IOP Conf. Series: Materials Science and Engineering **175** (2017) 012006 doi:10.1088/1757-899X/175/1/012006

Piezoresistive Carbon-based Hybrid Sensor for Body-Mounted Biomedical Applications

M Melnykowycz[1], M Tschudin[2] and F Clemens[1]

[1]Laboratory for High Performance Ceramics, Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland
[2]STBL Medical Research AG, Wilen, Switzerland

E-mail: mark.melnykowycz@empa.ch

Abstract. For body-mounted sensor applications, the evolution of soft condensed matter sensor (SCMS) materials offer conformability andit enables mechanical compliance between the body surface and the sensing mechanism. A piezoresistive hybrid sensor and compliant meta-material sub-structure provided a way to engineer sensor physical designs through modification of the mechanical properties of the compliant design. A piezoresistive fiber sensor was produced by combining a thermoplastic elastomer (TPE) matrix with Carbon Black (CB) particles in 1:1 mass ratio. Feedstock was extruded in monofilament fiber form (diameter of 300 microns), resulting in a highly stretchable sensor (strain sensor range up to 100%) with linear resistance signal response.

The soft condensed matter sensor was integrated into a hybrid design including a 3D printed metamaterial structure combined with a soft silicone. An auxetic unit cell was chosen (with negative Poisson's Ratio) in the design in order to combine with the soft silicon, which exhibits a high Poisson's Ratio. The hybrid sensor design was subjected to mechanical tensile testing up to 50% strain (with gauge factor calculation for sensor performance), and then utilized for strain-based sensing applications on the body including gesture recognition and vital function monitoring including blood pulse-wave and breath monitoring. A 10 gesture Natural User Interface (NUI) test protocol was utilized to show the effectiveness of a single wrist-mounted sensor to identify discrete gestures including finger and hand motions. These hand motions were chosen specifically for Human Computer Interaction (HCI) applications. The blood pulse-wave signal was monitored with the hand at rest, in a wrist-mounted. In addition different breathing patterns were investigated, including normal breathing and coughing, using a belt and chest-mounted configuration.

1. Sensor Designs and Body-Mounted Applications

The development of body-mounted sensor technologies is leading to the creation of compliant and soft sensor structures, which can augment or improve upon the use of conventional sensors currently in wide use. Soft condensed matter sensors (SCMS) can provide the ability to measure surface strains directly on the skin surface, and offer integration possibilities in clothing, or as standalone bands to be positioned at different locations.

1.1. Body-Mounted SensorApproaches

The explosion of wearable sensors and fitness trackers in the past years has been driven by the availability of low-cost MEM based sensors, specificallyinertial measurement unit (IMU) chips that include accelerometers and gyroscopes sensors that allow motion capture. Motion tracking can be accomplished with sensors placed at key linkage points on the human body, such as the wrist, elbow, and knee as well as on the torso, head etc. A rigid body model based on the human skeleton can then be used to track how a person is moving. Similarly, motion recognition and depth camera systems can be used to visually track motion. The information from both systems can then be used to animate characters in virtual environments. In 3D game and animation design, the movement of human or character 3D models are also based on rigid body motion, making it straightforward to use captured motion in designing virtual character motion. For consumer products, motion sensors can be easily integrated in devices such as smart watches or fitness trackers to track basic motions and extrapolate the activity of the person such as walking, running, sleep patterns, etc.

Motion sensors are not able to accurately determine the deformation of the body surface however. This makes it difficult to track the motion of individual muscles, where electrical impulse may be used instead. It is worthwhile to mention that electrical impulse measurements will also not allow for surface strain measurement. For strain measurements commercially piezoresistive bend sensors are available, which can be used to monitor the movement of individual fingers, or basic deflection and bending. Alternative electro-active polymer (EAP) sensors can be used to measure bending and strain as capacitive sensors mounted on the body.

In comparison to our soft body, commercial available piezoresistive sensors are still stiff and too large. In the current work, piezoresistive SCMS fibers were integrated into a compliant polymer substrate structure for body-mounted strain sensing, with applications in vital sign monitoring and gesture monitoring for Natural User Interface (NUI) design approaches.

1.2. Applications for Body-Mounted Sensors
In biomedical field, wearable sensors are already used to analyze motion, but consumer-grade devices do not provide data that can be trusted by medical practitioners for true remote medical use cases. The accuracy of heart rate monitors for example, can vary and therefore only be used to have a general understanding of how a patient's heart rate is changing. In the current work, a SCMS based on Carbon Black (CB) and a thermoplastic elastomer (TPE) was investigated for different body-mounted sensor applications, including wrist motion, blood pulse-wave, and breathing monitoring.

While the initial applications of wearable sensors have focused largely on fitness trackers, many applications exist in the biomedical and computing fields. User interaction patterns in personal computing have focused almost exclusively on the computer/mouse, as those were the input devices that were logical to build. The advent of mobile computing with the smartphone and tablet devices ushered in user interaction patters based around tapping, swiping, and pinch/zooming with the fingers. Currently the release of virtual reality devices brings another dimension to user interaction where a full 3D volume around a user may be used for interaction with a computing program. Later, smart glasses and augmented reality will also require novel interaction patters that are natural for people to perform as they move between different device types.

2. Sensor Material Production
The production of the carbon black based conductive polymer composites is documented in the previous work [1]. The SCMS fibers were extruded using a Capillary Rheometer (Rosand RH7Flowmaster). A Niggeloh 200 bar pressure transducer was used to monitor the pressure of the melt through an orifice of 0.3 mm in diameter.

3. Sensor Structural Design and Production
A primary design consideration for body-mounted sensor design is ensuring that the sensor conforms to and stays relatively fixed on the area of interest on the body. Silicone was a logical material choice for designing a structural carrier for the sensor, however silicone is also excessively deformable and with a high Poisson's Ratio, will contract when stretched over a surface, thereby reducing its surface area and creating a larger stress concentration on the body surface than may be necessary.

Sensor structures were produced with a hybrid TPE-silicone structure.Previouslya similar configuration worked well for initial investigationson textile substrate [2], but in order to better tune the mechanical properties to different applications, a hybrid sensor design approach was taken. In the current work, a compliant design approach was chosen(Figure 1a). An auxetic array was built up by 3D printing using a commercially available TPE (FilaFlex®), which was then casted in silicone together with the sensor fiber. The auxetic unit cell was chosen, since it displays a negative Poisson's Effect[3], and expands in the width direction while under tensile load. This would then counteract the contraction of the silicone material when stretched on the body.

Figure 1. Textile band sensor (a), hybrid structure (b), integration in Samsung Gear S2®band (c)

For soft body dynamic detection, the sensor structures was connected to a textile band (b) or smartwatch (b). The wires of the sensor structure were connected to the blood pressure watch prototype developed by STBL Medical Research AG (Freienbach, Switzerland). Via the blood pressure watch a current was applied to the band sensor and the resulting voltage across the sensor was recorded. A 24 bit analog-to-digital converter (ADC) was used in the design to provide a high resolution measurement of the band sensor signal with a data acquisition rate of 40 Hz. The blood pressure watch prototype was connected via Universal Serial Bus (USB) connection to a laptop with a custom LabView® program which ingested and saved the sensor data from the band sensor.

4. Evaluation for the use of Natural User Interfaces

NUI is an approach to Human Computer Interaction (HCI) which attempts to use gestures to interact with computing systems that are close to the natural movements of the human body. The development of NUI interaction devices is necessary for the evolution of computing, which is moving towards virtual and augmented reality technologies that are used in a mobile and room-scale or standing user environment. In order to design a motion-capture test specifically for NUI, an analysis was made of current NUI patterns utilized in mobile computing devices including smartphones, Leap Motion® Controller, Microsoft HoloLens®, and the Myo® Armband. A primary application concept for the strain sensor is as integration of the sensor in a smartwatch band. To evaluate this concept a wristband prototype was prepared by integrating the compliant sensor with the Samsung Gear S2®smartwatch, and evaluated using the NUI gesture test described in Table 1.

A previous investigation had focused on the motion capture capability of the textile wristband, placed at different positions around the wrist, and it was shown that multiple sensors would be able to define discrete hand positions [2]. The current work sought to integrate the sensor material in a form that can be built as a wristband for a smartwatch, and additionally to evaluate the gesture recognition ability of a single sensor to identify motions that would be useful from a HCI perspective. The NUI hand gestures are detail in Table 1, and were chosen for their use in different products that currently use an NUI approach to interfacing with a computer. The Samsung Gear S2®band (Figure 1c) was used in the NUI evaluation. The results are displayed in Figure 2where relative level of different gestures can be used to distinguish one from another in certain cases.

Table 1. NUI gesture evaluation test description.

Gesture	**Hold Time**	**Inspiration / Intent**	**Used in Product**
Double-click	-	Historical interaction pattern	HoloLens
Wave right	-	Natural forward movement	Myo / Leap
Wave left	-	Natural backward movement	Myo / Leap
Pinch	5 sec	Learned 2D surface pattern	Smartphones
Zoom	5 sec	Learned 2D surface pattern	Smartphones
Closed fist	5 sec	Hold a chosen virtual object	Myo
Flat Hand	5 sec	Logical starting/recovery position	
Spread-open hand	5 sec	Release an object or expand a workspace	Myo
Wrist Flexion	5 sec	Move an object up	Myo
Wrist Extension	5 sec	Move an object down	Myo

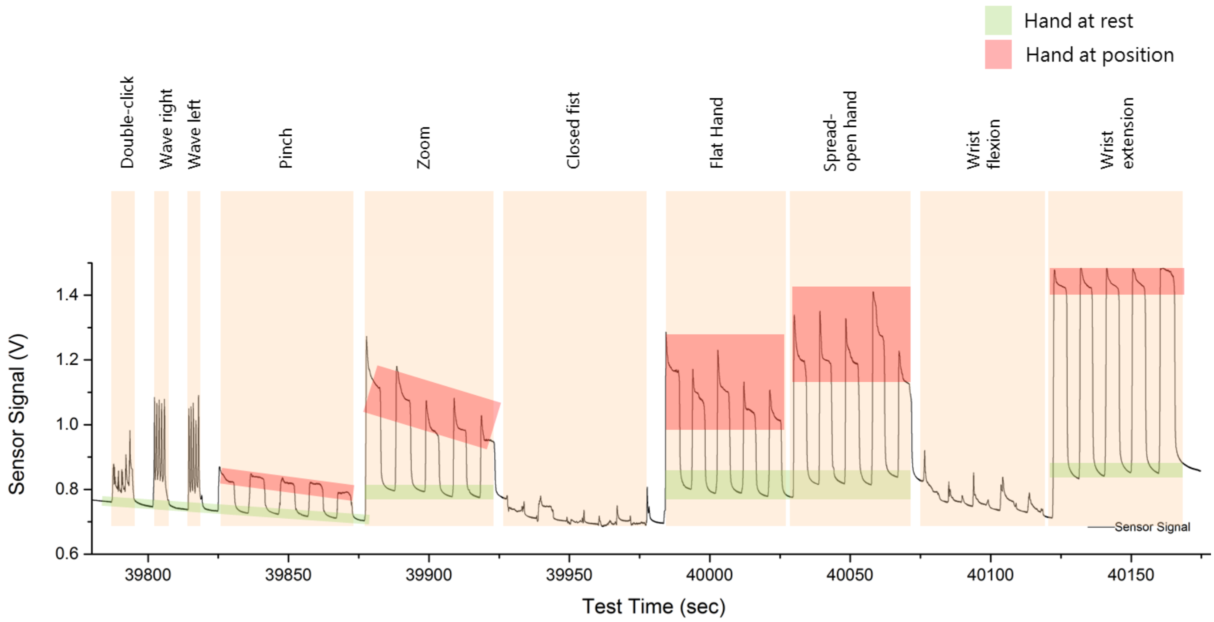

Figure 2. Sensor performance for the NUI gesture test sequence

5. Evaluation for the use of Pulse-Wave Monitoring

The pulse wave of the blood was detected at the three positions around the wrist. During the test, the subject sat in a chair with his hand on a table in front of him, the angle of his arm approximately 90° and in a relaxed state. The band sensor was secured around the wrist of the test subject so that it was tensioned but comfortable to wear. Data was acquired from the sensor for5 min at each of the three sensor positions (P1, P2, and P3). Given the position of the sensor with respect to the location of the ulnar and radial artery, it was expected that the posterior position (P3) would have the highest pulse wave signal. Figure 3 displays the raw data, which depicts the pulse wave of the test subject from

Position 3, which produced the best monitoring result where the peaks were discernable. In analyzing the waveform, the peaks and troughs were visually chosen, and then the Beats-Per-Minute (BPM) were calculated for the peak-to-peak and trough-to-trough data pairs. The average was taken for peak-to-peak and trough-to-trough data sets, and then the average of those final values was taken, resulting in a BPM of 60. This value was consistent for that test subject. Previous results of pulse-wave detection were done with the textile band sensor in previous work [2].

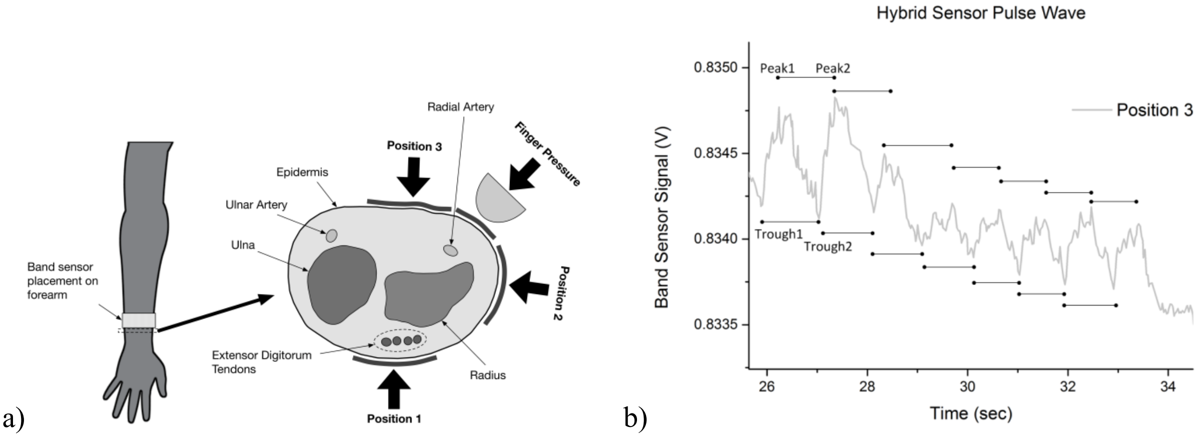

Figure 3. Positioning of the sensor on the wrist (a) and the pulse-wave raw data from Position 3 (b)

6. Evaluation for the use of Breathing Monitoring

As a first validation of the band sensor to the case of breath monitoring, a prototype chest band was developed using the textile band sensor configuration, with the SCMS material glued to an elastic textile substrate [2]. The textile sensor band was placed the band sensor near the abdomen of a patient, and then different breathing patterns were performed by the test subject, and the data analyzed. The data was collected through a smartwatch prototype, which included an accelerometer as well as two pressure sensors, which monitored the contact pressure. Therefore, the difference between the relative sensor values of the band sensor and the on-board accelerometer and pressure sensors could be compared against one another to gauge the difference in sensitivity of the different sensor types to measure breathing patterns.

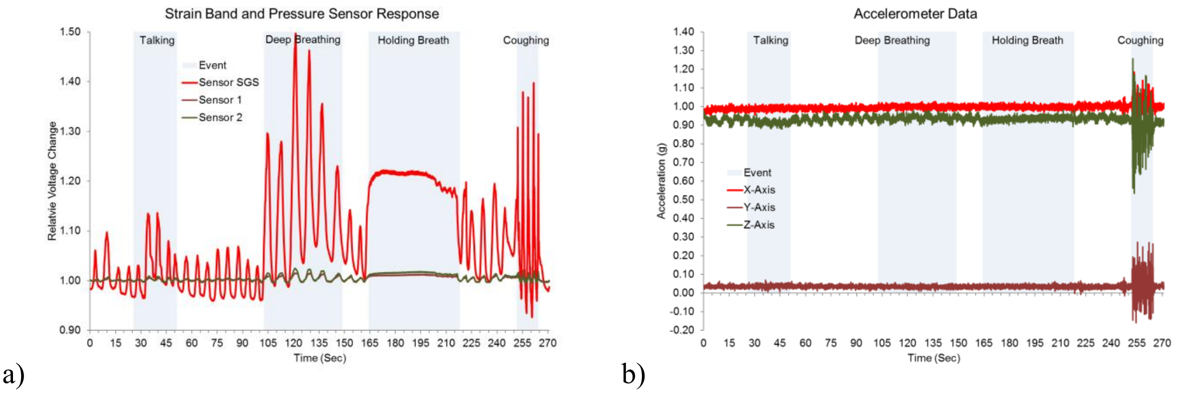

Figure 4. Sensor response for the band sensor (SGS) and pressure sensors (a), associated acceleration data (b)

The band sensor showed the highest relative signal change of the different sensors as shown in a, with the pressure sensors (a) providing better sensitivity than the accelerometer (b). Differentiation can be easily seen between normal breathing, deep breathing, coughing, and breath holding. Differentiation since the SCMS enables continuous monitoring of the strain state, it would be feasible to discern

IOP Conf. Series: Materials Science and Engineering **175** (2017) 012006 doi:10.1088/1757-899X/175/1/012006

between breathing states based on the amplitude along with frequency, in order to determine the relative change in frequency and breath deepness or coughing intensity and classify the different types.

7. Conclusions
The integration of a CB/TPE sensor in to a hybrid structure of 3D printed TPE and casted silicone showed the ability to fulfill different body-mounted sensor application concepts, including gesture recognition, pulse-wave monitoring, and breathing monitoring.Although the SCMS showed good performance in a controlled state, future applications would require evaluation during normal movement of a person, where motion artifacts may corrupt the desired vital monitoring signal (motion, breathing, hear rate).

References
[1] Melnykowycz M, Koll B, Scharf D, Clemens F. Comparison of Piezoresistive Monofilament Polymer Sensors. Sensors 2014, 14, 1278-1294.
[2] Melnykowycz M, Tschudin M, Clemens F. Piezoresistive Soft Condensed Matter Sensor for Body-Mounted Vital Function Applications. Sensors. 2016, 16, 326.
[3] Almgren A F. An isotropic three-dimensional structure with Poisson's ratio =−1. J. Elast.1985, 15, 427–30.