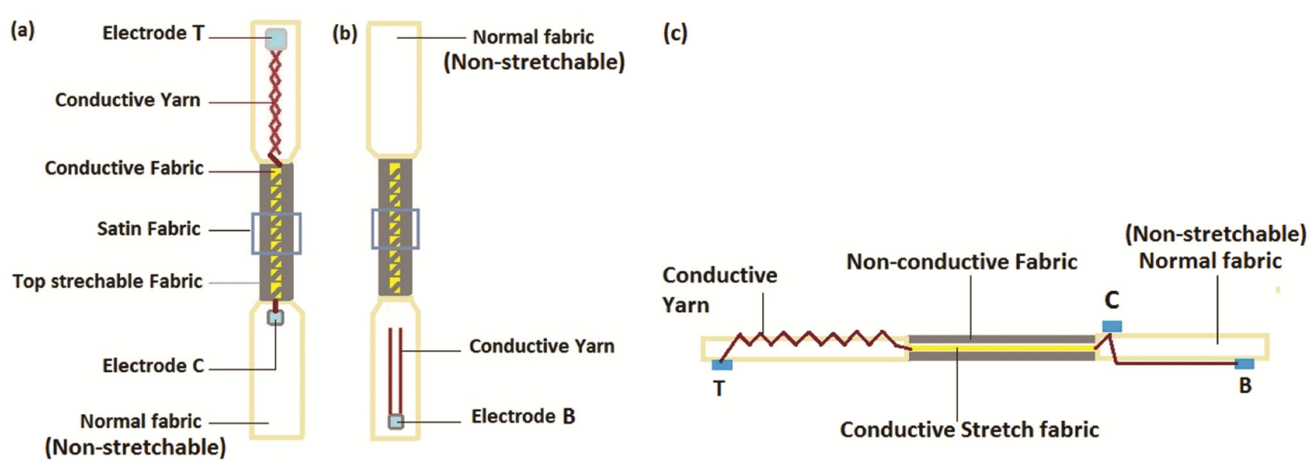

Fig. 1 — Design of novel textile sensor (a) face view, (b) back view and (c) side view

Figure 1 (c) depicts the individual parts of the TS. The top, middle and bottom parts were arranged one above the other vertically and sewn at fabric edges. To increase the strength, two layers of stretchable fabric were used. In the middle of the two layers, a stretchable conductive double knit fabric was used as the core conductive element, and the electrodes on both sides were connected using stainless steel conductive yarn. The stainless steel silver conducting fibre yarn is preferred for its excellent strength and electrical conductivity, especially in biomedical applications. Here, the TS come into contact with the human body (skin), and biocompatibility is essential. The stainless steel is safe, does not cause breakage during stretching actions of the knee, and also does not cause adverse reactions on skin or tissue. Hence preferred in biocompatible applications and can be used safely. A smooth satin fabric made belt was introduced in the middle section of the TS. This satin fabric holds the middle part of stretchable fabrics and grips them from slippage during elongation and restoring of stretchable fabrics.

In the face side of the top part, the stainless steel silver conductive yarn was sewn in a saw-tooth pattern and extended to the electrode T. In the bottom part, electrodes C and B were sewn in opposite sides and at opposite ends. The stainless steel silver conductive yarn was sewn in a straight pattern, forming two parallel conductors at the bottom part. The conductive yarn used is silver coated polyamide continuous filament yarn, 22 tex, resistance 300 ohm/m. Due to silver coated material, the yarn possesses washable and wear-resistant property. The wash resistance testing was performed for the silver-coated polyamide conducting fibre as per AATCC Test Method 61-2013. The silver-coated conductive fibre was subjected to 20 wash cycles and was assessed for properties such as color fading, surface degradation and loss of functionality.

The wear resistance was measured using the Martindale Abrasion Test. The test fabric sample was subjected to rubbing motion against a standard wool made abrasive material. A total of 30 cycles with 9 Kpa pressure was tested to evaluate the wear or damage to the fabric surface. After testing the surface morphology, abrasion resistance, and dimensional of the silver-coated polyamide was analyzed by comparing the results before and after wear testing. The silver coated conductive fibre was stable and showed promising results with minimal degradation. Also the yarn exhibits excellent electrical conductivity and strength to withstand force (stress). The top and bottom part conductive yarn patterns were energized individually, and the resistance of the conductive patterns was measured in up to 10 cycles. The average resistances of both conductive patterns were noted, and recorded as reference resistance values.

Figure 2 shows the fabricated prototype, detailing the components sewn in the TS. Electrode T was sewn in the non-stretchable normal fabric at the top part, while electrodes C and B were sewn in the non-stretchable normal fabric at the bottom part. The middle part consists of three fabric layers: two non-conductive stretchable layers covering a conductive stretchable core layer. The size of the non-stretchable fabric used in the top and bottom parts of TS is 6 cm width x 8 cm length. The size of the stretchable fabric used in the middle part is 4 cm in width x 15 cm in length. The core component stretchable conductive fabric used is 2 cm width x 15 cm length. The developed sensor was flexible, lightweight, and easily integrated into garments for wearable measurements.

The stretch and recovery tests were conducted using fabric stretch and recovery tester to measure the denim fabric's ability to stretch and return to its original shape. A sample fabric specimen was cut to a size equal to TS size 4 cm width and 15 cm. The fabric stretch and recovery tester is operated by a DC motor. The testers have movable and fixed jaws. The

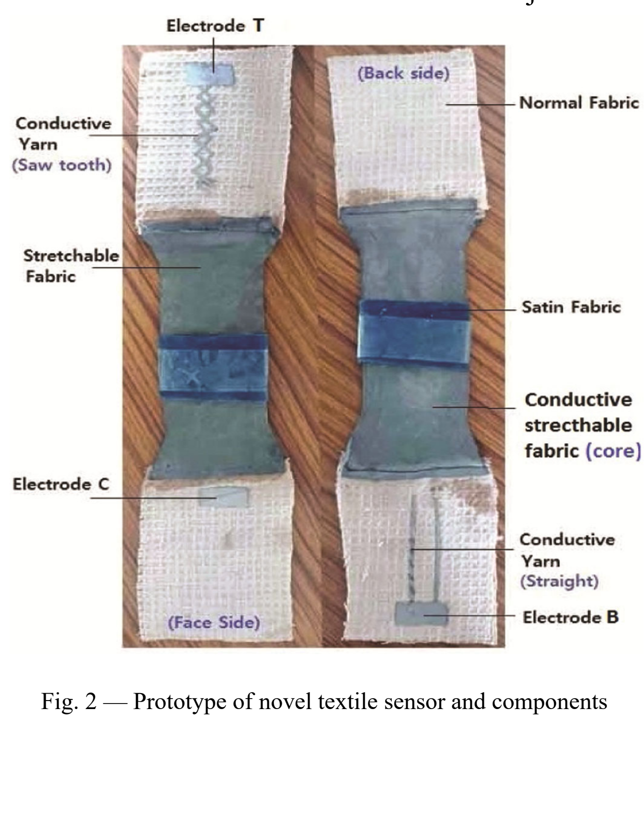

Fig. 2 — Prototype of novel textile sensor and components

speed of movable jaw and stretch length can be adjusted as per the user requirements.

As shown in Figure 3, TS operates like an electrical rheostat. The electrical resistance of electrode C was considered negligible to that of the resistance of silver conductive yarn. Generally, a change in electrical resistance is proportional to the area and length of any electrical conductor. TS is stretched and the electrical resistance of electrodes B and C changes, proportional to the force and displacement applied on conductive stretchable fabric sensor.

The changes in resistance (Rc) and length (Lc) are used to calculate sensitivity (Sc) using the following equation:

$$Sc = Rc/Lc \quad \dots (1)$$

The saw tooth patterns and straight patterns were sewn using conductive threads and taken as the fixed textile resistors with known resistance values.

As shown in Fig. 4, the TS attached to the lower limb at the knee portion, covering both the thigh and shank portions. When the wearer bent or moved the knee at an angle, the sensor stretched from the fixed edges, indicated by black dots positioned above and below the knee joint. This set up extended the sensor, but the length change in the non-stretchable fabric sections (top and bottom) remained minimal and was therefore disregarded. Only the middle stretchable fabric layer showed significant elongation, making it the focus of measurement. The knee movement was considered radial, and correspondingly, the measurements were taken for angle and length changes. The change in length (Lc), reference angle (q1), reference angle (q2), change in angle (Tc), and radius of knee joint (r) are the relational factors illustrated by the following equations:

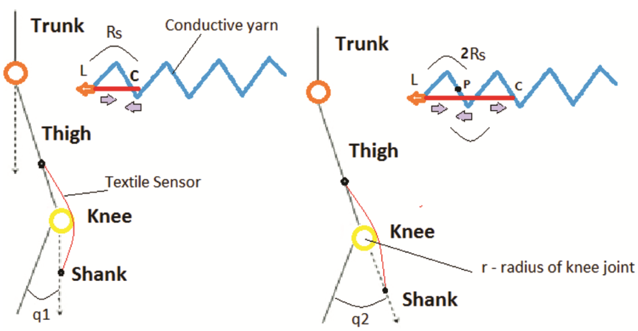

Fig. 3 — Knee motion and resistance measurement

$$Lc = r.Tc \quad \dots (2)$$

Eqs 1 and 2 can be used for estimating the value of Tc as shown below:

$$Tc = Rc/ r \times S \quad \dots (3)$$

2.1 Setup and Testing

The design and calibration of the sensor were predicated on the crucial factors of displacement angle and length. To ascertain the angles of the knee joint, a flexible line gauge was utilized, measuring within the range of 70° to 170°. Real-time testing of the TS was performed and practical evaluations were conducted. The sensor was powered by a 5V DC supply, with a microcontroller-based programmable device converting resistance changes into angular displacement values displayed on an LCD.

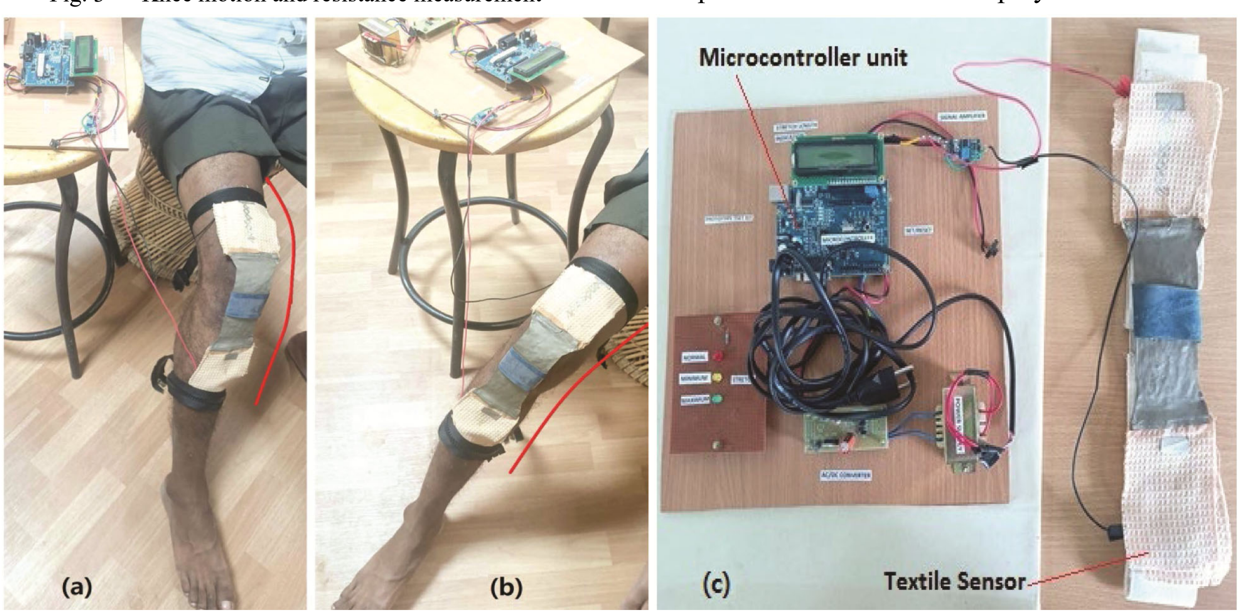

Fig. 4 —Textile sensor in a (a) knee-bent position, (b) straightened position and (c) electronic test kit unit with display

Incremental shifts of 10° were recorded, with a maximum angular displacement of 100° measured within the knee joint. Corresponding alterations in length were identified as the maximum displacement length necessary for sensor calibration, calculated at 55 mm ± 5 mm. For performance evaluation, tensile tests were conducted using a universal testing machine model QC-526M2F, applying controlled elongation at a rate of 10 mm/min.

The TS's elongation and electrical resistance were repeatedly measured during the stretching and contraction phases. The conductive fabric used featured a smooth surface finish, enhancing comfort and providing good contact with human skin without causing irritation or discomfort, making it suitable for this application and potential medical purposes. Before utilizing the sensor for musculoskeletal motion measurements, calibration was done using a digital output goniometer (DG). Comprising a common potentiometer and two extended wooden supports, the DG was employed alongside the prototype TS. Positioned on the thigh and shank of the test subject's leg, both the TS and the DG were connected to the microcontroller unit and processing computer to establish serial data communication. Subsequently, electrical signal values were recorded based on the knee movements performed by the test subject.

2.2 Knee Movement Testing Using Three Axis Accelerometer

A three-axis accelerometer (TA) sensor and its control unit were developed and calibrated by placing it on a stable, flat surface to record corresponding output values for each axis (x, y and z). Subsequently, the accelerometer setup was affixed to the lower limb of the test subject. The individual was positioned on a flat surface, such as the ground, and prompted to perform various knee extensions and muscular movements. Throughout these movements, the TA sensor, along with the microcontroller unit, continuously recorded all angle coordinates and stored the data for reference. This setup facilitated the TA-based wearable sensing system to capture and record the intricate knee joint movements. The data captured from the DG, TS, and TA sensors were recorded and evaluated independently for comprehensive analysis.

2.3 Different Knee Movement Test

A range of movements (walking, sitting, lying-flat, stair climbing) were tested. The test measurements of the TS were compared to the DG and TA sensors for accuracy. The textile sensor's smaller size provided airflow and limited skin contact time, reducing sweat interference during testing. By tabulating the data in excel spread sheet software a graph is generated and the variables of Time (s) axis and Knee angles (o) columns were selected to evaluate the correlation value. According to Pearson correlation coefficient (r)

The correlation coefficient ranges from -1 to 1:
r =1 indicates a perfect positive correlation,
r = -1 indicates a perfect negative correlation,
r = 0 indicates no correlation &
r = (range -1 to 1) represents varying degrees of correlation factors.

3 Results and Discussion

3.1 Non-Conductive Stretch Fabric Test

During the non-conductive stretch fabric testing, the fabric specimen is clamped, and the stretch length range is set to 16.5 to 22.5 cm (Fig. 5). The motor speed is adjusted to various cycles per min. The minimum knee stretch length required for TS is 1.5 cm, and the sensor textile material is stretched to a maximum of 7.5 cm. Results show that for a stretch length of 7.5 cm (50% of the total length of the test sample), there is a 2% change in length (Table 1).

This result from Table 1 indicates that the TS sensor can endure a maximum stress only up to a stretch length of 7.5 cm. The findings suggest that the stretchable textile material is suitable and reliable for developing this TS application.

3.2 Textile Sensor - Tensile Strength Testing

The tensile testing results, shown in Table 2 indicate that elongation and restoration length tests are not completely linear and have slight variations due to the design factors considerations of materials used in TS.

In the stretching test, a graph (Fig. 6) is plotted with elongation length (x-axis) against change in resistance (y-axis). The linear function is calculated using the known coordinates (a_1, b_1) and (a_2, b_2), where the slope (m) is calculated as (b_2 - b_1) / (a_2 - a_1) and the linear function is evaluated as $y = mx + b$. For the stretching test, the resulting linear function was $y = 0.9789x + 65.324$. Similarly, the restoration/contraction test generated the linear function $y = 0.9672x + 66.368$, where the x-axis is the distance (elongation), and y-axis is the electrical resistance of the sensor.

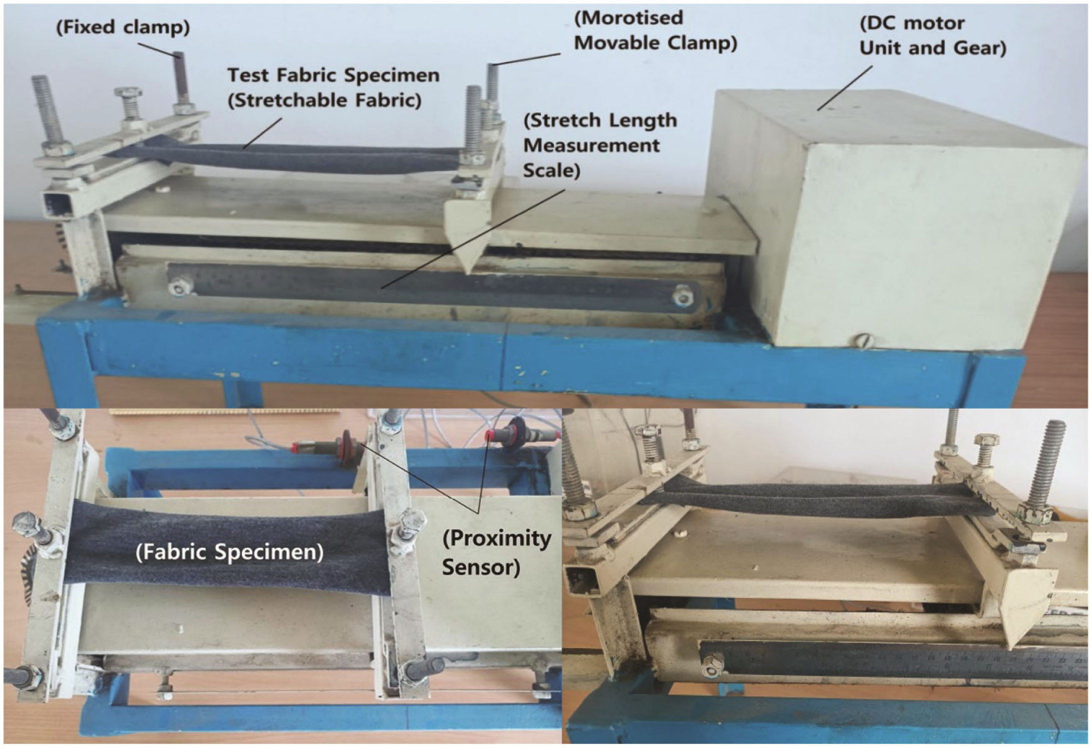

Fig. 5 — Instrument and fabric in stretch and recovery test

Table 1 — Stretchable fabric test

Stretch length cm	Predetermined length cm	Stretch length %	Cycles per min	Total cycles tested (5 min)	Change in length
1.5	16.5	10	20	100	No change
3	18	20	15	75	No change
4.5	19.5	30	10	50	No change
6	21	40	10	50	No change
7.5	22.5	50	5	25	2 %

Table 2 — Textile sensor tensile strength test

Elongation length, mm	Resistance stretching, Ω	Resistance restoration, Ω
5	68	69
10	72	74
15	89	90
20	82	83
25	85	86
30	90	90
35	93	93
40	98	98
45	103	103
50	106	107
55	111	112

The linear regression constants for the elongation and restoration curves are 0.9987 and 0.9905, respectively; with sensitivity values of 0.9789 and 0.9672 Ω/mm. These results indicate no hysteresis, providing the standard results of the sensor performance for daily activities involving lower limbs.

3.3 Knee Movement Test

As shown in Figure 1 (a) & (b), during the relative stretch motion of conductive TS, the resistance of the saw tooth pattern, electrode T, and the resistance between electrodes B and C vary quickly. Figure 3 demonstrates the resistance (Rs) generated by electrodes B and C. During consequent stretching, the resistance between electrodes B and C increases to 2Rs. This resistance varies depending upon the denier of the conductive yarn used for making saw tooth and straight conductive patterns. Based on this formulation, the knee movement test using the TS is conducted, and the results are recorded.

Figure 7 (a) shows the outcomes of knee angle measurements obtained from three sensor instruments. The flexible TS measurements closely align with standard DG and TA sensors, confirming the sensor's accuracy in knee movement detection.

The results reveal a positive correlation coefficient of 0.921 between the waveforms of the TS and the TA sensors. While the TS exhibits effectiveness, discrepancies appear in peak values, particularly at the knee joint’s maximum stretching and bending angles. These discrepancies are consistent, reflected in the sensor's detected angles, which are consistently lower than those registered by the DG and TA methods at the peaks and higher at the bottom. Overall, the TS

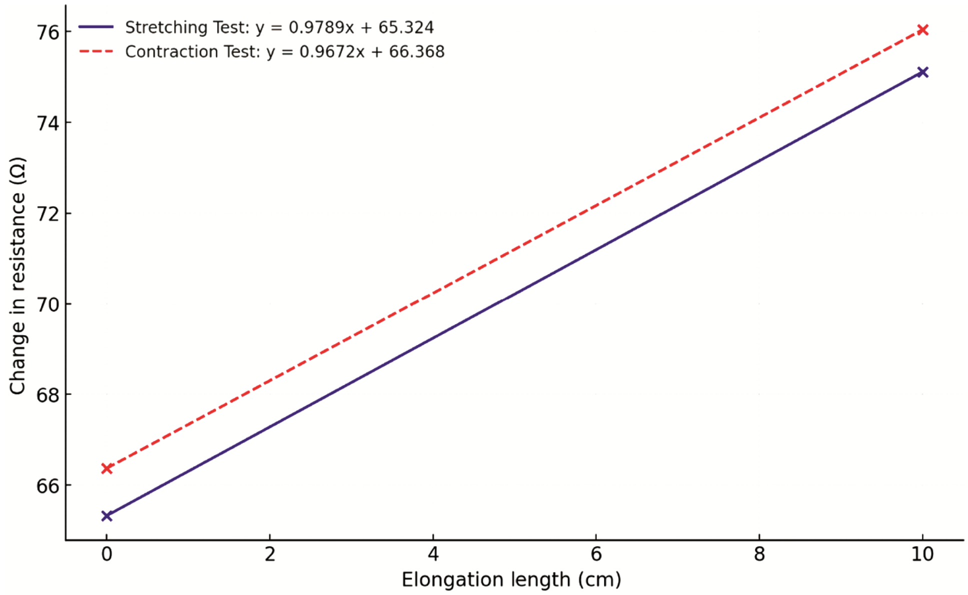

Fig. 6 — TS tensile strength test

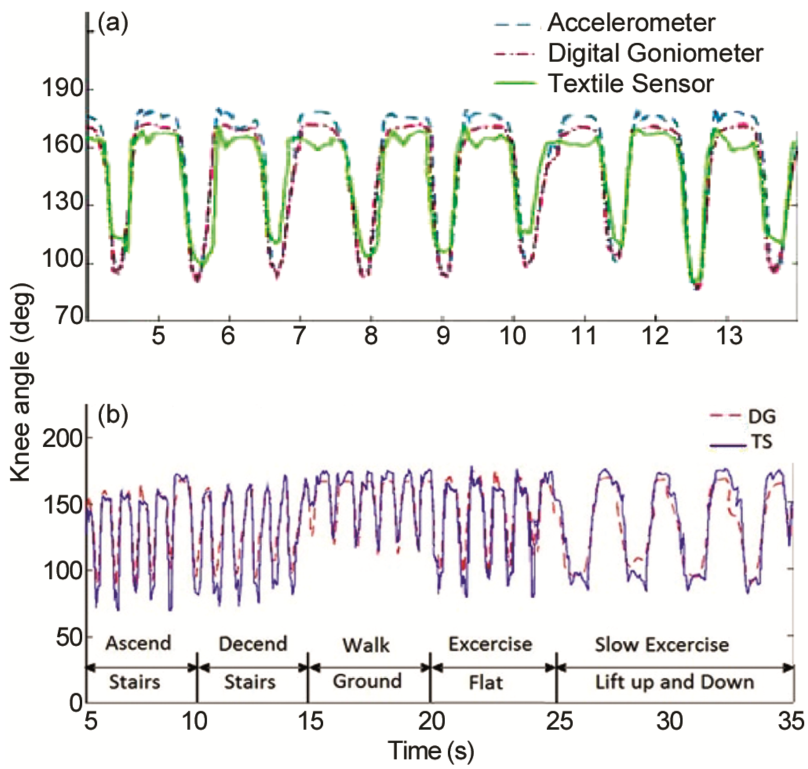

Fig. 7 — Knee movement testing (a) using three sensors and (b) during various activities

demonstrates robust performance in capturing knee movements, with only minor differences in peak values compared to the DG and TA methods.

3.4 Variable Knee Movement Tests

Figure 7 (b) shows knee angle measurements across various activities such as ascending/descending stairs, walking, foot lift-up exercise on a flat surface and slow exercise on a flat surface. The TS waveform shows a high correlation coefficient (0.931) with that of the DG sensor, supporting the textile sensor's capability for knee angle detection during diverse movements, which is essential for rehabilitation and patient care in daily life.

4 Conclusion

This study presents novel TS using conductive yarns and textile fabrics to measure knee joint movements accurately. The sensor exhibits remarkable flexibility, affordability, lightweight nature, compactness, and suitability for integration into extended wearable textiles. Results show excellent linearity and minimal hysteresis factor, with a high correlation coefficient (0.92 and 0.93), supporting non-invasive knee motion monitoring. While this study focuses on knee movement, the sensor's design suggests broader potential in human motion analysis, which is valuable for rehabilitation, sports medicine, and other applications requiring precise musculoskeletal monitoring. Further research directions may enhance the sensor's capabilities for multi-joint motion analysis in diverse wearable technologies, thereby broadening its scope and utility in understanding and improving human movement dynamics.

References

1 Yamada T, Hayamizu Y, Yamamoto Y, Yomogida Y, Izadi-Najafabadi A, Futaba D N & Hata K, *Nat Nanotechnol*, 6 (2011) 296.
2 Son D, Lee J, Qiao S, Ghaffari R, Kim J, Lee J E, Song C, Kim S J, Lee D J, Jun S W, Yang S, Park M, Shin J, Do K, Lee M, Kang K, Hwang C S, Lu N, Hyeon T & Kim D H, *Nat Nanotechnol*, 9 (2014) 397.
3 Son D, Kang J, Vardoulis O, Kim Y, Matsuhisa N, Oh J Y, To J W, Mun J, Katsumata T, Liu Y, McGuire A F, Krason M, Molina-Lopez F, Ham J, Kraft U, Lee Y, Yun Y, Tok J B H & Bao Z, *Nat Nanotechnol*, 13 (2018) 1057.
4 Bergmann J H M, Anastasova-Ivanova S, Spulber I, Gulati V, Georgiou P & McGregor A, *IEEE Sens J*, 13 (2013) 4090.
5 Suresh S S & Raja D, *Indian J Fibre Text Res*, 48 (2023) 124.
6 Bernardina G R D, Monnet T, Pinto H T, Barros R M C, Cerveri P & Silvatti A P, *Appl Biomech*, 35 (2019) 80.
7 Poitras I, Dupuis F, Bielmann M, Campeau-Lecours A, Mercier C, Bouyer L J & Jean-Sébastien R, *Sensors*, 19 (2019) 1555
8 Chih-Yen C, Kun-Hui C, Kai-Chun L, Steen-Jun-Ping H & Chia-Tai C, *Sensors*, 17 (2017).
9 Tien-Wei S, Jing-Wen S, Chang-Han J & Jung-Jen L, *Sensors*, 14 (2014) 4050.
10 Byeong-Ung H, Ju-Hyuck L, Tran-Quang T, Eun R, Do-II K, Sang-Woo K & Nae-Eung L, *ACS Nano*, 9 (2015) 8801.
11 Li X, Hua T & Xu B, *Carbon*, 118 (2017) 686.
12 Totaro M, Poliero T, Mondini A, Lucarotti C, Cairoli G, Ortiz J & Beccai L, *Sensors*, 17 (2017) 2314.
13 Suresh S S, Raja D & Thiyaneswaran B, *Indian J Fibre Text Res*, 47 (2) (2022) 212.
14 Raja D, Ramesh Babu V, Ramakrishnan G & Senthilkumar M, *J Text Inst*, 104 (5) (2013) 502.