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Design & Characterization of A Helmet-Based Smart Textile Pressure Sensor for Concussion

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Abstract: A Mild traumatic brain injury (mTBI) or concussion has become a public health problem in the United State. Sports and recreational activities are major sources of concussions; with the most incidents connected to American football. Recently, many companies and research institutions have started studying concussions and introduced some means of protection and some alarming systems of strong jolts. The major detection and protection system currently available on the market is the electronic helmet (e-helmet) composed of measurement devices to record head impact acceleration. The most commonly used devices in e-helmets are accelerometers to measure linear acceleration and gyroscopes for rotational/angular acceleration. Using smart textiles for concussion detection is currently uncommon and limited due to the lack of literature studying their voltage related errors. Actually, there are few works that characterize some voltage-force related errors for such type of sensors but for small impact forces and under bench testing while the behavior of those sensors was not described for higher ranges of applied forces and in field situations. This paper previews some common techniques used in e-helmets for concussion detection and highlights electronic textiles and smart fabric sensors that could be very useful for these applications. It discusses and validates the general behavior of such type of sensors under high impact forces and on field testing instead of bench testing, and also it characterizes the effect of increasing the thickness of the sensing element layer on the sensor. A custom-made pressure sensor was created of some available fabrics to be embedded within the padding of a football helmet to quantify the impacting force to the head. The sensor is mainly composed a Semi Conductive Polymer Composite SCPC layer with modifiable thickness that was modified three times with 0.2, 0.4, and 1.6mm to characterize the general behavior of the sensor due to a high amount of impacts and correlated with the thickness. A pendulum system was built to test the pressure sensors, while a special camera and an open-source video analysis software, Tracker was used to track the pendulum bob. The speed and the acceleration of the pendulum bob were measured, then the impact force was calculated and a voltage-force response was obtained. The results showed that no meaningful improvement occurs by small increase in the thickness but better sensor behavior could be obtained by significant increment to observe any difference. Despite that at a very high impacts, the suggested sensor with Velostat layers is not giving the real voltage readings that reflect the actual applied forces but it gives a helpful information that illustrate the distribution of the force through identification the place of the highest and lowest voltage readings regardless of the exact values of those readings. However, the proposed smart textile pressure sensor could be applicable in future e-helmet designs with additional research-based improvements especially on the structure of the sensing element layer to be able to withstand such high impacts which in turns improves the overall sensor performance and accurately measures pressure in concussion-inducing ranges.

Keywords: smart textiles; pressure sensor; concussion detection; Velostat; football helmet; head impacts.

1. Introduction

A concussion is a brain injury, typically caused by blows or jolts to the head and occasionally due to rapid back and forth movement of the head causing changes in the shape of brain tissues and damaging cells. As the brain is considered the control unit of the human body, any damage to its cells is a serious and far-reaching issue. According to a recent report from the Center for Disease Control (CDC), United States has about 1.7 to 3.8 million concussion cases annually [1].

Even though concussion is usually not life-threatening, it can be a life-changing injury. Brain cell damage is accompanied by metabolic and chemical changes that create communication and functioning problems, requiring serious treatment for concussions. Many injury identification criteria are followed according to available literature and based on brain injury thresholds [2]-[5]:

- The Wayne State Tolerance Curve (WSTC) is an indicator of the tolerance limits of the human head that identify skull fracture tolerance as an equivalent indication of brain injury tolerance suggested by Gurdjian et al [3].
- The Severity Index (SI) was suggested by Gadd [4] and includes the linear acceleration of the motion as an indicator of the severity and injury cause. One drawback is its failure to account for angular acceleration.
- The Head Impact Criteria (HIC) which was suggested by the US National Highway Traffic Safety Administration (NHTSA) as an alternative to the SI formulation [5]. It is now widely used for TBIs diagnoses based on linear head acceleration but still does not account for angular acceleration.
- The Abbreviated Injury Scale (AIS) is a coding system that anatomically identifies injury severity from 0 to 6, with 0 representing no injury and 6 representing fatal injury [3].

2. Available Technologies

Many applicable commercial products are available for concussion detection and measurement. This section summarizes the main technologies used, their producers, and some product information.

Most products use impact sensors or accelerometers to measure the number of impacts and the real-time forces a person sustains. The accelerometer measures object acceleration using measurement units of either meters per second squared (m/s^2) or G-force (g). 1 g of acceleration is equivalent to the typical 9.8 m/s^2 acceleration of gravity on earth. Measured accelerations could be for static (gravity) or dynamic forces including movement and vibrations on one, two or three-axis. Today, the 3-axis accelerometer is most commonly used.

The advantages of these accelerometers that they are small and provide real-time impact data monitoring for players throughout the game. In addition to accelerometers for linear acceleration, gyroscopes are commonly used to measure angular acceleration.

Most accelerometers operate using changes in capacitance. A combination of fixed and spring-connected internal capacitive plates experience changes in capacitance due to movement in the springs. These changes reflect changes in acceleration. Other accelerometers rely on piezoelectric effects that give electrical charge output under mechanical forces. Most of the accelerometers have ranges of impact forces that can be measured from $\pm 1\text{g}$ up to $\pm 250\text{g}$. With lower measurement ranges, more detailed information is available, with higher reading sensitivity.

An example of an available product using accelerometers is the Riddell sideline response system, composed of 6 single-axis accelerometers inserted in a helmet, which gives an alert when an impact exceeds a threshold value. The Riddell insight has a 5-zone sensor pad in the helmet [6] [7].

Many other products like the Impact Assessment System [8], BodiTrak Head Health Network [9], GForce Tracker [10], [11], SIM-P (individual) SIM-G (team) [12], Reebok Checklight [13], Shockbox by i1 Biometrics [14], and Vector [15], X-Patch and X-Guard by X2 Biosystems [16], offer different models and designs, generally using 3-axis accelerometers and gyroscopes at various locations. Typical locations include gyroscopes near the mouthguard and accelerometers behind the ear, headband or skullcap for accelerometers [6]- [25]. The following table summarizes the main names in the market and the technologies in their products.

Table 1. Commercial head impact devices

Device Name	Manufacturing Company	Technology used	Location and design
Brain Band [17]	Samsung	Unspecified number of impact sensors	Headband
Brain Sentry iC+ [18]	Brain Sentry	Unspecified impact sensors	Outer back side of helmet
BodiTrak Head Health Network [9]	Marucci Sports	Accelerometer, gyroscope, and thermometer and smart textile	In helmet
Checklight [13]	Reebok	Accelerometer and gyroscope	Skullcap with or without helmet
FITGuard [19], [20]	Force Impact Technology	3-axis accelerometer, 3-axis angular rate sensor	Mouthguard
GForce Tracker [10], [11]	GForce Tracker	3-Axis accelerometer and gyroscope	In helmet
Head Case [21]	Head Case	accelerometer	mounted inside headgear of helmet
HeadsUp [22]	Integrated Bionics, LLC	Unspecified	Headband or armband
Impact Assessment System [8]	Linx	3-Axis accelerometer and gyroscope,	Headband or skullcap
Jolt Sensor [23]	Jolt	Not provided	On headband or helmet

PlayerMD [24]	Archetype	6-Degree-of-freedom sensor array	Skullcap or Headband
Rosh headband [25]	Rosh	4 Impact Sensors	headband
Rosh Cap [25]	Rosh	4 Impact Sensors	Full headcap
Riddell Sideline Response System [6]	Riddell	6 Single-axis accelerometers	In helmet
Riddell Insight Training Tool ITT [6]	Riddell	5-Zone sensor pad	In helmet
SIM-P (individual)	Triax	3-Axis accelerometer and gyroscope	Headband or skullcap
SIM-G (team) [12]			
Shockbox [14]	i1 Biometrics	4Unidirectional, orthogonally placed force switches	Helmet
Vector [15]	Vector	3-Axis accelerometer and gyroscope	Mouthguard
X-Patch [16]	X2 Biosystems	3-Axis accelerometer and gyroscope	Behind ear
X-Guard [16]	X2 Biosystems	3-Axis accelerometer and gyroscope	Mouthguard

¹ [6]-[25]

As shown in the table, the main sensors used in devices for concussion detection are accelerometers and gyroscopes. Smart textiles are not commonly used but they may become useful alternatives to many conventional electronics.

3. Smart Textiles

Smart textiles, also known as electronic textiles or e-textiles are special kinds of fabrics that are modified or created in certain structures and designs to perform specific functions such as detecting and sensing different kinds of signals.

Smart textiles attract interest for their simplicity and wearability, which open a wide range of applications especially for biological signals sensing and biomedical applications [26]. The idea of smart textiles represented in that an extrinsic or intrinsic modification can be done on the substrates of some kinds of fabrics in order to create a type of sensing functionality when they interact with the wearer or the surrounding environment [27].

Fabrics with sensing properties are called Smart Fabric Sensors (SFSs). SFSs can be designed to sense temperature, pressure, applied force, electrical current, humidity, and chemicals. SFSs are a subset of smart fabric transducers (SFTs), fabrics that are modified, built and treated so they can be used as sensors, actuators or batteries and energy harvesting systems. SFTs can be used for many other advanced functions, but the mentioned ones are the main function categories of SFTs. This work focuses primarily on SFSs, particularly pressure sensing SFSs. Semiconductive polymer composites are a common example of piezoresistivity based force or pressure sensing smart fabrics [28]-[31].

Current literature categorizes the applications of available smart textiles into two major groups, aesthetic and performance-enhancing. Aesthetic smart textiles are most commonly used in commercial applications such as producing lights or changing colors under pressure, force, heat, vibration or even sound. Many electronics could also be embedded within the fabric to power and control these processes, like controlling the light intensity. Performance-enhancing smart textiles are mainly used in wearable applications for sports, medicine [32], and aerospace [33], and military applications to provide protection against external hazardous effects or enhancing functional performance [27]. Some examples of smart fabric functions include body temperature regulation, drug-releasing, muscle contraction control, radiation protection, and space travel.

There are some patented materials and designs for smart textiles but no standard elements or ways to build SFSs or fabrication methods so far, as it is still a new field of research in the development phase. It would be beneficial to use smart textiles in portable and wearable devices, but it remains difficult to build a whole system with incorporated functionality using only smart fabrics, without conventional electronics. Therefore, combining both technologies alongside continued development of fabric elements, designs, and fabrication techniques could achieve more robust and complete sensing systems. Improving and standardizing the elements and methodology of smart textiles sensors requires comprehensive studies of their behavior and voltage related errors by robust testing protocols including in field testing beside bench tests. The behavior of some commercial flexible smart fabric sensors has been investigated before, but very few literatures studying the linearity and voltage response errors of sensors made of Velostat under high impact forces and in field testing. This paper provides a general characterization of the voltage response of semiconductive polymer composites pressure sensor made of Velostat under very high impacts and similar to real in field situation.

3.1. Pressure Sensor

SFSs must be constructed from appropriate smart textiles. The creation of smart textiles requires sensing functionality. Either intrinsic or extrinsic modifications are required to turn regular fabrics into smart fabrics with the desired sensing features.

Most SFSs consist of three main parts; sensing elements, connectors, and the insulating and integrating textile [27], [29].

A simple custom pressure sensing design was hand-sewn from smart fabrics to detect force impacts for integration in the padding of the e-helmet. However, this type of pressure sensor is ideal for low levels of pressure such as finger pressure. Readings become stable and nonlinear for high-pressure ranges; therefore, the design of the sensor needs to be modified for application to the high-pressure ranges that cause concussion. An initial idea for that modification was suggested in this work through increasing the thickness of the sensing element layer as we believe increased thickness of the semiconductive polymer composite (sensing element) could increase the value of pressures that can be detected by this SFS or at least maintain linearity of the sensor at higher applied forces.

4. Materials and Method

4.1. General Evaluation Factors of the SFS

Like any sensor, there are different factors to evaluate regarding their overall performance and specific applications. These factors can be summarized as:

- Stability or Drift: output variation while a constant input is maintained over a long period of time.
- Homogeneity: output consistency when applying the same input to two identical sensors under the same circumstances.
- Linearity: linearity of the relationship between outputs and inputs.
- Repeatability: output variability under the same input repeated many times under the same circumstances and experimental conditions.
- Sensitivity: the minimum change in input (applied pressure) to create a change in output (voltage).
- Hysteresis: changes in output due to repeated loading and unloading (applying and removing load cycles) of equal inputs.

This work does not include exact measurements and calculations of those factors but provides a general characterization of the sensor behavior and the effect of increasing the thickness of the sensing element layer on their performance addressing linearity, stability and hysteresis in the experiment and results.

4.2. Design and Test Assumptions

This work is considered as a first step towards more comprehensive studies in the future. As such, the model was simplified using many assumptions. Although the system looks simple as a design, it is more complicated than our assumptions, especially with the regard to its sensing procedure.

Tests will be performed for individual pressure sensor, shown in Figure 1, while the number and arrangement of sensors of the whole embedded design within the helmet can be extended and modified based on the needs and intended area for detection. Actual improvement of these sensors requires not only performing bench tests in experimental labs with exact amounts of stimulations, but also tests in realistic situations and on-field circumstances to provide a better picture of what could happen in real cases and thereby ensure effective and safe utilization of this type of sensor [34, 35, 36, 37]. In this research, the experiments were performed to mimic real situations.

In general, semiconductive polymer composite (SCPC) force sensors show sensitivity drift in their output reading compared to the original calibrated sensor. That is, sensors show different output readings (offset) under constant long term inputs (impact force). This offset is mostly due to creep, or cold flow of these composites. Creep is a slow move or long term deformation of a solid material subjected to long term exposure to a continual high mechanical stress that stays below material's yield strength [37].

Figure 1. a) Upper face of the pressure sensor (without sponge layer) b) lower face of the pressure sensor

This work does not focus on sensors stability as the main goal of this research work is to evaluate the performance of a suggested smart fabric pressure sensor that can be used for concussion detection in applications such as football games. Thus, this work addresses the detection of instantaneous impact pressure, not long sustained pressures.

Sensor linearity, however, is a critical issue that must be considered in the high-pressure ranges encountered in concussion detection. This type of pressure sensor has high sensitivity and linear output in low-pressure ranges, but as the pressure increases the sensor tends toward saturation and its output becomes almost constant. Unless this problem is addressed, these sensors are not effective in high-pressure ranges for concussion detection.

Based on the available literature on flexible pressure sensors' performance; improved detection ranges have been achieved using many piezoresistive materials. Their detection range varies between about 0.2Pa to 10kPa using Polydimethylsiloxane PDMS dispersed with conductive particles (such as Gold or Carbon), or Aligned Carbon Nanotube ACNT and Vertically Aligned Carbon Nanotube VACNT. Better ranges of about 0.2 Pa to 59 kPa were achieved using an interlocked microdome array [38], [39]. This is a crucial improvement in detecting ranges, particularly the maximum detection level of 59kPa. Additional improvement is needed to increase the maximum and measure all concussions.

To deal with the linearity issue, an appropriate conditioning circuit is needed. Using a trans-impedance amplifier is an option to obtain a response closer to linearity. With more improvement and using a polynomial equation, calibration can improve responses [37], [40], [41]. Sometimes when dealing with qualitative data only, a bias resistor could be enough to eliminate nonlinearity [37], [40], [42]. A logarithmic like-response for high-pressure ranges is extracted based on the sensor's transfer function.

The current research gave some attention to maintaining linearity in high pressure ranges, but did not use conditioning circuits for this. Instead, we sought to improve linearity by increasing the thickness of the semiconductive polymer composite (Veloster layer), so tests repeated while the thickness was gradually increased by adding additional Velostat sheets in hopes of detecting higher pressures.

As mentioned before, for dealing with output drift and hysteresis and in order to include the creep behavior of the polymer composite it needs to be modeled as a viscoelastic material [43]. However, in a first-order viscoelastic model, the time constant is relatively long [37]. Thus, the response of these materials is slow, and that there will be hysteresis in the response if the sensor is sequentially impacted without sufficient relaxation time. Hysteresis can be addressed in the lab by simply giving enough time between tests to let the sensing material finish its response before repeated stimulation through a new impact. However, this is not feasible in the field when using these sensors in applications that need sequential immediate detection. Based on the available

literature, a cycle that is less than or equal to 0.01 times the time constant of a first-order system is considered a short cycle, while one that takes more than 5 times the time constant is considered a long cycle [37], [43].

For Velostat, the time constant was calculated and found to be 311 seconds [37]. Therefore, its short testing cycle is 3.11 seconds or less while a long cycle is approximately 26 minutes.

Going back to American football, according to a current research study, within one season some players could receive 1400-1500 hits directly impacted to the head, or “head impact exposures,” with an average of about six exposures per practice and 14 per game [44]. While the average time for a professional football game is about 3 hours 12 minutes, the actual time that the ball is in play is about 11 minutes. That is, there are approximately 11 minutes during which players from different teams are in direct contact and hits could occur.

Thus, there are approximately 1.83 minutes of play time (11/6) between sequential hits, with a significantly longer total time between hits due to the difference between game time and active time when the ball is in play. Therefore, there will be enough relaxation time for the sensor between contacts. A cycle of 2.5 times 311, or about 13 minutes, is a reasonable cycle period. We therefore wait 13 minutes between tests.

4.3. Smart Textile Pressure Sensor Design

The sensor has three main layers; the upper and the lower layers are integrated insulating textiles, and the middle layer holds the sensing and conduction materials. A sponge layer was added to the top of the sensor, which will be in direct contact with applied force, shown in Figure. 2.

A carbon-filled conductive polyethylene film called Velostat [45], was used for the middle layer. Other conductive materials like Graphene could also be used and may be tested for their pressure detection ranges.

Figure 2. Pressure sensor layer

The Velostat layer is 0.1mm, but this thickness is insufficient at high pressure ranges. We began with two layers for a total thickness of 0.2 mm, and that thickness was modified and increased gradually during the sensor testing steps to characterize the voltage response according to that thickness increment.

A 100% Nylon plain weave was used for the two integrating textile layers. Nylon is a popular elastic synthetic fiber that is highly durable, with good weather and abrasion resistance properties and a volume resistivity of 1016 Ohm/cm. However, when using Nylon, static electricity is periodically produced which could potentially short a circuit [46].

Figure 3. Internal structure of the suggested pressure sensor

The pressure sensor is further divided into four sensors or sensing areas, one at each corner (Figure.3); each senses independently from the others and gives feedback about impact locations and the amount of pressure applied through its own electrode. These subdivided four sensors together form a 2x2 pressure sensing matrix.

A conductive thread is hand-sewn to form the circuit within the sensor. The conductive thread must be sewn within the Nylon layers to make direct contact with the Velostat layer at the main sensing area, and from both sides as shown in figures (3 and 4). A continuously drawn 2-ply 316L stainless steel was used as a conductive thread; it has a resistivity of 1.3 Ohm/inch.

The layers and conductive thread together create a piezo-resistive effect under applied forces. Applied pressures in the sensing areas can be linearly translated from the sensed resistances [47].

Each subdivided sensing area is connected at its own knot and through a separated connector to the Microcontroller unit (Arduino), and the outputs were displayed on a laptop (Figure. 4) then data analysis was performed with custom made scripts in Microsoft Excel.

Figure 4. Main Components of the Sensing System

4.3. Pressure sensor experimental setup

As the Velostat pressure sensors used in this system gave output in Volts, testing was required to correlate the output voltage readings to the impact force in order to obtain the voltage-force related response of the sensor. To provide real like situation a pendulum was built with an arm length of 1.6 meters and a 17 Kg mass was attached to the bottom as shown in Figure 5 and Figure 6.

The sensor was attached to a sandbag at the bottom of the pendulum's arc so impact strength could be controlled based on the height from which the weight was dropped. Using the open-source video analysis software, Tracker, the speed and acceleration of the pendulum at impact could be measured (Figure 5). Data from the pressure sensors were collected through the analog pins of an Arduino Uno.

Figure 5. Open-source tracking system of the pendulum

Three sets of tests were completed on two different days. In each set of tests, a different Velostat thickness (0.2 mm, two layers; 0.4 mm, four layers; and 1.6 mm, sixteen layers) was tested, with five trials per set of tests. As previously discussed, there were 13 minutes between trials for material relaxation within each set of tests.

In each test, the 17 Kg mass will be released from 1m above and 1.7m horizontally from the bottom of the pendulum, with the pendulum arm at 68 degrees as shown in Figure 6.

Figure 6. Main dimensions of the pendulum experimental setup

The distance that the massive bob of the pendulum travels each trial was calculated with the arc length formula:

$$\text{Arc length} = 2\pi r(\theta/360), \quad (1)$$

Where r is the length of the pendulum arm, or 1.6 m and θ is the angle (in degrees) of the pendulum arm from vertical at the release point. It was found to be about 1.9 m. All the data values were approximated and rounded to the third decimal place.

3. Results and Discussion

As mentioned earlier, five trials have been done on each thickness, and the data was collected from each trial. Four voltage readings were recorded each time reflecting the amount of pressure applied to the four sensing areas. The relevant momentum, kinetic energy and acceleration of each trial have been also measured. The average voltage over the four sensing areas was calculated. Data collected from trials of the three attempts were summarized in the following tables:

First attempt (0.2 mm Velostat thickness)

For two Velostat layers							
Trial #	Velostat Readings (V)	Average Reading (V)	Angular Momentum (Kg*m ² /s) $p = mvr$	Kinetic Energy (J) $KE = 0.5mvr^2$	Tangential Velocity (m/s) $=Q/m$	Tangential Acceleration (m/s ²)	Applied Force (Kg*m/s ²) $F = ma$
2	1.242 1.187 0.784 0.632	0.961	154.331	273.6456	5.67394	10.59	180.03
3	0.516 0.710 0.355 0.245	0.456	171.584	338.246	6.308	13.09	222.53
1	0.545 0.826 0.635 0.532	0.635	194.442	434.370	7.149	16.81	285.77
4	0.319 2.174 0.513 2.177	1.296	222.341	567.963	8.174	21.98	373.66
5	0.532 0.536 0.668 2.177	0.978	239.108	656.853	8.791	25.42	432.14

Table 2. Collected and calculated data from 1st attempt for two Velostat layers

Second attempt (0.4 mm Velostat thickness)

For Four Velostat layers							
Trial#	Velostat Readings (V)	Average Reading (V)	Angular Momentum (Kg*m ² /s) $\rho = mvr$	Kinetic Energy (J) KE=0.5mv ²	Tangential Velocity (m/s) =q/m	Tangential Acceleration (m/s ²)	Applied Force (Kg*m/s ²) F=ma
3	0.213 0.494 2.177 0.403	0.822	182.015	380.6232	6.691726	14.73	250.41
1	0.858 0.365 0.845 0.352	0.605	202.154	469.513	7.432	18.17	308.89
2	0.916 0.848 0.926 0.394	0.771	224.856	580.883	8.267	22.48	382.16
4	1.081 0.632 1.081 0.587	0.845	250.320	719.902	9.203	27.86	473.62
5	0.477 0.626 0.510 1.381	0.748	264.646	804.658	9.730	31.14	529.38

Table 3. Collected data from second attempt for four Velostat layers

Third attempt (1.6 mm Velostat thickness)

For Sixteen Velostat layers							
Tria l#	Velostat Reading s (V)	Average Reading (V)	Angular Momentum (Kg*m ² /s) $\rho = mvr$	Kinetic Energy (J) KE= 0.5mv ²	Tangential Velocity (m/s) =q/m	Tangential Acceleration (m/s ²)	Applied Force (Kg*m/s ²) F=ma
2	1.336 0.852 1.336 0.597	1.336	247.019	701.039	9.082	14.73	461.21
5	0.561	0.602	283.242	921.713	10.414	18.17	606.39

	0.671						
	0.571						
	0.607						
4	1.423	1.423	295.331	1002.075	10.858	22.48	659.26
	1.426						
	1.429						
	0.742						
3	0.639	0.639	295.94	1006.21	10.880	27.86	661.98
	0.784						
	0.661						
	0.558						
1	1.165	0.902	308.954	1096.65	11.359	31.14	721.48
	0.877						
	1.161						
	0.403						

Table 4. Collected data from third attempt for sixteen Velostat layers

Now, the force that was exerted on the sensor can be calculated easily by multiplying mass with acceleration and the applied pressure can be calculated as well by dividing the exerted force by (0.016 m) the surface area of the sensor.

The Force-Voltage relationship of the four sensing areas of the sensor with two Velostat layer (0.2mm) is represented in Figure 7 (a, b, c, and d).

Figure 7: Force-voltage relationship of each sensing area of the pressure sensor with (0.2mm) Velostat layer

The following chart represents the average reading of the sensor of two Velostat layers with respect to the actual applied pressure on it for the first five trials.

Figure 8: Average Voltage readings with respect to applied pressure for (0.2mm Velostat layers)

As mentioned before, and according to the voltage divider circuit that has been used, for a normal behavior of the sensor the voltage readings supposed to decrease with increasing the applied force as a result of decreasing the resistance of the sensor when impacted by a compression force. As shown in Figure 7 and 8, it is clearly shown that the sensor with this thickness and under high pressures as well as none of its sensing area is following a normal behavior, the linearity is not maintained and the hysteresis effect is obvious. This hysteric effect is mainly due to the deformation that occurs to the material that is not able to maintain its original internal structure when undergoes very high impacts. Also if we focus to the chart we can observe that a very closed voltage readings were obtained in the first and the fifth trial (0.961 and 0.978V respectively) while the difference in the applied pressure is too big between the two trials and does not accordingly reflect real reasonable readings, this open eyes on a repeatability issue that will also be exist under such high impacts.

Figure 9. Voltage reading at each sensing area for pressure sensor of (0.2mm Velostat layers)

As shown in Figure 9, the voltage reading values were almost in the range of 0.2-1.4 V for the five trials but three peculiar readings were observed of about 2.17 V at the second and the fourth

sensing area of trial number 4 and again in the fourth sensing area of trial number 5. There are two choices to obtain such readings, either that those sensing areas were not quite affected by the hit or just a hysteric behavior of the sensor.

For the sensor with 0.4mm Velostat layer, the force-voltage relationship for the four sensing areas is describe in Figure 10 and 11. Same as 0.2mm none of the sensing areas followed a linear behavior and the voltage readings are not reflecting the actual values of the applied force. If we compare the average voltage readings with the applied pressure, we can observe that the readings are closed while the pressure difference is big.

Figure 10. Force-voltage relationship of each sensing area of the pressure sensor with (0.4mm) Velostat layer

Figure 11. Average Voltage readings with respect to applied pressure for (0.4mm Velostat layers)

The distribution of the force at this thickness is described in Figure 12

Figure 12. Voltage reading at each sensing area for pressure sensor of (0.4mm Velostat layers)

It is observed that the voltage readings are mainly in between 0.2-1.4 V while we got one peculiar reading of 2.177 V in the first trial at the third sensing area. This high value compared with the other values indicates that the hit was centered in the first, second and the fourth sensing area while the third sensing area did not receive that big hit but again this might be due to a hysteric behavior of the sensor. It is clearly shown that there is no actual improvement on the sensor behavior by increasing the thickness of the Velostat layer to 0.4mm. Therefore, we have decided to double the thickness 8 times. Now we have 1.6mm Velostat layers. All data collected and calculated from the five trials that have been done on the sensor of a 1.6mm Velostat layers are represented on Table 4.

For 1.6mm thickness the force-voltage relationship of the four sensing areas is described in Figure 13 (a, b, c, and d).

Figure 13. Force-voltage relationship of each sensing area of the pressure sensor with (1.6mm) Velostat layer

From Figure 13 and 14 it is clearly shown that the overall sensor behavior was not linear and also hysteric at some points but at the same time the charts of all sensing areas are almost similar despite of the variation of the values between each one. What this tells us is that all sensing areas at this thickness are acting almost similarly and the hysteric effect occurs at same time on all sensing areas and not randomly like in the previous thicknesses.

Figure 14. Force-voltage relationship of each sensing area of the pressure sensor with (1.6mm) Velostat layer

The distribution of the force for at this 1.6mm thickness is described in Figure 15.

Figure 15. Voltage reading at each sensing area for pressure sensor of (1.6mm Velostat layers)

This time the voltage readings are in between 0.4-1.4 V while the peculiar reading above the 2 V was not observed The results looks more reasonable and the sensor behavior less hysteric, but still not linear and the voltage readings are not reflecting the actual applied force.

However, in many times and for all tested thicknesses the sensor seems to be acting correctly and reflecting the real case but at the same time the readings cannot be trusted.

Despite that the sensor was given 13-minute cycle period which is supposed to be fair enough as a relaxation time to return to its original state, but the variation in the readings still exist.

This faulty variation is mostly due to hysteresis phenomena caused of loading and unloading pressures and seems to be general issue for all sensors with sensing element layer based on

semiconductive polymer composite such as Velostat. But for a very high impacts the main reason is mostly due to the deformation that occurred to the sensor materials as a result of strong strikes.

Despite that the sensor is not giving the real voltage readings that reflect the actual applied forces but it gives a helpful data regarding the distribution of the force through identification the place of the highest and lowest voltage readings regardless of the exact real values, for instant, based on data represented on Figure 9, for the first trial the lowest voltage readings were in the third and the fourth sensing area so we can conclude that the hit was mainly centered on those areas at the lower part of the sensor, while for the second and the third trials, readings obtained from all sensing areas are almost close which means that the hit is around the center of the sensor with little shifting to one or more of the sensing areas as shown in Figure 16.

Figure 16: The approximate location and concentration of the applied force for the five trials on pressure sensor with (0.2mm) Velostat layer, a) 1st trial, b) 2nd trial, c) 3rd trial, d) 4th trial, and e) 5th trial.

This can provide illustration schematics about the location and the distribution of the hits and would be used in e-helmets for such purpose.

4. Conclusion

Using smart fabrics of SCPC such as Velostat to create reputable pressure sensor for detecting high pressure ranges is still very challenging and without finding effective solutions for nonlinearity and hysteresis as well as repeatability, it would not be able to be used in applications such as concussion detection.

Increasing the thickness of the SCPC would improve the total performance of the sensor but it should be significant increment to get observable changes. Also more robust testing techniques could be used especially bench testing beside the real field testing to get more reputable results.

In general, polymeric based sensors show poor performance for almost all assessment factors. But even though they are still very promising for their simplicity, low cost, and for being wearable and with more research on improving the materials and the structure design of these sensor it could be possible to overcome all the limitations and improving their performance.

Despite that at a very high impacts, the suggested sensor with Velostat layers is not giving the real voltage readings that reflect the actual applied forces but it gives a helpful information that illustrate the distribution of the force through identification the place of the highest and lowest voltage readings regardless of the exact values of those readings.

The suggested smart textile pressure sensor would be a precious applicable design for e-helmet in the future and it is believed that with more research and work in this field it could be modified and improved to be able to accurately measure concussion pressure ranges.

Major improvement could be achieved by improving the structure of the sensing element layer like finding an alternative SCPC materials that are able to withstand such high impacts without

deforming the internal structure of their materials which in turn reflects on the reputability of the voltage readings.

RECOMMENDATIONS AND FUTURE WORK

Smart textiles are very interesting and promising field, so in the next work, new combinations of materials and structures will be examined using more robust testing procedures and protocols as well as comprehensive studies including mathematical and computational modeling will be performed to identify the actual behavior of such type of sensor

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