A Design-Led, Materials Based Approach to Human Centered Applications Using Modified Dielectric Electroactive Polymer Sensors

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Abstract. This paper describes a design-led exploratory scoping study into the potential use of an industry standard dielectric electroactive polymer (DEAP) sensor for applications in assistive healthcare. The focus of this activity was to explore the physical format and integration of soft materials and sensor combinations with properties that afford an opportunity for accurate and unobtrusive real time body mapping and monitoring. The work involved a series of practical investigations into the capacitance changes in the sensor brought on by deformation through different ways of stretching. The dielectric sensors were selected as a direct mapping tool against the body based on the similarity of the stretch qualities of both the sensor and human skin and muscle resulting in a prototype vest for real time breathing monitoring through sensing thoracic movement. This involved modification of the standard sensors and handcrafting bespoke sensors to map critically relevant areas of the thorax.

Keywords: Dielectric electroactive polymers · Breathing monitoring · Handcrafted sensors · Stretchable electronics

1 Introduction

This paper describes a 10-week exploratory study carried out by our design-led interdisciplinary research group that explores future ways of living through materials and technology interrogation to determine and demonstrate innovative interventions that resonate with the way we experience our material world [1]. We recognise that the products of tomorrow have to 'do more with less' in order to attempt to meet the societal challenges of the 21st century. A significant domain for smarter products is within assistive healthcare [2–4]. Products that incorporate sensors and sensing are increasing and have a pivotal role in assistive healthcare and personalized monitoring [5]. However, sensors, actuators and other electronic components are frequently made of rigid and stiff materials that limit their incorporation into products and the type of product that they can be used for. Much work has been done in the area of smart textiles, integrated sensors and wearable computing [6–10]. In recent years however, two major

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developments are changing the form and function of sensors and their incorporation into wearable or on-body solutions. These are conductive polymers (high electron mobility) that can be solution processed and hence form the basis for printable sensor fabrication via ink jet and screen printing technology [11, 12]. The other is stretchable electronics which are light, flexible and can withstand robust handling [13–15]. Of particular interest is the class of stretchable electronics based on electro-active or electro-responsive polymers (EAP's). These form a family of useful sensor materials as follows:

EAP's

Ionic	Electronic	Piezo	Other stimuli
° Ionic polymer metal composites ° Carbon nanotubes ° Ionic polymer gels	° Piezo electric polymers ° Electro- strictive polymers ° Liquid Xtal elastomers ° Ferroelectric polymers ° Dielectric electro active polymers (DEAP)	° Piezoelectric ceramics ° Piezoelectric inorganic composites ° Electro rheological fluids	° Shape memory alloys ° Shape memory polymers ° Magneto- strictive Xtals

Of these, we have chosen to examine dielectric electro active polymers (DEAP) in some detail because they offer a large degree of freedom in terms of their strain behaviour under an applied electric field [4–8].

The DEAP basic structure is made up of a film of a dielectric elastomer material that is coated on both sides by another expandable film of a conducting electrode. When voltage is applied to the two electrodes a Maxwell pressure is created upon the dielectric layer. The elastic dielectric polymer acts as an incompressible fluid which means that the electrode pressure comes the dielectric film to become thinner in the 2 directions and expansive in the planar directions (x,y). When this occurs, the electric force field is converted to mechanical actuation and motion.

We explored the DEAP sensors developed by the Danfoss company in Denmark which have the added benefit of specific electrode shape and topology which gives use to an accentuated movement in either the x or y direction with the other constrained to the mechanical structure of the assembly [5].

DEAP are intrinsically position or strain sensors. DEAP sensors have certain advantages even when an actuation function is not included. The large strain characteristics and environmental tolerance of DEAP materials allow for sensors that are simple and robust. In sensor mode, it is often not important to maximise energy density since relatively small amounts of energy are converted. Thus the selection of DEAP materials can be based on criteria such as biocompatibility, maximum strain, environmental robustness and cost.

Sensor Form Factors: Thin tubes, filaments, flat strips and ribbons, arrays of diaphragms or large area sheets are all possible. In filament or ribbon formats, DEAP sensors can be woven and integrated into textiles and provide positive feedback for human movement. The softness and compliance of DEAP sensors is ideal for interaction with the human body therefore [6]. DEAP sensors can also be integrated into flexible structures and surfaces to provide position and eventually volumetric information for multifunctional 'smart' products. It is these particular properties that make DEAP systems ideal for real time analysis of physical functions that are discrete and generally unobtrusive. In addition, the sensor could be flexed or stretched many times with no loss of reproducibility. Under these conditions the DEAP sensors could be used to measure sensitive movements of the human body. In our case, monitoring breathing through measuring thoracic activity allowed lung capacity to be described under different physical states of exertion.

As will be demonstrated later, the response of the particular DEAP materials used were highly linear and so allowed us to work at strain behaviour (in the form of a capacitance output signal that allowed us to infer a linear displacement) for the range $L(x) + 0.1L(x)$ to $L(x) + 0.9\,L(x)$.

Below, how we used the sensors and the outputs are described in more detail.

2 Materials and Methods

Our scoping activity involved a series of practical investigations into the capacitance changes in the sensor brought on by deformation through different ways of stretching. An understanding of the construction of the sensor was gained through a site visit to the industrial partner's lab and also by the deconstruction of the industrial sensors and handcrafting our own versions in our studio-lab. Sensor readings were taken under a range of temperatures in order to determine if external parameters such as ambient temperature would affect performance. None was found. The stretch capability of the sensor is up to 100 % and enables a sliding scale between 'on' and 'off' and scope for nuanced effects. The sensor has good stretch compatibility and affinity with human movement. From this start point of ideas generation one embryonic demonstrator was selected. The purpose of the demonstrator was to create a probe for further investigation and development rather than demonstrate a resolved design prototype.

2.1 Demonstrator: Thoracic Motion and Volume Sensor for Respiratory Monitoring

The aim of the demonstrator was to align the DEAP sensors to the outside of the body to tell us what is going on inside the body. Both Lycra and the stretch sensors have ideal softness and compliance for interaction with the human body [8]. The sensors behave as variable capacitors and to measure their capacitance at any given time, and under any given load, a number of methods were used. To get usable readings from the sensors, custom circuitry and software was produced to measure and interpret the data. The range of the sensors is typically between 100e-12 F to 100e-9 F; therefore a capacitance meter able to measure down to 90pF was required. Firstly we tested a UNI-T desktop multimeter, secondly a self-solder capacitance measuring printed circuit board from Sparkfun Electronics and thirdly an ATMega328pu microprocessor in the form of an arduino uno board. This board was used, with the addition of an external resistor and capacitor of known values, to create a basic RC circuit with a low pass filter. Using this circuit, and the following equation;

$$c = \frac{1}{\sqrt{2\pi f}} \cdot \frac{1}{\left(\sqrt{\left[\left(\frac{V_i}{V_o}\right) - 1\right]}\right)^{0.5}}.$$

C = capacitance (Farads), f = frequency (Hz), Vi = voltage in, Vo = voltage out (Volts)

it was possible to derive the capacitance of the sensor accurately. It is important to note here that the capacitance of the sensor was being inferred rather than directly measured. The values actually being received from the sensor into the arduino were changes in voltage. These voltage changes were then used to calculate the capacitance. As a result, there maybe minor inaccuracies due to measurement error in terms of the minimum values able to be detected, but these were shown to be small enough as to be negligible in relation to the calculated readings. For each of the tests performed, it was shown that the DEAP sensor had a linear response. The third method for data collection proved to be most successful for gathering real time results in large numbers, and had the additional benefit of the information being able to be instantly plotted on a line graph.

2.2 Integrating the Sensors with the Vest

The areas of the thorax where the biggest movement occurs during respiration were mapped out together with essential anchor points of least or no movement by drawing directly onto a model wearing a pre-made white Lycra vest. The positioning of the sensor ribbons was chosen to correlate with specific areas of movement during respiration. Shorter sensors are used to read the smaller movements of the inspiratory and expiratory muscles while the longer sensor ribbons are used to measure the overall movement of the thorax. To enable individual readings from each sensor ribbon an anchoring system was developed to stabilise the end points and isolate the deformation. The specific length required for each sensor necessitated a bespoke, made to fit sensor for each measuring area, the design of which enabled the sensor ribbons to be slightly under strain when placed on the vest, allowing the sensor to work at maximum efficiency (see Fig. 1). The positioning of the sensor ribbons for the initial testing are Shoulder Sensor, 1, Upper Chest Sensor, 2, Lower Chest Sensor, 3 and Lower Rib Sensor 4 (see Fig. 2).

2.3 Construction of the Vest

We used a medium weight 2 way stretch Lycra, allowing a skintight cover of the body while enabling the integration of the sensor ribbon without hindering or altering the movement of the thorax and the sensor. Lycra also has good stretch and recovery

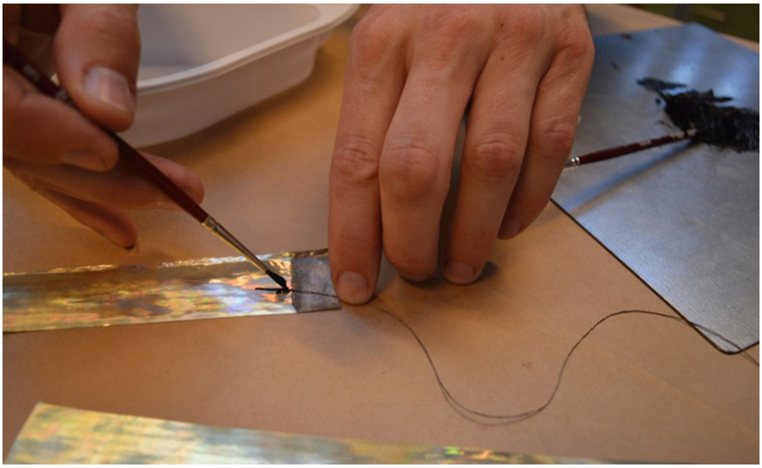

Fig. 1. Handcrafting bespoke sensors

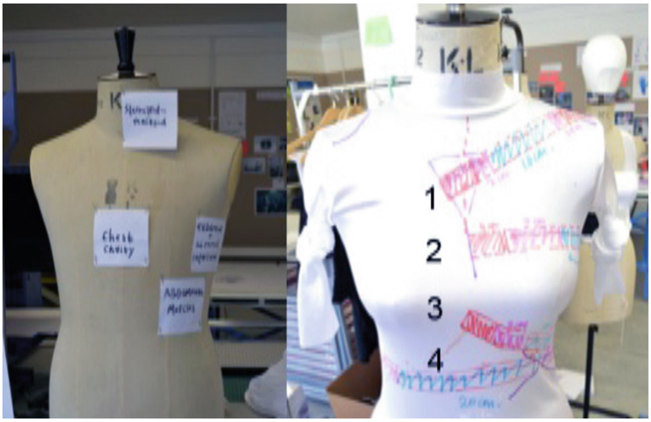

Fig. 2. Positioning the sensors

properties [7]. Velcro was used to attach the sensors to the vest. The loop side of the Velcro is sewn with a zig-zag stitch onto the anchor areas and retains a slight movement in the Lycra without the thread breaking. The hook side of the Velcro is embedded into the sensor ribbon by firstly sewing Zeelon, a heavy weight nonwoven, onto the base of the hook side of the Velcro with a zig-zag stitch. The new base is then thinly coated with T13 silicone. When dried the nonwoven Velcro base and the nonwoven silicone encased sensor ribbon base are thinly coated with Wacker E 43 silicone. The two are then sandwiched together to create a secure joining. Due to the nature of the sensor, using Lycra for the vest and using Velcro for integration there is room for flexibility in placement. This allows the vest to be worn by different users of varying sizes.

2.4 Data Collection

The vest is worn by the wearer. One at a time each sensor ribbon is placed on its set anchor points, secured and connected to the laptop. Once the wearer is connected a live reading is taken (see Fig. 3). The wearer is asked to undertake a number of tasks, such as shallow breathing, deep breathing, normal breathing, inhale and hold, exhale and hold, swallowing and chewing to stimulate different breathing patterns.The wearer is asked to perform each task twice, resting for 1 minute between each task to regulate breathing. Every task is video recorded and the live graph readings are video recorded with sound. The sensor ribbon is removed. The same sequence of tasks is then repeated for each sensor ribbon on its set position and recordings taken (see Figs. 4 and 5). An arduino pro mini was used due to its reduced size, however the ATMega processor and external components remained the same as the third method for data collection.

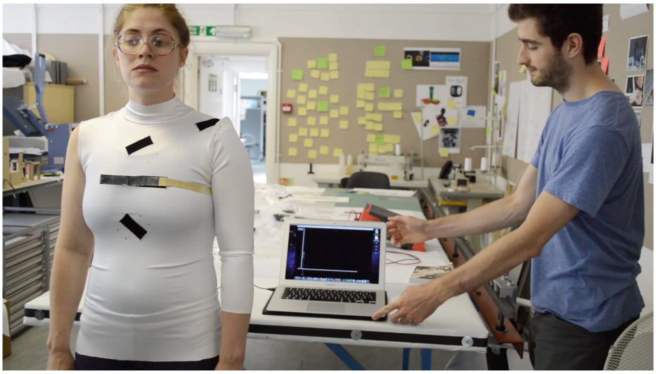

Fig. 3. Taking live readings

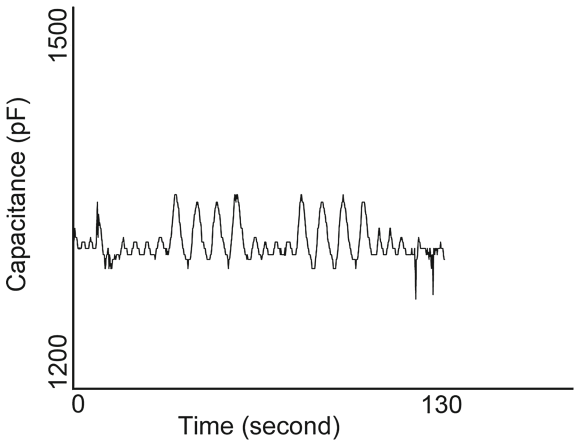

Fig. 4. Deep breathing using lower rib sensor

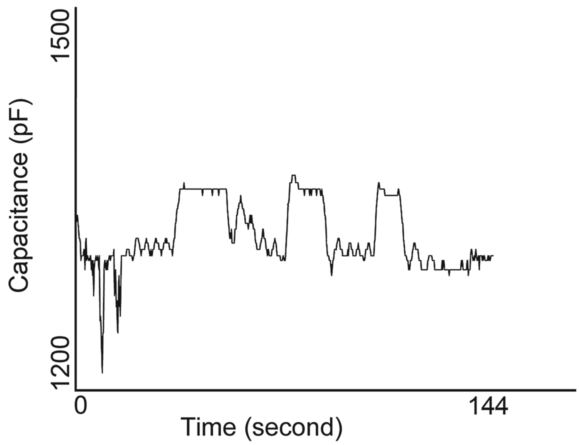

Fig. 5. Inhale and hold using lower rib sensor

3 Findings

The embryonic prototype demonstrates that there is significant scope for DEAP technology in human centered design applications for assistive healthcare and could support a sensing platform. Materiality and physical forms require careful consideration when designing products for on-body and real time monitoring. Devices and systems need to be as unobtrusive as possible. Materials that are soft, stretchable and conformable such as elastomers offer promising opportunities for accurate and unobtrusive body mapping in real time. We demonstrate the use of elastomeric sensors as a valuable tool for dynamically mapping the physical self. The thoracic sensor vest is an example of an intuitive, unconsciously interactive mapping tool aligned to the outside of the body to tell us what is going on inside the body. For expediency and deadline constraints we used a physical connection between the sensor and the computer, but envisage a wireless connection. We recorded markedly different patterns for each of the different breathing movements, two of which are shown, (see Figs. 4 and 5) and suggests that with further work, particularly on the cross correlating the breathing movements data with volume change data, the stretch sensors could potentially be used for sensitive measuring of volume changes within the lung and that would allow an understanding of both the breathing rate and the capacity simultaneously and unobtrusively in real time.

4 Conclusion

We consider the sensor vest to have potential for a sensitive and accurate breathing monitor, subject to further tests, data collection and correlation. The development of wearable or on-body assistive healthcare devices necessitates the convergence of both digital and physical platforms. However, materials are invested with social and cultural values that supersede their functional physical properties and we must explore and understand these relationships in order to design assistive healthcare devices and systems successfully and meaningfully [8]. Physical materials are being re-imagined as substrates invested with computational properties [9]. So-called transitive materials have been identified as revoking the gap between artefact and gadget [10]. It is essential that these functional and transitive materials that can span digital and physical platforms be exposed to practical design interrogation in order to develop their cultural currency [11]. Among these is the relationship of analogue values on a digital platform that can go beyond the now conventional motor parameters of the digit to larger scale interactive devices activated by limbs and/or whole bodies. Through this short scoping study we would envisage developing a range of product ideas for educational and rehabilitation uses, possibly for multi sensory environments and people with learning difficulties or neuro-disabilities, that could exploit the idea of using different parts of the body and different motor skills to activate and control responses through a stretchable electronics platform.

The scope to alter both the sensor's physical dimensions and encapsulant are important opportunities for design intervention and offer possibilities for large scale ambient sensing [12], bi-directional stretch sensing and alternative encapsulants for engineered responses such as embedded materials for controlled release, modification of the encapsulant to swell in the presence of specific stimuli, e.g., changes in pH and embedding chromics within the encapsulant for real time visual indicators.

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