RELIABILITY OF A NOVEL PRINTED PIEZORESISTIVE PRESSURE SENSOR

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Printed pressure sensors have the potential to be useful for measuring pressure in a multitude of sports biomechanics applications. This study was a proof of concept of a novel printed piezoresistive pressure sensor array with the aim of assessing the reliability of the sensor. The relationship between the force applied to the sensor and resistance was well described by an exponential equation ($r^2 > 0.962$), which provides confidence in the piezoresistive nature of the response. This demonstrates that, with further refinement and development, the currently-designed pressure sensor array has the potential to measure pressure during field-based sporting movements. Further research and development are required to improve reliability and to test sensor performance under dynamic loading conditions similar to those typically experienced in sport.

KEYWORDS: graphene, pressure measurement, printed electronics, test-retest reliability, wearable technology.

INTRODUCTION: Pressure sensors have various applications in sports biomechanics which include measuring foot plantar pressures during sporting movements, and pressure at contact points between athletes and their equipment. The majority of the pressure measurement devices currently on the market measure foot plantar pressures using either a pressure mat, walkway, or insoles based on capacitive, piezoelectric or resistive sensor technology (De Pasquale & Ruggeri, 2019). Researchers have recently developed printed pressure sensors which change electrical resistance in response to applied pressure and have several potential advantages for bespoke sporting applications - they are thin and flexible, can be printed to different shapes, sizes and cell resolutions, the piezoresistive range can be tuned by changing the number of printed layers, and they also have the potential to be cheap to manufacture (Mouhamad et al., 2016; Webb et al., 2013).

It is important to ensure that the pressure sensors are accurate and reliable for the loading rate, range and duration of the intended application (Urry, 1999). The current study was a proof of concept of a novel printed piezoresistive pressure sensor array based on the piezoresistive pressure sensor design described in Mouhamad et al. (2016). The aim was to quantify the within- and between-days reliability of the applied force-resistance response of individual cells within the pressure sensor array and to also quantify the between-cells reliability of the applied force-resistance response.

METHODS: The pressure sensor (160 x 300 mm) contained 32 cells in a four by eight array: eight large cells (59.5 x 39.5 mm) in the two central rows and 24 small cells (29.5 x 39.5 mm) in the other six rows. The sensor array was manufactured using two perpendicular conductive silver screen prints, overprinted with piezoresistive carbon ink, which were laser cut and assembled to form the pressure sensor array. All screen printing was performed on a DEK 248 screen printer and prints were dried using a convection oven set at 80˚C.

The testing protocol for the individual cells in the pressure sensor array consisted of:
1. Applying 20 compression loading and unloading cycles between 100 N to 3000 N to one large and one small cell within the pressure sensor array.
2. Applying five compression loading and unloading cycles between 100 N to 3000 N to all individual cells within the pressure sensor array. Repeated seven days later.

The above compression loading and unloading cycles were applied using a Hounsfield testing machine (H10KS, Tinius Olsen Ltd, Salfords, UK). The loading rate of the applied force was 0.5 mm/min (approximately 65 N/s). Stainless steel blocks 10 mm thick, which matched the dimensions of the pressure sensor cells were placed on top of the cell being tested to ensure

only the individual cell of interest was loaded. The resistance of the cell was monitored using a digital multimeter (HMC 8012, Rohde & Schwarz, Fleet, UK). Miniature crocodile clips attached to cables from the multimeter were connected to the silver conductive paths linked to the individual cell. The testing equipment was operated using a custom programme written in LabVIEW software (2014, National Instruments, Austin, USA) which controlled the loading rate and number of loading and unloading cycles applied. The programme also synchronised the force data from the Hounsfield testing machine with the resistance data from the multimeter, sampling data at 3.9 Hz.

Data were analysed using a custom Matlab script (2018a, MathWorks, Cambridge, UK). Each trial was split into individual loading and unloading cycles which were resampled (spline interpolation) to 146 data points per loading/unloading cycle (force resampled at 20 N intervals). The resistance at each force was averaged over all cycles for a trial (excluding the first two cycles where plastic deformation of the substrate was assumed to take place) to obtain mean values for each cell for each trial. Owing to technical problems with the data for 4 small cells, the daily small cells average was calculated from 20 instead of 24 cells.

A two-term exponential was fitted to the mean force-resistance data for a large and small single cell loaded and unloaded 20 times to calculate the coefficients in the equation:

$R = ae^{bF} + ce^{dF}$, where R = resistance, F = applied force, and a, b, c and d are the coefficients. The goodness of fit was quantified using the coefficient of determination (r^2).The hysteresis between loading and unloading cycles for the large and small single cells were calculated by finding the difference in the resistance between each loading and unloading cycle (20 cycles in total) at an applied force of 1500 N. This value was then divided by the mean resistance at 1500 N for all loading and unloading of all cycles in the trial for the cell. The standard error of measurement (SEM) was calculated for the force-resistance curves to quantify the between-days reliability of the pressure sensor cells using the methods described in Pini, Markström, and Schelin (2019).

RESULTS: When a single large and small cell were loaded and unloaded 20 times within a single trial, for applied forces greater than 500 N there was a consistent reduction in resistance with each loading and unloading cycle (Figure 1).The variations in the resistance at applied forces below 500 N for each subsequent loading and unloading cycle were more random (Figure 1).There was an approximate exponential relationship between applied force and resistance. When exponential equations were fitted to the mean loading and unloading force-resistance curves for the large and small cells there were high values of r^2 (> 0.962) indicating the models were a good fit to the data (Figure 1). The large and small cells demonstrated hysteresis of 7% and 3.5%, respectively, for the trials presented in Figure 1.
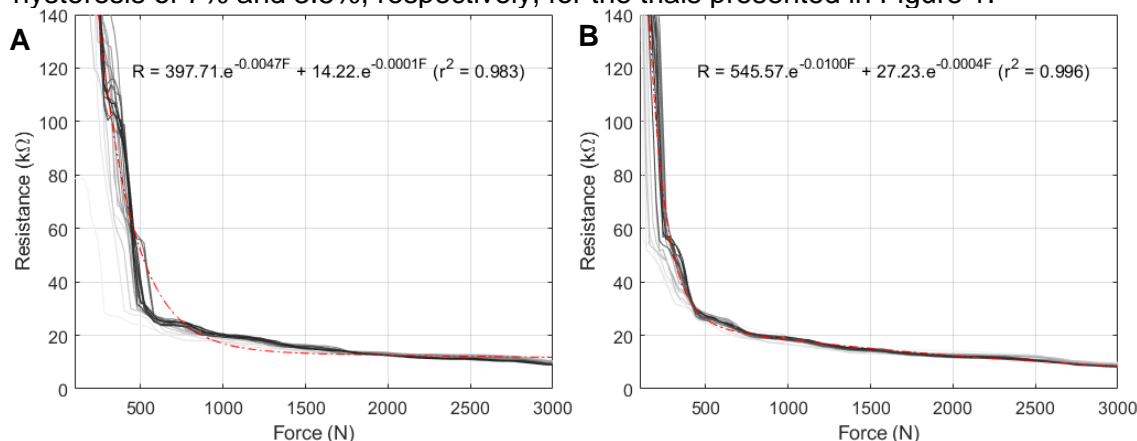

Figure 1: Large cell: 20 loading (A) and unloading (B) cycles between 100 and 3000 N. Lightest shade of grey indicates first loading cycle through to darkest shade of grey indicating final loading cycle. Dashed red line indicates fitted exponential equation to data, R = resistance, F = force, and r^2 = coefficient of determination. Presented data for large cells only as the small cells demonstrated similar behaviour. r^2 = 0.962 and 0.978 for the exponential equation fitted to loading and unloading curves for the small cells, respectively.

The between-days reliability of the applied force-resistance response for the loading and unloading cycles were poor for applied forces below 1000 N, which was demonstrated by the large SEM in this region of the force–resistance curve (Figure 2). At higher applied forces the SEM reduced (approximately 30% and 45% of mean resistance for the large and small cells respectively, compared to 80% at applied forces below 200 N, Figure 2).
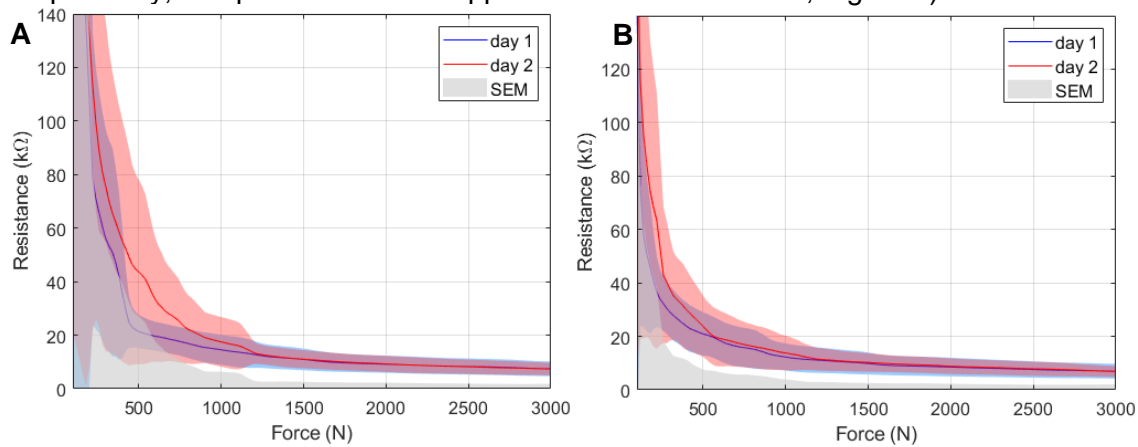

Figure 2: Large cell loading (A) and unloading (B) cycles between 100 and 3000 N: group means for day one and two. SEM = standard error of measurement between these two days. Presented data for large cells only as the small cells demonstrated similar behaviour.

There was high between-cells variability in the force-resistance curves, which was demonstrated by the wide standard deviation of the force-resistance curves for the large and small cells for a given day (Figure 2). When the behaviour of the large and small cells was compared to each other by plotting pressure-resistance curves to account for difference in area of the cells, there also appeared to be an influence of cell area on the resistance of the sensor for a given applied pressure (Figure 3).
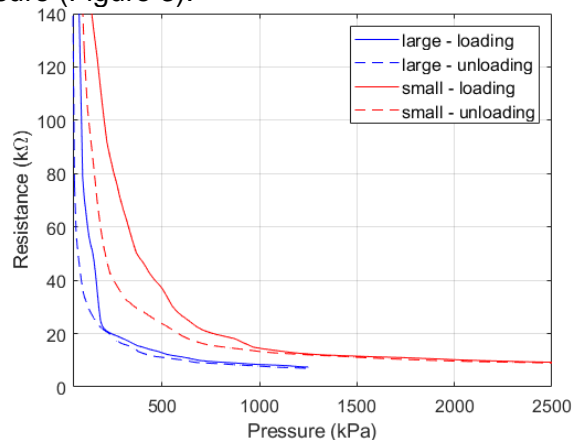

Figure 3: Comparison of large and small cells for loading and unloading cycles between 100 and 3000 N: group means for day one.

DISCUSSION: This study investigated the reliability of a printed piezoresistive pressure sensor array. The large and small individual cells demonstrated a reasonably repeatable applied force-resistance response for multiple loading and unloading cycles within a trial (hysteresis ≤ 7%). The relationship between the force applied to the cell and resistance was well described by an exponential equation, which provides confidence in the piezoresistive nature of the response. This demonstrates that, with further refinement and development which are discussed below, the currently-designed pressure sensor array has the potential to offer a solution for the measurement of pressure in the field, as the resistance of the pressure sensor cell could be measured and then converted to applied pressure using an exponential equation. The between-days reliability of the applied force-resistance response of the large and the small cells was poor for applied forces below 1000 N. One of the possible sources of this low

between-days reliability could be measurement error owing to how the chosen digital multimeter measures resistance. The digital multimeter contains a series of resistors with different capacities, and choses the appropriate resistor based on the resistance measured. When the multimeter switches between the 400 kΩ to 40 kΩ resistor, this is associated with a sudden reduction in resistance with applied force (this typically occurs around an applied force of 500 N). This behaviour is therefore likely a property of the measurement technique and not the sensor itself. Therefore, other methods to measure resistance should be adopted when assessing the reliability of the measured resistance of future iterations of the sensor. A further possible solution to improve the reliability at applied forces below 1000 N is to reformulate the ink so it is more conductive (i.e. reducing the resistance of the sensor), making it more sensitive at lower applied forces. This is important when measuring pressure in sports biomechanics applications, as typically pressures during sporting movement range from 15 to 1000 kPa (Urry, 1999, 15 kPa is equivalent to applied forces of 18 N for the small cell).

The high between-cells variability in force-resistance curves would mean that an equation relating force and resistance would ideally be calculated for each individual cell, and therefore each cell within the pressure sensor array would have to be calibrated individually. Further development of the ink formulation and printing techniques could also be undertaken to increase the consistency of the printed piezoresistive ink across the array to reduce the between-cell variability in applied force-resistance behaviour. The fact that there also appears to be an influence of cell area on the resistance measured for a given applied pressure also requires further investigation as future iterations are developed.

At higher applied forces the pressure sensor begins to reach saturation (i.e. the resistance of the sensor remains relatively constant with increasing applied force). Similar behaviour was demonstrated for the piezoresistive ink developed by Mouhamad et al. (2016). However, in sports biomechanics applications it is unlikely pressures will exceed 1000 kPa (equates to forces of 2400 N and 1200 N for the large and small cells respectively) (Urry, 1999).

Future research should include testing the pressure sensor at applied forces below 100 N and during dynamic loading at a higher rate of force development (Urry, 1999) to ensure the pressure sensor is suitable for a wide variety of sports biomechanics applications.

CONCLUSION: This proof of concept study demonstrated the potential of a printed piezoresistive sensor array for measuring pressure. The sensor demonstrated a decaying exponential relationship between applied force and resistance, which was well described by a two-term exponential equation. Further research and development are required to improve the reliability of the sensor and to test sensor performance under more dynamic loading conditions typically experienced in sports.

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