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Pressure Monitoring for Scoliosis Braces using Textile-based Pressure Sensor Arrays

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Abstract

Scoliosis is a type of spine deformity that commonly arises during adolescence. The usage of a brace is an effective method in the conservative treatment of scoliosis. The aim of this study is to examine the pressure applied to the brace that is used in the treatment of scoliosis by integrating a textile-based capacitive pressure sensor array. By considering the sensitivity, durability, recovery/response time, and working range, appropriate sensor cells were chosen. The characterization of the selected pressure sensor cell and its coherence with other cells were examined in the experiments. It is observed that the overall average relative error for the proposed pressure estimation process is 0.18.

Keywords: Wearable Technology; Scoliosis; Assistive Technology; Capacitive Sensors; E-textile; Healthcare Systems

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1. Introduction

Scoliosis is a multifactorial and complex three-dimensional deformity of the spine that often occurs during adolescence. The Thoracic Lumbar Sacral Orthosis (TLSO) braces used in scoliosis treatment are offered in various designs worldwide, all of which attempt to prevent prognosis until the patient achieves skeletal maturity [13]. TLSO braces consist of pressure areas and expansion chambers and are custom-made for each patient. By tightening the brace straps, the necessary force is applied to the pressure areas. Consequently, the body shifts away from the pressure areas towards the expansion chambers.

The use of spinal bracing is one of the standard nonoperative treatments for scoliosis [19, 11]. The brace is prescribed by a doctor along with a treatment protocol that specifies the required tightness and daily usage period of the brace. Although a brace is produced for the patient as prescribed, there are several aspects that determine the success of the brace treatment. One of the main aspects is the adjustment of adequate corrective force via brace which mainly depends on the experience and intuition of health professionals. The correction rate of the brace treatment increases as keeping it constantly tight [6], so patients are frequently told to tighten their braces as much as possible. Another aspect is the wearing time of the brace; the efficiency increases proportionally to the duration of daily wear [2]. Depending on the brace utilized and the specific scenario, prescriptions range from 8 to 20 hours each day [17].

In this study, a pressure monitoring system was proposed by using a textile-based capacitive pressure sensor array (2-dimensional) for scoliosis braces. Our main contribution was to detect interface pressure applied to the skin of the patient by a brace using a wearable sensor array which is suitable for this purpose in terms of sensitivity, durability, recovery/response time, and working range. By collecting data from each cell of the sensor array, and calibrating them with curve fitting, the characterization of the pressure sensor array cells was examined in the offline laboratory experiments. Then, the same sensor array was placed inside the brace to test the proposed monitoring system on a foam human figure.

2. Literature Review

Although a brace is an effective method used in the conservative treatment of scoliosis, some subjective circumstances in treatment cause problems. The first problem is the duration of brace wear is unknown to health professionals, and the second problem is the lack of evidence of the tightness of the strap [3, 16]. The decision regarding the tightness of the brace is closely related to the experience of the health professionals, especially in clinical cases, and that causes individual differences in each case [5]. Numerous studies have been carried out to find solutions to these problems. In order to analyze wear-time and/or brace tightness, force sensors [16], pressure sensors [4], temperature sensors [14] and [18], and pressure switches [10] have been utilized.

Temperature sensors measure body temperature based on threshold values. The measurements are not effective if brace athletes are worn in order to prevent the plastic material from disturbing the skin in the use of braces or if the outdoor temperature rises above a certain level. Although the thermosensor is a good indicator of the wearing time of the brace, it does not give any information about the applied forces [15]. Pressure sensors used in studies to evaluate the pressures inside the brace also have many problems [21] such as the size and weight of the sensors, and short battery life. Besides the products designed are not suitable for daily practice in routine use [20]. We believe that a textile-based capacitive sensor array can be used for daily practice in routine use and the size and weight of the sensors.

In the work of Gesbert et al., textile sensors that are produced with piezo-resistant polymers have been used to observe the biomechanical influence of brace treatment [7]. This system allows both the conduction of electricity and the measurement of pressure and is based solely on its composition of textile fibers. The textile-based mat consists of 1024 sensor cells with a number of 32 sensors in each direction. In this study, the relative error is found around 0.30, the calibration was static and the sensor's dynamic diagram was not confirmed [7]. On the other hand, our experiments were performed in a wider pressure interval ranging between 0.218 kPA and 13.1 kPa. Also, the average relative error is significantly reduced thanks to the manufacturing technique of the sensor mat. In clinical scenarios, Ahmad et al. [1] used F-Socket transducers (9811E) and the commercially available Tekscan system to analyze the interface pressure exerted by the Cheneau brace in patients with double-curve AIS.

In another study conducted by Chalmers et al., the development of a system that modulates brace pressure according to the three-point principle while causing the patient the least amount of discomfort was reported [4]. This study demonstrates that a brace pressure regulation system may be implemented with an air bladder, pneumatic, and piezoresistive gauge pressure sensor. The applied pressure was set as 5.3 kPa which is sufficient and comfortable pressure for treatment. The sensor used in the study shows a linear increase as the pressure increases, whereas our sensor is designed to yield exponential results up to 8 kPa because it makes a precise measurement. As mentioned in the study, the pressure measurement of a brace generally is between 4 kPa and 8 kPa [12], so our sensors are suitable for use in this field.

3. Pressure Monitoring System using Textile-based Pressure Sensor Array

3.1. Hardware

In the overview, we obtain the data from the textile-based capacitive pressure sensor array (Figure 1a)) to estimate the pressure on its cells. Sensor values are measured by Arduino UNO board (Figure 1b) and 1c)) and sent to the computer.

Textile-based capacitive pressure sensor array consists of sensor cells made by sandwiching dielectric material and generating air gaps between two electrically conductive knit fabrics. Since the selected sensor array design consists of n rows and n columns, n^2 capacitive sensor cells exist. Thus, the data which is obtained from the array consists of n^2 measured sensor value.

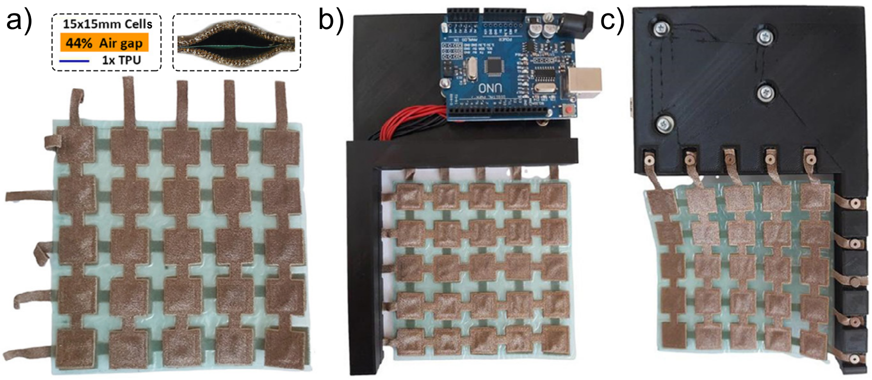

Fig. 1. a) Close-up view of the textile-based pressure sensor array (n=5); b) Front side of the data acquisition system; c) Back side of the data acquisition system.

The textile sensor array follows the same idea as capacitive sensors in their operation. The capacitance value created in sensors as a result of the dielectric Thermoplastic Poly Urethane (TPU) layer and air gap put between two conducting materials (sensor layers) is directly proportional to the insulating material's dielectric coefficient and the area of the conductive materials as shown in Equation (1), and inversely proportional to the distance between them.

$$C = \varepsilon_0 \varepsilon_r \frac{S}{\delta}, \tag{1}$$

where C denotes the capacitance, and $\varepsilon_0, \varepsilon_r, S$, and δ correspond to respectively the free space permittivity, relative permittivity, the area of the conductive plates, and the distance between the plates. When pressure is applied to a cell of the textile arrays produced by placing a dielectric layer between two conductive textile electrodes, the distance between the conductive fabrics will decrease, leading to an increase in capacitance value.

Generally, the brace used in the treatment of scoliosis applies pressure on the patient's body from 2 main points: the back and waist. In order to examine the distribution of pressure around the textile-based capacitive sensor array, it was determined by the physical therapy and rehabilitation professionals that a 5x5 cells array will give enough coverage in the back area of a brace. The sensor cells are manufactured by us to be sensitive to accurately predict the applied pressure. The cells with 1 TPU are more sensitive than the others. Also, the enlargement of the air gap in the cells increases their sensitivity. Therefore, as expected, dielectric thickness has a detrimental influence on sensor sensitivity. Since the patients have to wear the brace for about 20 hours a day, pressure sensors are required to work at constant pressure. When constant pressure was applied to the sensor cells, the capacitance rose dramatically within milliseconds, then plateaued, and no more significant capacitance changes were seen over the duration of 1 hour. This trend corresponding to an apparent pattern of the desired quality shows that the suggested sensors can withstand constant pressure and are appropriate for this study that demands long-term stability [9]. As a result, the textile-based capacitive sensor array that consists of 15 mm x 15 mm sensor cells with 1 TPU and 44% gap amount were determined to be used in the study.

3.2. *Software*

3.2.1. *Preprocessing*

The data string gathered by our data acquisition module was split to obtain the list with 25 elements in the sensor array with their indices of individual cells depicted as in Figure 2a). At this point, the analog values of each cell were obtained and the change in the analog value of a cell according to the applied pressure was examined. The analog values were collected without applying any pressure to find the base values of the cells, which are later on subtracted from the instantaneously read values from sensor array elements during operation. Figure 2b) shows the behavior of row and column cells of cell 12. When pressure is applied to one cell, the analog values of the row and column cells connected to it decrease, which is called the cross-talk effect. Also, row cells were affected more than column cells as seen in analog value changes in cells. These undesired changes were eliminated because the changes in other sensor cells were significantly smaller than the sensor cell's where the pressure was applied.

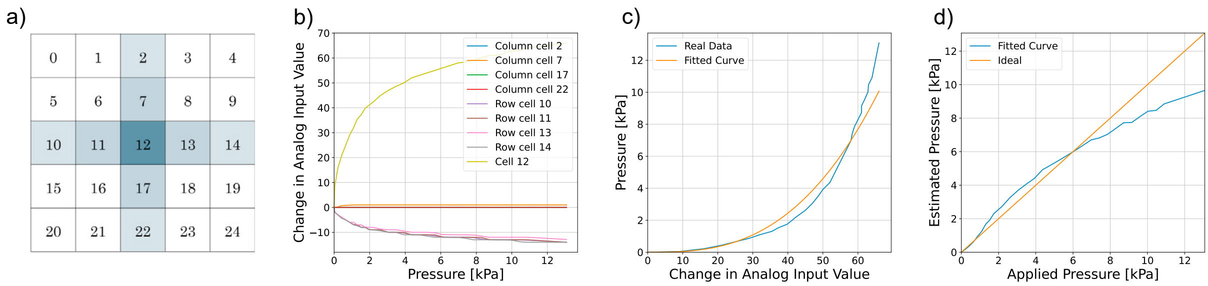

Fig. 2. a) Textile-based pressure sensor array scheme; b) Change in analog input values of the same row and column cells when pressure is applied to cell 12 (cells 2, 7, 17, and 22 are overlapped, and cells 10, 11, 13, and 14 are overlapped); c) Comparison between real data and fitted curve of cell 12; d) Comparison between fitted curve pressure and the ideal pressure of cell 12.

3.2.2. *Pressure Estimation*

In order to estimate the pressure, a change in the analog value of each cell corresponding to determined weights were needed to be obtained and examined. Therefore, changes in analog values were collected by applying different weights to achieve the characterization of the sensors. The weight that was applied was increased from 0 g to 50 g in multiples of 5 g. From 50 g to 250 g, the applied weight was in multiples of 10 g. Eventually, 300 g weight was used for each cell. For each cell, 33 values corresponding to different weights were measured. The applied pressure was calculated using weight and cell area (15 mm x 15 mm). The Change in Analog Input Value corresponding to the determined pressure for cell 12 is seen in Figure 2c). It is not worthy to mention that each cell has its own characteristic curve due to minor material differences in the production phase as well.

The characteristic curve (Equation (2)) of each cell was obtained by using 33 data points to fit the curve so that the 2 coefficients which are a and b were calculated [8]. As shown in Figure 2c), the difference between the curve that was obtained by calculation with these two coefficients and the real data can be computed for cell 12.

$$y = ax^b. \tag{2}$$

In Figure 2d), the result of estimated pressure corresponding to real pressure can be observed. In the ideal case, the result needs to be linear as $y = x$. As shown in Figure 2c) and 2d), the error of the fitted curve increased after 6.54 kPa pressure for cell 12. When applied pressure increases, an exponential increase is formed because there is a gap in the sensor cell. After the gap is exhausted, the sensor makes a linear increase.

4. Experiments and Results

The experimental phase is split into two parts: offline evaluation and evaluation inside the brace.

4.1. Offline Evaluation

For offline experiments, a stand (Figure 1b) and 1c)) that is printed from a 3D printer was used. Analog values corresponding to 33 different pressure values were collected for 25 cells. At each data collection point, namely each cell of the array, 250 consequent analog input values were read, then the average of them was calculated. After that, a base value was subtracted from all values, so a change in analog value was obtained for each cell.

For the evaluation of performance on pressure estimation, the relative error is calculated as an assessment criterium. The relative error (E_{rel}) is calculated by dividing the difference between the estimated pressure (P_{est}) and the real pressure (P_{real}) by the real pressure as seen in Equation (3).

$$E_{rel} = \frac{|P_{est} - P_{real}|}{P_{real}} \tag{3}$$

4.1.1. Pressure Estimation Performance

The average relative error was calculated as shown in Figure 3a). When all cells were taken into account, the overall average error was calculated as 0.18. When pressure estimation was run on the data that were already used to find a and b coefficients of the curve, figures similar to Figure 3b) and 3c) were obtained for each cell. The relative error results of cell 12 and cell 18 were obtained. The relative error graphs of the two cells are utterly similar. For both cells, the relative error did not exceed 0.33, and the average error was 0.14.

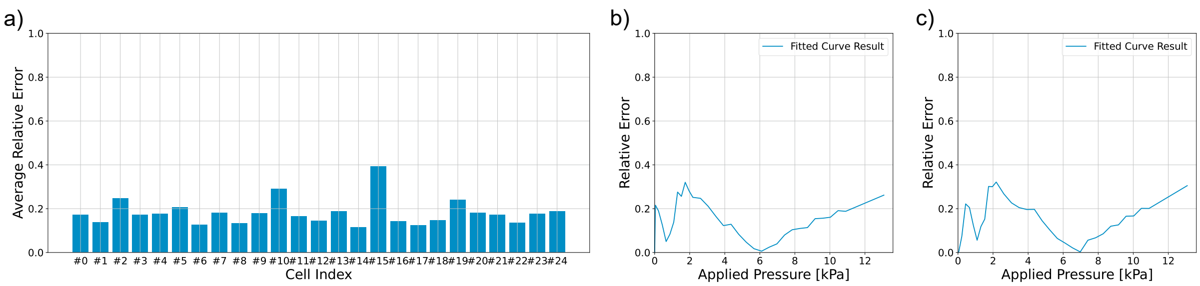

Fig. 3. a) Average relative error for each cell of the used sensor array; b) Relative error results of cell 12; c) Relative error results of cell 18.

4.1.2. Investigation of Performance using Single and Multiple Pressure Point

When a single weight (50 g and 2.18 kPa) was applied to cell 6 (Figure 4a)), changes in the analog input value of all cells (Figure 4b)) and estimated pressure values on them (Figure 4c)) can be observed in our monitoring tool visualizing individual measurements in all cells. Row and column cells of cell 6 were affected by the applied pressure as depicted in Figure 4b); nevertheless, this effect was eliminated thanks to the preprocessing of the software system (Figure 4c)). Also, the system successfully estimated the applied pressure with an absolute error of 0.04 kPa and a relative error of 0.02.

Our pressure estimation system can deal with arbitrarily scattered surface pressure represented by weights put on multiple pressure points in our experiments. When pressure was applied on the sensor array from multiple contact

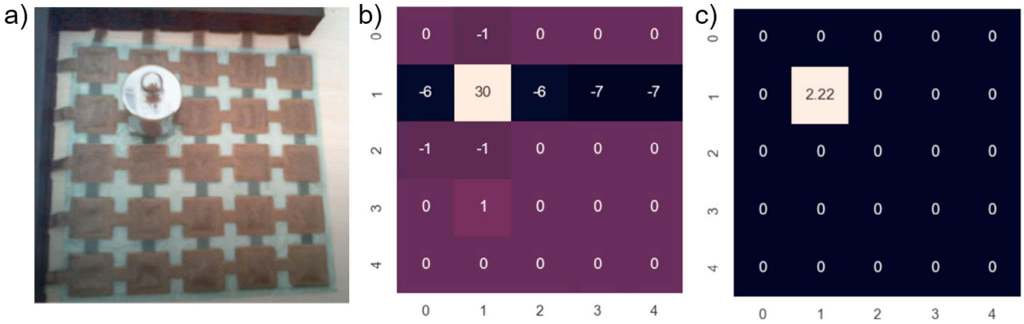

Fig. 4. a) A frame while applying 2.18 kPa on cell 6; b) Analog values of the sensor array while applying the pressure; c) Estimated pressure heat map [kPa] of the sensor array.

points (Figure 5a)), changes in the analog value of all cells (Figure 5b)) and estimated pressure values on them (Figure 5c)) can be observed in our monitoring tool visualizing individual measurements in all cells. Weights put on sensor cells 7 (100g and 4.36kPa), 13 (100g and 4.36kPa), and 17 (50g and 2.18kPa) were selected randomly for this part of the experiment. Analog input values in almost all cells were affected by placing weights on cells 7, 13, and 17, but due to preprocessing step, the cross-talk effect was not observed in the estimated pressure heat map. Eventually, the system estimated 2.18 kPa with 0.218 kPa of error for cell 17 and 4.36 kPa with 0.12 kPa and 0.13 kPa of absolute error for cell 7 and cell 13 respectively. Relative errors can be calculated as 0.1 for 2.18 kPa and 0.03 for 4.36 kPa.

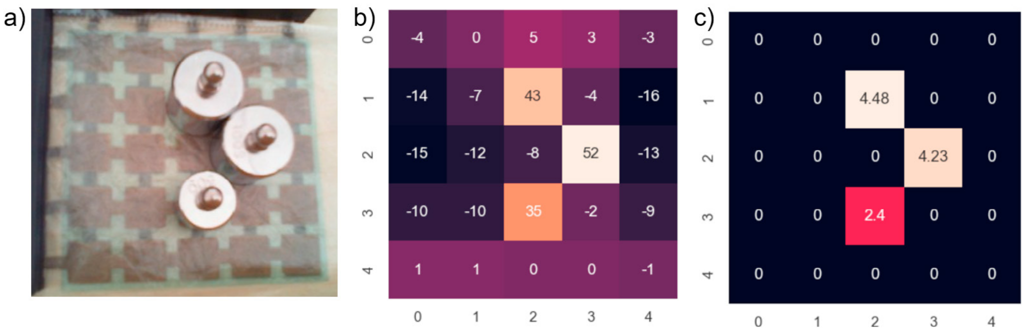

Fig. 5. a) A frame while applying 4.36 kPa on cell 7, 4.36 kPa on cell 13, and 2.18 kPa on cell 17; b) Analog values of the sensor array while applying pressures; c) Estimated pressure heat map [kPa] of the sensor array.

4.2. Evaluation Inside Brace

For the second type of experiment, the textile-based capacitive pressure sensor array was placed onto the back pressure point of the brace as shown in Figure 6a) and 6b). To demonstrate the feasibility of the proposed approach of pressure estimation with a textile-based pressure sensor array during live usage in an online scenario, the sensor array was removed from the stand and placed into the inner side of the brace. Then, it was connected to the Arduino via jumper cables which were passed through the air holes of the brace, so that the Arduino was placed on the outer surface of the brace. The proposed system with the brace is applied to a foam human figure that fits perfectly to the brace as seen in Figure 6c).

Figure 7 shows the brace being loose and tightened as well as the heat maps of estimated pressures for both cases. In Figure 7a), the brace was simply put on the foam figure, so most of the pressure is applied to the part of the sensor array that first made contact with the body. Then, in the second case as seen in Figure 7b), the brace is tightened as much as possible by using straps. The pressure dispersed from the edge of the textile-based pressure sensor array rather towards the middle. While 9.19 kPa pressure was applied on cell 13 in the first case, the applied force increased to 9.37 kPa in the second case due to tightening with the straps.

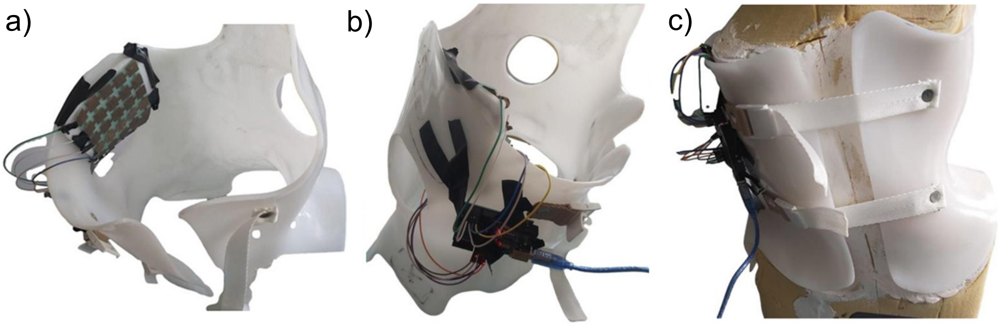

Fig. 6. a) Interior view of the brace with 5x5 sensor array; b) Exterior view of the brace with sensor array; c) The brace with sensor array on foam human figure.

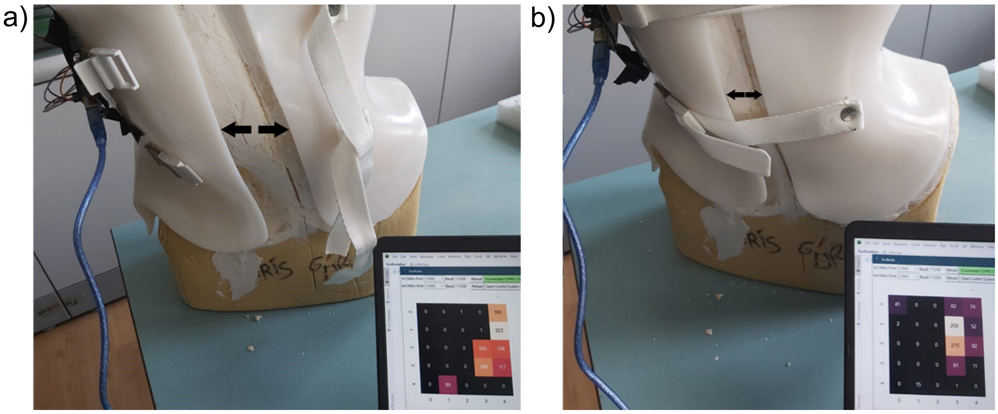

Fig. 7. a) Brace mounted on the foam figure; b) Brace mounted on the foam figure and tightened.

5. Conclusion and Future Work

In this study, a pressure monitoring system was proposed for scoliosis braces, utilizing a textile-based capacitive pressure sensor array. The detection of interface pressure applied to the patient's skin by a brace was the main contribution of our research. For this purpose, a wearable sensor array was used, which exhibited suitable sensitivity, durability, recovery/response time, and working range. The characterization of the pressure sensor array cells was examined in offline laboratory experiments by collecting data from each cell of the sensor array and calibrating them with curve fitting. Subsequently, the same sensor array was placed inside the brace to test the proposed monitoring system on a foam human figure.

Further improvements will be made to this study in order to make the design of scoliosis braces using textile-based capacitive sensor arrays more usable and robust. For the sake of convenience, in this study experiments were only done in the laboratory environment; however, in the future, we plan to apply our system to human test subjects wearing braces to show the effectiveness of the proposed system. For body capacitance and sweat problems, the antistatic fabric will be used to coat the capacitive sensor array. By storing the data in an SD card, battery life will be extended. For long-term use, a mobile application will be developed in order to transfer data from brace storage to a patient's phone via Bluetooth. An interface that visualizes the data will be designed so that long-term and short-term analyzes will be made by the medical personnel.

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