Design and Fabrication of Flexible Carbon Fabric PDMS Based Strain Sensor for Human Motion Monitoring

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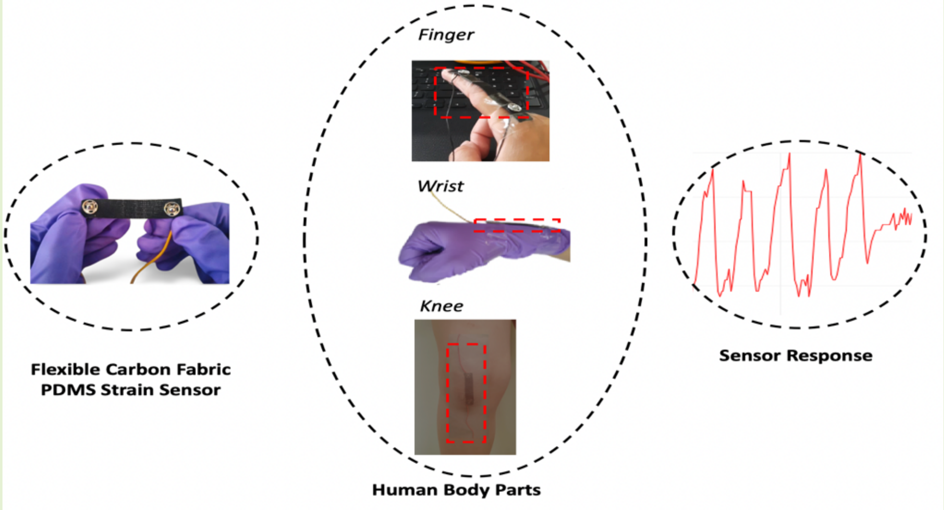
Abstract—**This work describes the fabrication of a carbon fabric polydimethylsiloxane (PDMS) based strain sensor to monitor the human kinematics with high flexibility, durability, and sensitivity. A flexible stretchable strain sensor is fabricated by using activated carbon fabric and PDMS to form the nanocomposite film. For the fabrication of the flexible sensor, robustness and durability of electrodes is essential for its performance. To create robust electrodes, a novel idea of using snap buttons is introduced. The various material, electrical and mechanical characteristics of the sensor samples have been analysed and discussed. To understand the behaviour of the sensor under varied environmental conditions, variations with respect to change in temperature, humidity and moisture conditions are comprehensively studied. The developed sensor has Young's modulus of elasticity (0.0127 MPa), high gauge factor (25.9), faster response time (~ms), excellent cyclic repeatability, and robustness to variation in temperature and humidity. Finally, the developed sensor is tested on the forefinger, wrist and knees for monitoring human motions while performing different physical activities. The developed sensor has shown promising results and will be useful for applications across the field of wearable electronics and biomedical devices.**



Index Terms— **Carbon, PDMS, Flexible, Sensor, Human Motion**

I. INTRODUCTION

With the current advancement in Internet of Things (IoT) technology, wearable electronics is turning out to be one of the leading areas of research [1]. Wearable devices collect data through sensors and use the internet for transmission or reception of information. Sensors are the core component of wearable electronics with their flexibility, durability and sensing capability the considerable focus of research [2]. Commercial strain sensors based on thin metal

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wires and semiconductors are widely developed. These include strain gauge sensors [4-5], flex sensors [6], lead zirconate titanate (PZT) sensors [7], polyvinylidene fluoride (PVDF) sensors [8] and carbon nanotubes (CNT) sensors [9-11] are available, where electrical properties vary with applied mechanical force. These have several limitations, however, including their measurable range and ability to be integrated on curved surfaces due to their stiffness, and sensitivity to environmental conditions [3]. Flexible strain sensors are therefore emerging rapidly in an attempt to overcome some of the drawbacks of traditional strain sensors. These include flexible skin mounted sensors integrated with the human body to gather biometric parameters in various applications related to strain, pressure, and temperature [12-17].

Synthetic fibre is one of the materials that has demonstrated promise in the construction of flexible strain sensors [18]. In recent years, synthetic fibre-based strain sensors have been widely used for wearable strain sensing applications such as health indicators [19], motion sensing [20], human machine interactions [21], automobiles [22], wearable electronics [18], bioelectronics [24] and robotics [25]. Synthetic fibres made of CNTs, graphene and their composites with commercial polymers such as polydimethylsiloxane (PDMS), polyaniline (PANI), polystyrene (PSS), PVDF, rubber, eco-flex, polyimide (PI) and polyethylene (PE) have paved a new path for low-cost flexible strain sensors [26].

Among the electrically conductive polymers composites available, CNT-PDMS composite has been widely used for stretchable strain sensors on the account of its high piezoresistive sensitivity, wide sensing range, high elastic modulus, good thermal behaviour, wide linear range and biocompatible properties [27-28]. It works on the principle of piezo resistivity i.e., the resistance changes with a change in applied strain. Although flexible wearable sensors exist, a number of challenges exist in real-world application. Some of the challenges previously reported are: (i) uncomfortable wearing, (ii) slippage, (iii) weak adhesive between film and substrate, (iv)variation with environmental conditions and (v) brittle electrodes [29].

To address these challenges, this paper focuses on the design and development of a novel carbon fabric PDMS based strain sensor with durable electrodes. It also discusses in detail the various characterisations of the sensor sample. Tensile loading test results with varied temperature and humidity sensitivity are also reported. Finally, an application of human motion monitoring with the developed sensor is also demonstrated in this work.

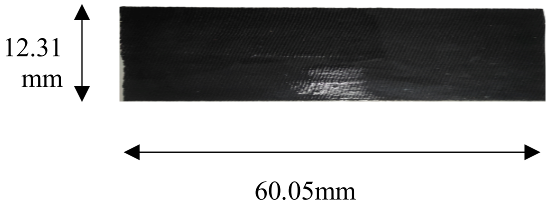
II. EXPERIMENTAL DETAILS

A. *Materials Required*

Activated carbon fabric in the flexible form of activated carbon with a purity higher than 90%, BET surface area in the range of 1000 ± 50 Sq. meter per gram, GSM 130± 15 and decomposition temperature >450°C was procured. PDMS (Sylgard 184, Dow Corning, USA) was used as the polymer matrix. To form electrical contacts on carbon fabric PDMS, nanocomposite film snap button was used.

B. *Fabrication of Carbon Fabric PDMS based Flexible Strain Sensor*

To fabricate a carbon fabric/PDMS nanocomposite film the following steps need to be taken. The first step is to cut the carbon fabric in the dimension of 60.05 x 12.31 x 0.86 mm as shown in Fig. 1(a). A few grams of Sylgard 184, Dow Corning, USA (PDMS) is then bath sonicated until the bubbles are removed. The curing agent is then added to the solution using a ratio of 1 part to 10 parts of PDMS. The solution is then softly stirred by magnetic stirrer for 10 minutes. A Teflon mould matching the fabric dimension is patterned with the help of tapes. Carbon fabric is placed inside the cavity and the prepared solution is poured into it. The solution dipped fabric is then peeled off from the Teflon cavity and placed for curing at 80° C and post cured for 24 hours at room temperature. When it comes to performance, the flexible sensor's construction, robustness, and electrode endurance are crucial. Flexible sensors require electrodes with high electrical conductivity and mechanical strength to withstand large deformations. Most common flexible electrodes break down with large deformations. To create robust electrodes, snap buttons were used. Snap button is a pair of two interlocking discs and is usually used as a substitute to the traditional buttons to fasten clothing. When a specific amount of force is applied, a circular lip under one of the discs fits into a groove on the top of the other, locking them tightly together. In our application, we solder the ends of the copper wires after weaving it through the holes in the base disc and then sandwich the fabric sensor between two button discs as shown in Fig. 1(b), rather than riveting them into the fabric surface as they are typically used in clothing. This wiring configuration, incorporating buttons and sensor, establishes a reliable electrical connection and was determined to be sturdy enough to endure all of the tests carried out while engaging in physical activity as shown in Fig. 1(c). The resistance of the sensor was tested using a laboratory multi-meter after establishing secure connections with snap buttons and copper wires. It was discovered to be 1.7KΩ and 1.5KΩ in its unstretched state and when stretched by 20mm, respectively. With a gauge factor of 25.9, the designed flexible sensor has demonstrated extremely high strain sensitivity.



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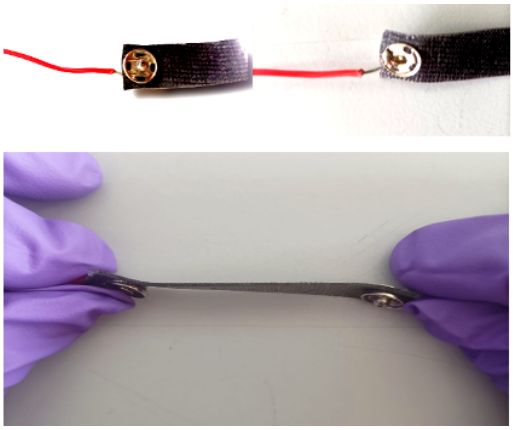


(c)

Figure 1. (a) Carbon fabric PDMS flexible composite film and (b) Carbon fabric PDMS based flexible sensor with snap button electrodes and c) front, back & top view of snap button electrodes

III. RESULTS AND DISCUSSIONS

A. *Material Characterisation*

1. Field Emission Scanning Electron Microscope (FESEM)

FESEM characterisation was used to investigate the morphology of the carbon fabric PDMS sample. FESEM analysis was obtained by using a Hitachi SU 8010 SEM device. The parameters used to analyse the samples were: accelerating voltage of 5 KV, current emission of 3.9 μA and e-beam working distance of 7.5 mm. FESEM micrograph showed the conductive carbon threads in PDMS. PDMS made a uniform coating over the threads and provided better flexibility, and stability to external environment such as temperature, moisture etc [30]. The inset in Fig. 2 shows the magnified view showing the graphite sheet-like structures.

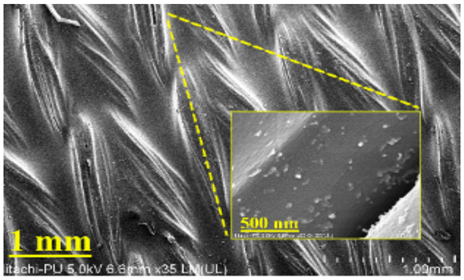


Figure 2. FESEM characterisation of carbon fabric PDMS sample using at the magnification of 1mm and 500 nm (inset picture).

2. RAMAN Spectroscopy

Raman spectra of graphite fabric. D band at 1306 depicts the defect in structures during the conversion of graphite into graphene oxide or reduced graphene oxide (Fig. 3). Further the G band corroborated the graphitic nature of carbon fabric which is also supported by the FESEM images. The Raman shift related to CH3 vibrational band of PDMS is around 2900cm^{-1} (equivalent to 1 stretching)[31-32].Given that Si atoms have a greater mass than carbon atoms, their vibration is lower than that of a bond involving carbon atoms as heavier atoms vibrate less than lighter ones[27]. Thus, G peak in the spectra corresponds to the Raman peak for the combination of PDMS and CNT, is at 1600cm^{-1} which is in conformation with the reported literature [31][34].

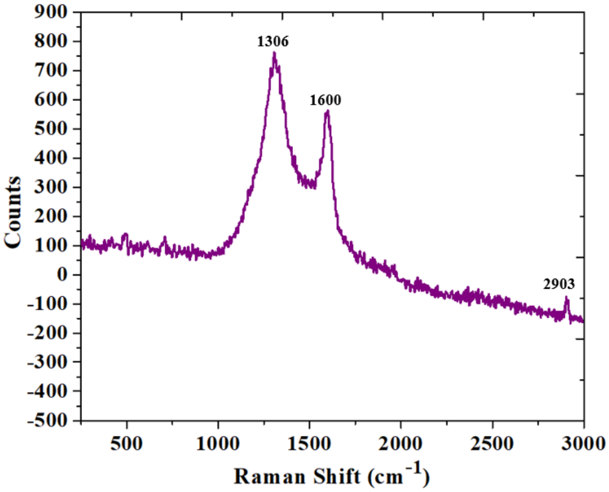


Figure 3. Raman spectroscopy of carbon fabric PDMS sample.

3. Fourier Transform Infra-Red (FTIR) Spectroscopy

FTIR spectroscopic measurements were done by using Per-kin Elmer Spectrum 400 FTIR spectrometer with Mercury Cadmium Telluride (MCT) detector unit in the wavenumber range of 600–4000 cm^{-1}. The FTIR spectrum of the PDMS membrane is represented in Fig 4. The characteristic peaks at 873 and 1257 cm^{-1} are attributed to Si—C—H stretching and -CH3 rocking vibrations of PDMS spectrum respectively. The peak corresponding to 1257cm^{-1} is also attributed to the CO-H bond in the graphitic structure. It seems that some degree of oxidation is required to make the fabric conductive. The absorption peaks at 2962.5 cm^{-1} which is attributed to the symmetric and asymmetric stretching vibration of the -CH3 groups in Si—CH3 of the PDMS. The spectrum peaks observed at 1010 cm^{-1}, characterize the symmetric stretching of the Si—O in Si—O—Si straight chain. The results match well with the reported literature [32].

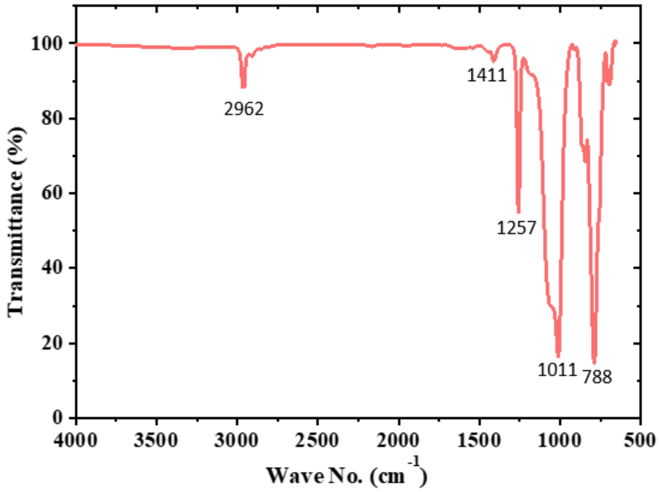
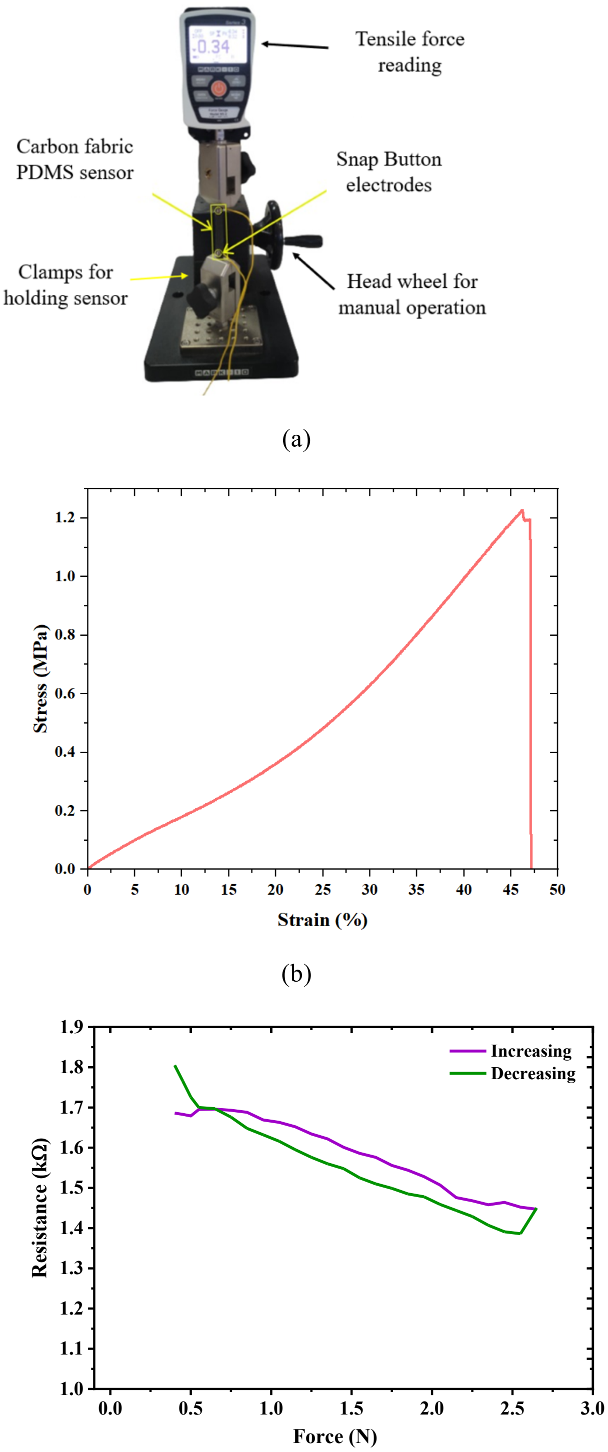


Figure 4. FTIR spectra of carbon fabric PDMS sensor sample.

B. Strain Sensing Characterisation of Fabric Sample

To analyse the performance of the fabricated nanocomposite sample as a strain sensor, electromechanical testing using Marks-10 Corporation, USA series 3 Universal Testing Machine (UTM) was undertaken. A maximum of 2.6 N tensile force was applied to the fabric sample without breaking the sensor band as shown in Fig. 5(a). The resistance is measured for each gradual increase in force applied while the sensor stretches with the applied force. Fig. 5(b) shows the stress-strain curve of the nanocomposite sensor. The change in resistance during the stretching and relaxation period is also observed as shown in Fig. 5(c). The change in resistance was observed to be similar regardless of whether the sensor is being stretched or being brought back to its mean position. Sensor resistance was determined to be 1.45KΩ when stretched by the application of 2.5N from its mean (unstretched) position. Tensile loading test results of the nanocomposite sensor sample is compiled in the tabular format (Table 1).



(a)

(b)

(c)

Figure 5. Strain sensing characterization of carbon fabric PDMS sensor sample a) view of fabric sensor sample mounted in Marks-10 Corporation, USA series 3 instrument, b) Stress versus strain curve and c) Resistance change as observed during the stretching period and relaxation period.

Table 1. Tensile loading test results for carbon fabric PDMS nanocomposite sensor sample

Type of Sample	Parameters	Value
Carbon fabric PDMS nanocomposite sample. Sample Dimensions: Length: 15 mm Width: 12 mm Thickness: 0.8 mm	Peak load	8 N
	Peak stress	0.77 MPa
	Stiffness	0.879 N/mm
	Yield point extension	2.49 mm
	Strain at maximum load	58.63%
	Elongation at break	63.61%
	Young's Modulus	0.0127 MPa
	Gauge Factor	25.9

C. *Effect of Ambient Temperature and Humidity on the Performance of Carbon Fabric PDMS Nanocomposite Sensor*

To analyse the effect of ambient temperature on the performance of the carbon fabric nanocomposite strain sensor, a thermal imaging technique is used. The sample was connected to a different supply voltage in the range of 50-80 V. The percentage change in resistance decreases from 0.65 to 0.05 with the increase in temperature through 5-45 °C respectively. From the results displayed in Fig. 6, it is clear that the percentage change of nanocomposite resistance of the developed sensor was robust to variation in ambient temperature.

Tests were also conducted to check the effect of varied humidity conditions and moisture content on the performance of the nanocomposite sensor. Change in resistance was recorded for varying humidity conditions (%) is shown in Fig. 7(a). The result shows that the percentage change in resistance of developed sensor is minimal with respect to varied relative humidity conditions i.e. from 40% to 85 %. The sensor sample was immersed in water, creating a wet sample, in order to take into account how moisture content affects the performance of the produced sensor. To compare the performance of a wet sample with dry sample, variation in resistance was recorded with applied strain. It was found that developed sensor behave in a similar fashion for both dry and wet conditions as shown in Fig. 7(b). This shows that developed sensor is water resistant.

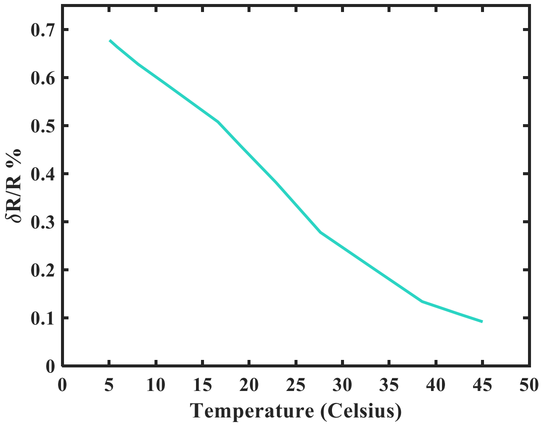
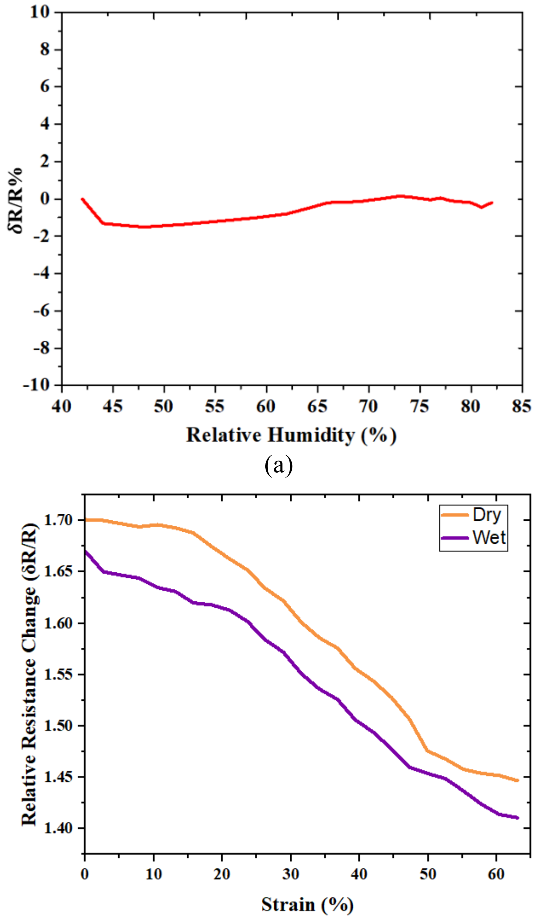


Figure 6. Change in resistance of carbon fabric PDMS sensor sample with respect to temperature



(a)

(b)

Figure 7. (a) Relative change in resistance of carbon fabric PDMS sensor with percent change in relative humidity b) Relative resistance change of wet and dry sensor samples with percent change in strain

D. I-V Characteristics

The electrical conductivity measurements of the carbon fabric PDMS nanocomposite was also assessed using a Keithley source measure unit. The conductivity of the nanocomposite sample was found to vary linearly with increases in applied voltage (Fig. 8) suggesting it exhibits a linear resistive behaviour.

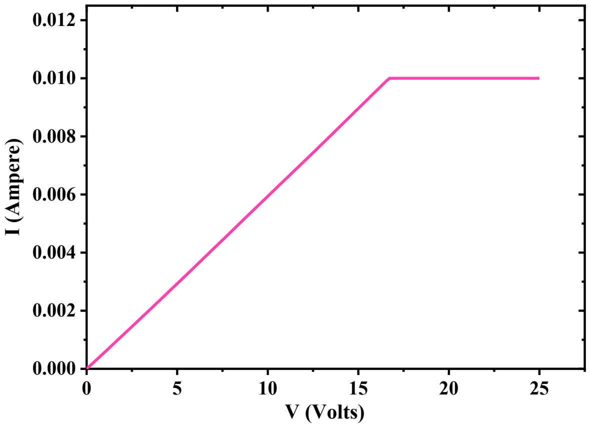


Figure 8. I-V characteristics of carbon fabric PDMS nanocomposite strain sensor.

IV. HUMAN MOTION MONITORING APPLICATIONS

The high sensitivity, flexibility, stretch ability, and robust electrodes of the carbon fabric PDMS nanocomposite strain sensor makes it capable to monitor human motion [29]. Faster response times are the primary attribute of human motion monitoring sensors. On that front, our PDMS-based fabric sensors promised superior performance. During numerous tests, it was discovered that sensors had a response time of only a few milliseconds. According to the authors' information, this reaction time is faster than the ones of current CNT strain sensors [23], [33-36]. Smart fabric applications and human-machine interfaces are ideally suited for wearable electronic systems. The flexible and stretchable strain sensors are capable of integrating with curved surfaces.

We also examined the cyclic repeatability of sensor and discovered that the relative change in resistance 2000 cycles was minimal as can be seen in Fig. 9.

To demonstrate the use of the developed sensor for human motion monitoring it was fixed across the joints on the finger, wrist, and knee. When the sensor was fixed on the forefinger, as the interphalangeal joint was bent to 30º, 60º and 90º joint angles (Fig. 10), the relative change in voltage varied. When the bending angle was greater, the voltage fluctuation was greater. The explanation for this might be that bending at a greater angle causes the sensor to stretch more strongly. For each angle at which the sensor is stretched, a real-time voltage plot is produced with discrete peaks. (Fig. 11).

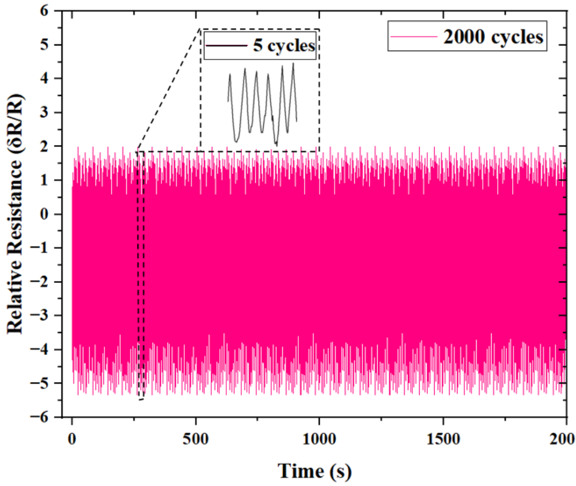
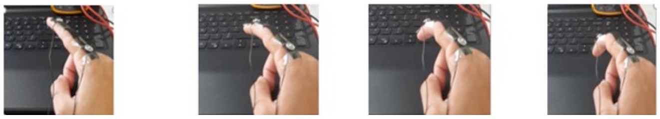


Figure 9. Relative change in resistance for 2000 cycles of stretching and relaxing the sensor.



(a) (b) (c) (d)

Figure 10. Bending of CNT sensor on forefinger at different angles a) mean position, b) 30º, c) 60º, d) 90º

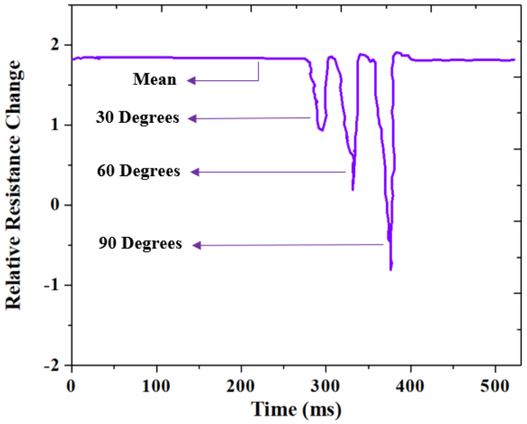
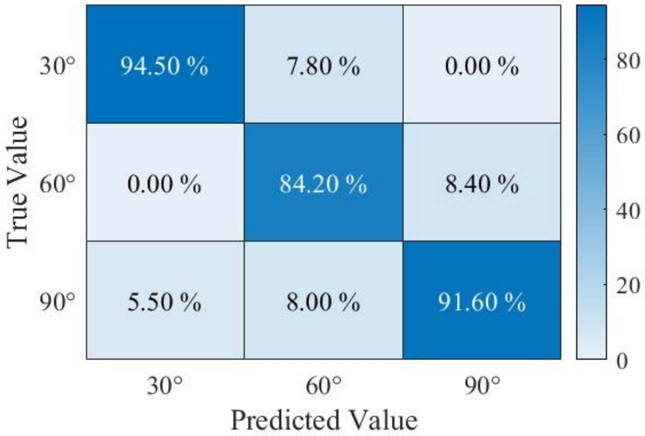


Figure 11. Peak of voltages recorded when sensor is bent at different angles.

A kNN (k Nearest neighbour) classifier is trained to predict the degree of bent in the developed sensor. A dataset of 30 subjects wearing the sensor for each degree of bent, 30º, 60º and 90º. Further, the noise (20%) is added to evaluate the reliability of sensor, resulting in 180 data points. The dataset into a training set (80% of the data) and a test set (20% of the data). Then the performance of the classifier is evaluated on the test set. After training and evaluating the KNN classifier, results obtained is compiled in Fig. 12.



	30°	60°	90°
30°	94.50 %	7.80 %	0.00 %
60°	0.00 %	84.20 %	8.40 %
90°	5.50 %	8.00 %	91.60 %

Figure 12. Confusion matrix for the developed sensor mounted on the forefinger at different angles.

Based on these results, it can inferred that the KNN classifier is fairly accurate, with an overall accuracy of 89.82%.

Similarly, when the sensor was fixed on wrist a change in the relative resistance change was observed with wrist flexion as shown in Fig. 13.

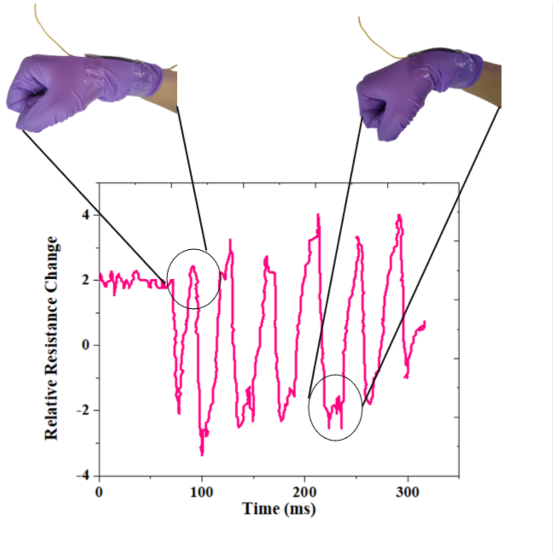


Figure 13. Response of the developed sensor when mounted on wrist to follow the motion of the wrist being bent or straightened.

The real time response of the sensor was also observed when mounted across the knee joint while doing different activities including marching, jogging, squats and jumping squats as shown in Fig. 14. It is evident from the relative change in resistance of sensor recorded throughout various activities, how the amplitude and frequency of the signals from the various activities differ from one another significantly [35].

Evidently, continued use does not reduce the relative change in resistance [15]. Significantly supports assertions made about the sensors' cyclic performance.

These experimental results show a promising future of the developed sensor in a vast range of applications such as wearable electronics, home rehabilitation, biomedical instruments, defence and automobiles.

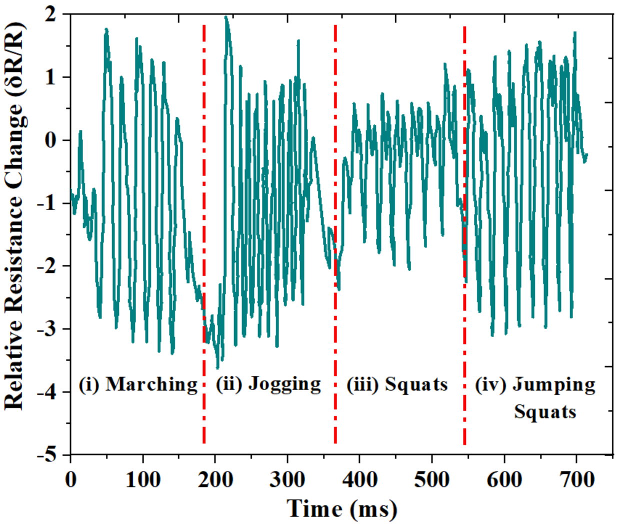


Figure 14. Response of the developed sensor mounted on knee while doing different activities a) marching, b) jogging, c) squats and d) jumping squats.

V. CONCLUSION

In this study, the fabrication process, design, and characterizations of a carbon fabric PDMS based strain sensor is reported. The novel electrodes are designed using snap buttons that account for robust and stable connections. FESEM results show the uniform dispersion of PDMS over carbon thread which provides flexibility and stability to external environmental conditions such as temperature, moisture etc. Raman spectra shows that the intensity ratio of the sample is very low (~1.2) which indicates negligible presence of defects in the structure. To identify the functionalized group in the sample, FTIR characterisation was performed. The sensor sample was also tested for varied temperature and it was found that the relative resistance (%) of the developed sensor changes linearly from 0.65 to 0.05 with a variation in temperature from 5 to 45 °C respectively. It was also found to be robust to variation in moisture content and humidity conditions. Tensile loading test results of the sensor samples showed that it has a long working range (maximum strain ~60%), excellent stability (reverse electrical properties with applied force), high sensitivity (gauge factor=25.9), high Young’s modulus (.0127 MPa) and maximum elongation at break (63.61%). The sensor sample showed excellent repeatability and worked in tandem with the applied strains. Finally, the developed sensor was observed measuring the interphalangeal, wrist, and knee joint angles, with the relative change in resistance following the joint motion. Results of KNN classifier for predicting the degree of forefinger bent based on the developed sensor output shows an overall accuracy of 89.82%. Overall, this highlights potential for the developed flexible strain sensor to be incorporated in wearable electronics, and diagnostic tools used to monitor daily changes in measures which can be measured using a strain sensor.

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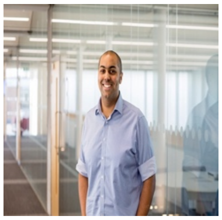

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