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DEVELOPMENT OF A STRETCHABLE CONDUCTIVE SENSOR FOR FLEXIBLE DEFORMATION: A PRELIMINARY STUDY

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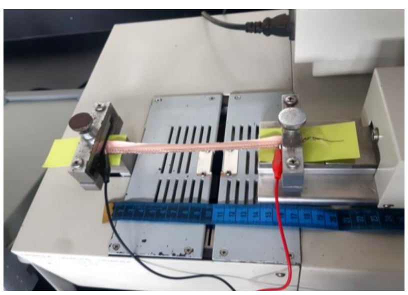
Graphical abstract



Abstract

This research presents preliminary characterization studies for a stretchable conductive sensor. It was developed specifically to detect strain changes that occur including flex changes. Some issues in conventional strain measurement are found to be less suitable due to the inaccuracy to measure the strain for an elongation using a flexible curve ruler, especially strain related to angle changes. Therefore, a study on the development of a stretchable conductive sensor is required. This initial study will focus on characterizing the suitability of fabric materials and thread patterns to develop a sensor that will be used to measure stretch more accurately. In this study, conductive yarns were constructed with two types of stretchable fabrics having different percentages of spandex elements. The thread will be sewn to the side of the fabric in two of the fabric states, namely course (horizontal) and wales (vertical). For both conditions, five (5) similar samples were sewn for 8% and 15% spandex fabric. Preliminary results found that the best sensor performance was a fabric containing 15% spandex material with conductive threads sewn along the horizontal orientation of the fabric. In a study on resistance varying with the tension applied to the sensor, model D showed the best performance when stretched up to a force of 4 N. The resistance shown by the sensor varies from 47MΩ to 66MΩ relative to the applied force from 0 N to 4 N. The results of this preliminary study are expected to be used in widespread measurement applications.

Keywords: Stretchable sensor, conductive material, conductive stretchable sensor, flexible deformation, measurement

Abstrak

Penyelidikan ini membentangkan kajian pencirian awal untuk penderia konduktif boleh regang. Ia dibangunkan khusus untuk mengesan perubahan terikan yang berlaku termasuk perubahan flex. Beberapa isu dalam pengukuran terikan konvensional didapati kurang sesuai disebabkan oleh ketidaktepatan untuk mengukur terikan untuk pemanjangan menggunakan pembaris lengkung fleksibel, terutamanya terikan yang berkaitan dengan perubahan sudut. Oleh itu, kajian mengenai pembangunan penderia konduktif boleh regang diperlukan. Kajian awal ini akan memberi tumpuan kepada pencirian kesesuaian bahan fabrik dan corak benang untuk membangunkan sensor yang akan digunakan untuk mengukur regangan dengan lebih tepat. Dalam kajian ini, benang konduktif telah dibina dengan dua jenis fabrik boleh regang yang mempunyai peratusan unsur spandeks yang berbeza. Benang akan dijahit ke sisi fabrik dalam dua keadaan fabrik iaitu course (mendatar) dan wales (menegak). Bagi kedua-dua keadaan, lima (5) sampel yang serupa telah dijahit untuk fabrik spandeks 8% dan 15%. Keputusan awal mendapati prestasi sensor terbaik adalah fabrik yang mengandungi bahan spandeks 15% dengan benang konduktif yang dijahit sepanjang orientasi mendatar fabrik. Dalam kajian tentang rintangan yang berbeza-beza dengan tegangan yang dikenakan pada sensor, model D menunjukkan prestasi terbaik apabila diregangkan sehingga daya 4 N. Rintangan yang ditunjukkan oleh sensor berbeza dari 47MΩ hingga 66MΩ berbanding dengan daya yang dikenakan dari 0 N hingga 4 N. Hasil kajian awal ini dijangka dapat digunakan dalam aplikasi pengukuran yang meluas.

Kata kunci: Penderia boleh regang, bahan pengalir, penderia regangan konduktif, ubah bentuk fleksibel, pengukuran

1.0 INTRODUCTION

Flexible deformation in various applications including in the field of robotics such as soft actuators is an important mechanism because it is able to move with high flexibility, simple structure, resistance to water, high compliance and lightness [1]. Unlike existing actuators that are widely used in traditional robots that use rigid materials such as motors, soft actuator capabilities are seen as more suitable because they can mimic movements in the real or natural world which are mostly flexible. Soft actuators also have the potential to be used in industrial applications to handle soft or fragile objects such as in rehabilitation process by wearing a soft wearable device, holding fragile materials such as glass and egg, movements involving organs or soft tissues and so on [2-3].

Several issues involving the measurement of flexible movement in the rehabilitation process have been identified. For example, accurate measurement of range of motion (ROM) for joints is important for clinical evaluation of patients including osteoarthritis patients. Goniometers have been widely used to measure ROM by many medical practitioners, such as orthopedic surgeons and physical therapists, and are considered the gold standard. Although the goniometer is a simple and compact measuring device, there is a significant problem that occurs which is the accuracy in taking readings between examiners due to the influence of soft tissue [4].

Several types of alternative measurements have been proposed including radiographic measurements. This method has shown a higher level of accuracy. However, it requires a radiological imaging system, time, cost, and even radiation exposure for the patient [4]. Innovations in measurement are also evolving and recent, there are researchers who develop mobile applications to take photo-based knee joint angle ROM readings [5] and some even propose a simplified inertial sensor method [6]. Although these innovative methods can provide more sensitive digital readings, the accuracy in taking repeat readings is low because the same level and position setting is required when taking readings at the next assessment.

This issue has led to a solution in the development of flexible and stretchable sensor technology to improve motion detection by integration of composite materials [7-8]. In general, there are two types of stretchable sensors developed namely conductive inks type or printed electronics [9-10] and by using conductive threads [11]. For conductive thread type sensors, resistance is measured when there is a change in its stretching state. The stretching of the conductive yarn has consequence. It is commonly known that stretching a conductive material reduces its cross-section while increasing its conductive channel, resulting in higher resistance. The relative importance of each effect is determined on the stitch style, strain, and conductive element type. The best sensor design is examined in various types of stitch constructions, with the ability to record strain deformations and electromechanical properties [11].

Based on a review of existing flexible sensors, it was found that conductive materials play an important role in the manufacture of stretchable sensors. Basically, the combination of material type and device architecture will enable improvements in conductivity and higher and flexible deformation capabilities [12-14]. Various stitch patterns for embroidering conductive materials suggested from previous research include zigzag, platform, cloudy, and decorative patterns. It was found that the zigzag pattern shows the most encouraging resistance-voltage response with the highest gauge factor [15]. Nevertheless, there are many unexplored seams for conductive thread embroidery [16]. After referring to the previous study, the overlock stitch has the potential to be used in sensor manufacturing due to its zigzag-like pattern. This is because the zig-zag pattern sewn on the edge of the fabric fulfills the important criteria for flexible sensors which are stretchability, elasticity and wearability. This criterion will allow elongation without significant changes after the stretching process is carried out and flexible detection of flexible movements such as applications on the human body [17-20].

In summary, this study was conducted to propose an overlock stitch with four threads to be embroidered on stretchable fabrics containing a certain amount of spandex. The results of this exploratory investigation are expected to be beneficial in a variety of measurement tasks, including arm or leg stretching during rehabilitation or other assessments involving human body movements.

2.0 METHODOLOGY

A summary of the research process is illustrated in Figure 1. At the beginning, the conductive thread is first tested for its resistance. To get a more accurate reading that can be used to analyze the resistance of each thread length, the resistance value is obtained by taking the reading from the average of similar samples. Further pattern optimization will be determined based on analysis of resistance based on fabric material and stitching method. For testing the fabric material, as many as five similar samples were sewn with a spandex mixture of 8% and 15% respectively. As for the stitching method experiment, it involves the process of thread fabrication that is sewn on the edge of the fabric in two conditions, namely course (horizontal) and wales (vertical). The samples will then go through a tensile test, and the changes in resistance that occur during the test are recorded and plotted in a graph of resistance against force.

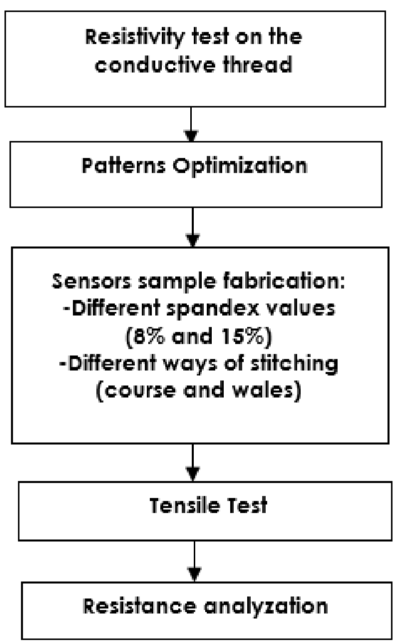


Figure 1 Flowchart of the study

Resistance is directly proportional to the length of a conductor. However, the resistance value can change when the current path is in a different state such as a path that changes from straight to bent, or the path overlaps with the path of another conductive material. When developing a sensor, a more in-depth study of the effect of changing the conductive material or the path pattern of the conductive material is necessary to identify the changing rate of resistance. In this study, some properties of yarn conductivity and yarn pattern will be manipulated, then changes in resistance will be observed. For example, before a thread is stretched, its initial shape is round. Once the thread is stretched, it will turn into an elliptical shape. This phenomenon causes the total distance of the conductive path to change in turn changing the total resistance due to the nature of the current that tends to choose shorter paths.

The conductive thread used in this experiment is a stainless-steel conductive thread consisting of three layers. The thread is silver in color and look almost identical to non-conductive threads. With a diameter of 0.12 mm, this conductive thread is easy to shape and stick-on paper. The patterns studied consists of straight lines, spiral, sine waves, square waves and higher frequency sine waves. All patterns have been set to 20 cm length as can be seen in Figure 2. After that, the study of the conductive yarn will be manipulated which measures the length of the yarn in a straight line with length values of 5 cm, 10 cm, 15 cm, 20 cm and 25 cm.

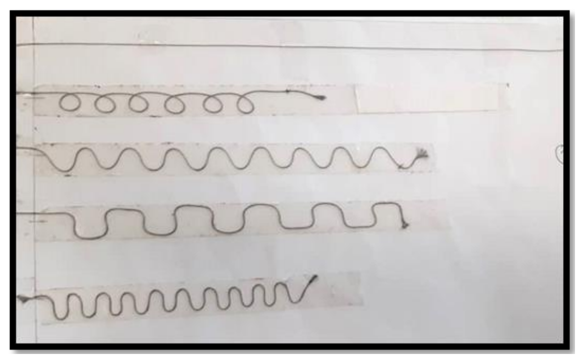


Figure 2 Measurement setup for different patterns of conductive thread in fixed total length of 20 cm

Resistance tests are also performed on yarns with different thicknesses by separating the yarn plies. The thread used consists of three plies. Therefore, the measurement of the resistance rate is done by separating the thread into one ply, two plies and three plies. For all resistance experiments, it was measured using a Bench GDM-8255A digital multimeter. This multimeter was chosen because of its unique ability to provide readings up to three decimal places. The measurement setup is shown in Figure 3.

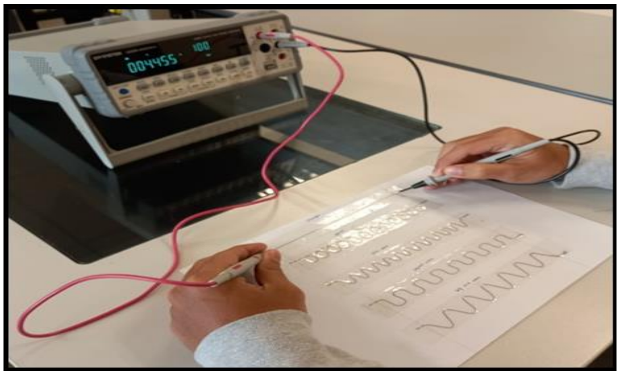


Figure 3 Measuring setup of conductive thread

Further, conductive thread was sewn to the fabric before the tension test was performed. There are two different types of fabric chosen to be tested in this study. Both are selected based on their blend materials that have different percentages of spandex elements. Both types of fabric are sewn on the sides with the same pattern. This edge stitch involves four (4) strands of thread. One of them is a conductive type thread while the other three strands are non-conductive threads. Figure 4 shows a fabric with a 15% spandex blend, while Figure 5 shows a fabric consisting of an 8% spandex blend. The percentage of the spandex blend can be known from the material specifications. A mixture of spandex 8% and 15% is used due to being commercially available. The difference between 8% and 15% of the mixture is to observe the difference that occurs to the resistance when the spandex mixture is doubled.

Figure 4 Pattern of thread sewed onto the fabric with 15% spandex

Figure 5 Pattern of thread sewed onto the fabric with 8% spandex

There are four models of conductive sensors provided with differences in the percentage of spandex material and the direction of the stitch along the edge of the fabric. The differences between these four models are tabulated in Table 1. All sensor models that have been tabulated in Table 1 have been set to an initial length of 20 cm with at least five similar samples for each model have been prepared and repeated to obtain a better analysis.

Table 1 Model of conductive stretchable sensors with different spandex percentage and stitching direction

Model	Spandex Material Percentage (%)	Stitching Direction (along the Course/Wales)
A	8	Wales
B	8	Course
C	15	Wales
D	15	Course

After the process of preparing the edge sewing thread sample is done, the next step is to test the change in resistance against the tension of the thread that has been sewn on the fabric. This test involves a hot tack tensile machine where this machine will pull the ends of both fabrics sewn with conductive thread slowly until it reaches maximum tension. At the same time, the ends of the two conductive threads will be clamped to the multimeter to take resistance readings.

The hot tack tensile machine is used because of its ability to stretch any type of element such as plastic, fabric, rubber or paper. It can also apply tensile force to the sample until it reaches a maximum tension of 200 N or a maximum length of 50 cm. However, it will stop automatically when any cracks or breaking points occur on the tested sample. The sample must first be cut according to a certain length which is 16 cm long and 2 cm wide. It is a standard size set for the sample to be tested which is compatible with the tensile test port of the machine. The tensile test setup is illustrated in Figure 6.

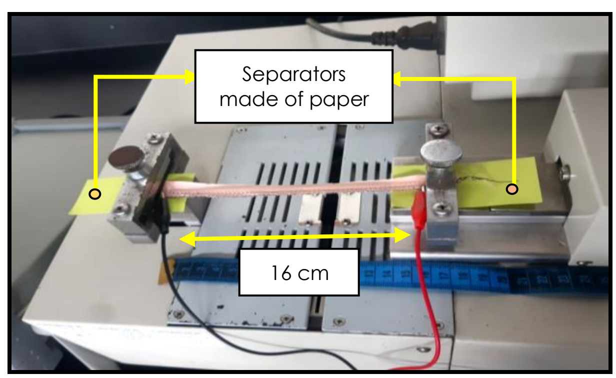


Figure 6 Tensile test setup with a probe connected to a multimeter to read the resistance value

Referring to Figure 6, there is a piece of green paper placed between the clamp and the machine body on both sides of the clamp. This step is taken to ensure that the flow of current through the sensor will not be shorted to the holder of the machine which is made of metal.

3.0 RESULTS AND DISCUSSION

The experimental results of stretchable conductive threads are tabulated in Table 2, Table 3, Table 4 and Table 5. Table 2 shows the resistance readings for different lengths of conductive threads whereas the resistance readings for different thicknesses of conductive threads are shown in Table 3. Table 4 and Table 5 show the resistance readings for the pattern that changed from the original pattern to the straight line.

To test the effect of thickness on resistance, the three threads have been set to have different thicknesses. However, the length of all three threads is the same which is 15 cm. Based on Table 2, it was found that thin thread which is as low as 1 ply, gives the highest resistance reading which is 0.71 ohm per meter. On the other hand, the thicker the conductive thread, which in this case is 3 plies, it shows the lowest resistance of 0.24 ohms per meter.

Table 2 Resistance readings for conductive threads of different thicknesses

Thickness of Conductive Thread (number of plies)	Average Resistance (Ω)	Average Resistance per Length (Ω/cm)
1	10.712	0.71
2	5.219	0.35
3	3.588	0.24

For the test of the resistance against the length of the thread, as many as 5 strands of thread with different lengths have been measured. The five threads that were measured were arranged in a straight line. Referring to Table 3, it was found that the average resistance reading for the conductive thread increased when the length of the thread was increased. Further analysis is focused on comparing the value of resistance per length by dividing the average value of resistance by the length of the thread. Based on observations, it was found that the value of resistance per length decreases as the length of the thread increases. However, the difference is not very significant because the length of the thread with 5 cm and 25 cm only differs by 0.048 ohm per meter.

Table 3 Resistance readings for different lengths of conductive thread

Length of Conductive Thread (cm)	Average Resistance (Ω)	Average Resistance per Length (Ω/cm)
5	1.381	0.276
10	2.456	0.246
15	3.600	0.240
20	4.653	0.233
25	5.693	0.228

In the experiment of the effect of conductive yarn pattern on resistance, several patterns have been proposed such as spiral, straight line, sine wave, square wave and higher frequency sine wave. All these patterns were set the same length in the patterned state which is 15 cm to see the resistance difference after being straightened as shown in Table 4. In a simple word, the conductive threads will then compare their resistance readings when in a patterned state and in a straight-line state. Based on Table 4, it was found that only the spiral pattern gave an average resistance reading before and after which was different by 0.03 ohm per cm, measured by subtracting the resistance per length after straighten and before straighten. A conductive thread with a sine wave pattern also gives a different reading when straightened but not significantly with a difference of 0.01 ohm per cm. While other patterns such as straight line, square wave and higher frequency sine wave have no difference in resistance after the thread is straightened.

Table 4 Resistance reading for different stitch patterns of conductive thread in 15 cm length

Conductive Thread Pattern	Length in Straight Line (cm)	Average Resistance Reading (Ω)	Average Resistance per Length (Ω/cm)	
			Before Straighten	After Straighten
Spiral	44.5	8.721	0.20	0.23
Straight line	15.0	3.462	0.23	0.23
Sine wave	20.6	4.758	0.23	0.24
Square wave	25.5	5.756	0.23	0.23
Higher Frequency Sine wave	35.7	8.461	0.24	0.24

The resistance difference for the spiral pattern is believed to be related to the inherent nature of the resistance which has a high tendency to take the shortest conductive path. In this case, only the spiral pattern has a condition where some overlapping of the conductive thread occurs when in the spiral pattern state, and no overlap occurs when the thread is straightened. Based on this test, it was found that thread patterns that have overlapping threads and the overlap can change when stretched, will have a significant result and it is appropriate for developing a sensor based on conductive threads. This characteristic will be taken into account and further research is needed to develop an optimal conductive thread sensor.

Further, the same test as the test of the effect of the conductive thread pattern on the resistance was repeated by manipulating the length of the conductive thread. This experiment uses conductive thread with the same length of 20 cm even though the patterns are different. The results in Table 5 clearly support the results in Table 4 where the thread with an overlapping spiral pattern will have a lower resistance than the non-overlapping pattern. In this experiment, the spiral pattern had an increase of 0.01 ohm per meter when the thread was straightened while the other patterns did not experience any change in resistance when straightened.

For the tension test, as many as four models namely model A, model B, model C and model D have been prepared as described in Table 1. The test for each model is repeated four times and the test results are plotted as in Figure 7, Figure 8, Figure 9 and Figure 10. The figures show the relationship between the resistance and the tensile force applied to each model. The test is important to determine which method of strain can produce a significant change in resistance.

Table 5 Resistance reading for different stitch patterns of conductive thread with fixed total length 20 cm

Stitch Pattern of Conductive Thread	Average Resistance Reading (Ω)	Average Resistance per length (Ω/cm)	
		Before Straighten	After Straighten
Spiral	4.383	0.22	0.23
Straight line	4.515	0.23	0.23
Sine wave	4.502	0.23	0.23
Square wave	4.502	0.23	0.23
Higher Frequency Sine wave	4.535	0.23	0.23

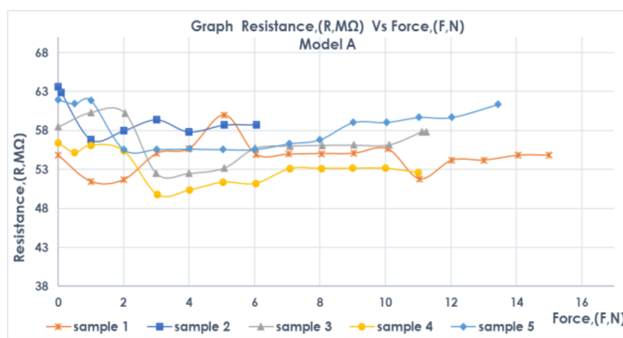


Figure 7 Graph of resistance against force for Model A

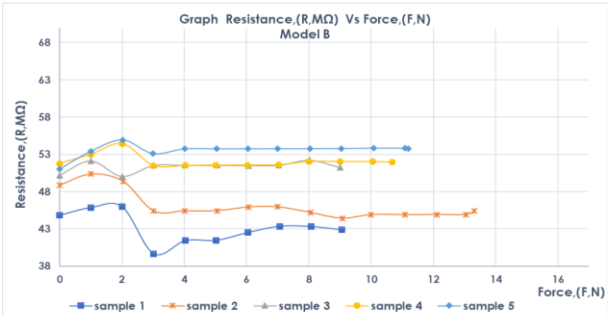


Figure 8 Graph of resistance against force for Model B

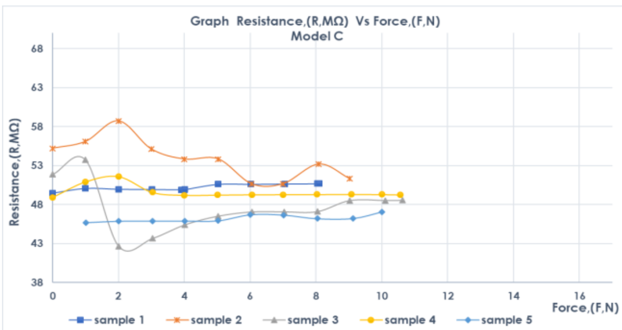


Figure 9 Graph of resistance against force for Model C

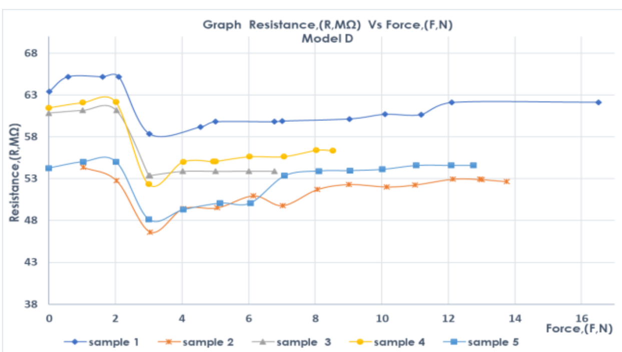


Figure 10 Graph of resistance against force for Model D

To evaluate the impact of resistance against the tensile force applied to the sensor, five similar samples were fabricated for the Model A sensor, which is a sensor with a fabric blend containing 8% spandex, were pulled vertically (wales). Based on the results in Figure 6, it was found that the five samples did not show a uniform reading trend. There are samples that decrease in resistance when they start to be pulled and there are also samples that increase when they start to be pulled. All five samples can be stretched up to a force range of 11 N to 15 N with a resistance reading range between 49M Ω and 64M Ω.

In the case of the Model B sensor, which is a sensor with 8% spandex mixture and pulled horizontally (course), the resistance reading trend when the sensor is stretched rises slightly, then decreases before rising again as can be observed in Figure 7. This trend is almost the same for each sample with a maximum tensile force range between 9 N and 13 N and a resistance reading range between 39M Ω and 56M Ω.

For a low pulling force of around 2 N, the resistance increases due to the increase in the length of the conductive thread on the sensor when the original overlock stitch starts to straighten when tensioning. This coincides with the test results as shown in Table 4 and Table 5, where the resistance of the overlock patterned thread increases when straightened. For the tensile force between 2 N and 3 N, the reading decreases due to the overlap that occurs between the conductive threads that have an overlock pattern, causing the conductivity path to become shorter and further lowering the resistance value. Next, at the stretching force of the sensor after 3 N, the resistance reading increases again due to the sensor pattern that starts to straighten and causes the total length of the conductivity path to increase and further increase the resistance reading. The difference between the straightened pattern at the beginning with a force of less than 2 N and the overlock pattern straightened with a force of more than 3 N is that at the initial stage, the overlock pattern is slack and there is not much overlap on the conductive threads. After being pulled until the force exceeds 2 N, the yarn starts to become taut and more overlap occurs on the conductive yarn.

The test on Model C is a repeat of the test on Model A by changing the type of fabric used. In the Model C test, the fabric used is a fabric blend with 15% spandex. This model is subjected to vertical tension (wales). The results as shown in Figure 8 show that the resistance trend when tensile force is applied to the fabric is uncertain. There are some samples of Model C that at the beginning of fabric tension increase its resistance and there are also samples that do not experience significant changes. In general, the results of model C are almost similar to the results from the Model A test with a reduction in tensile strength around the 8 N to 11 N force range.

The Model D test is a repeat of the Model B test with a different fabric. Model D uses fabric with a spandex mixture of 15% and is stretched horizontally (course). A total of five similar samples were fabricated and the results of the resistance due to the tensile force of the sensor are recorded in Figure 9. Based on the figure, the trend shown by Model D is almost similar to Model B, i.e. the resistance reading at the beginning of the stretch increases slightly until the stretch of 2 N before decreasing until the stretch 3 N and increases again after stretching beyond 3 N. Through the same figure, it can be observed that sample 2 and sample 5 as well as sample 3 and sample 4 show almost similar trends with several crossing points. The stretching range for Model D is between 7 N and 17 N. The highest stretching is sample 1 with a stretching force of 17 N which is the highest among the four models tested. The resistance reading range is between 46M Ω and 65MΩ. Among the four models tested, Model D was found to be more stable in terms of the resistance change trend against the applied stretching force with a resistance reading range of about 19 MΩ. A summary of the test results for models A-D is shown in Table 6.

Table 6 Summary of the test results for model A-D

Sensor model	Material	Condition of stiches	Findings
A	8% spandex	Wales	Did not show a uniform reading trend.
B	8% spandex	Course	The resistance trend is almost the same for each sample
C	15% spandex	Wales	The resistance trend is uncertain
D	15% spandex	Course	Almost similar resistance trends with several crossing points

4.0 CONCLUSION

In this study, a stretchable conductive sensor has been developed and tested to measure the resulting resistance when subjected to a tensile force. From the tests conducted, it was found that the resistance value is proportional to the length of the conductive thread. By manipulating the pattern of conductive threads like a spiral, changes in resistance can be observed as the spiral pattern changes when stretched. This is due to the intersection point of the conductive thread that has changed and resulted in a change in the amount of the shortest distance of conductivity in the conductive thread. In the tensile test of conductive thread sewn into the fabric, a higher spandex blend and stretched horizontally (course) can increase the resistance reading range for the sensor and provide a more consistent resistance reading trend when the sensor is stretched as shown by Model D.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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