Integration of capillaric strain sensors towards digital recognition of human movements

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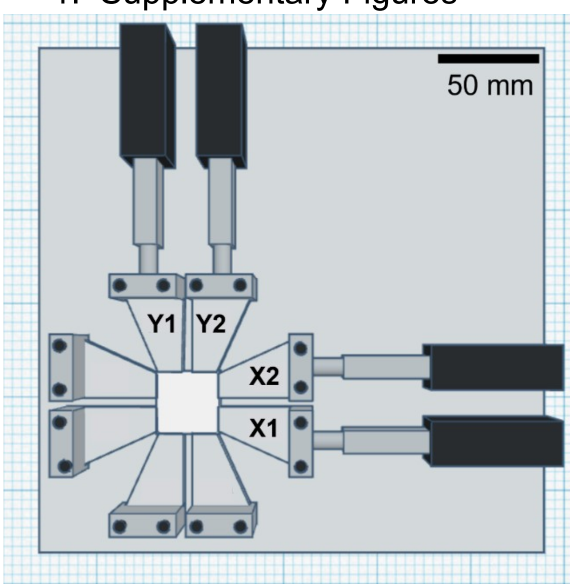
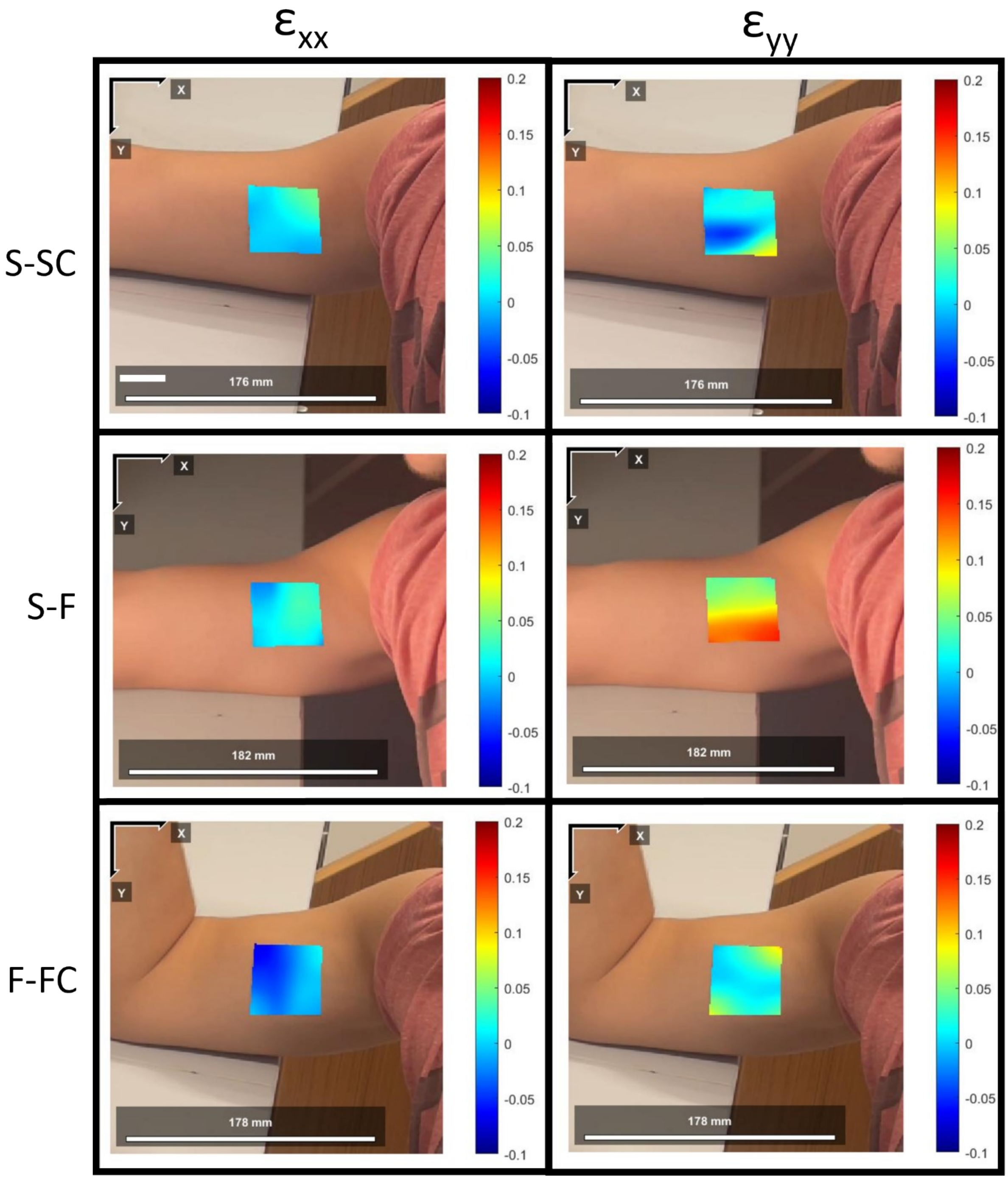
Keywords: *Wearables; Skin-strain-field; Capillarics; Digital Image Correlation; Human movement recognition*

Supplementary Information

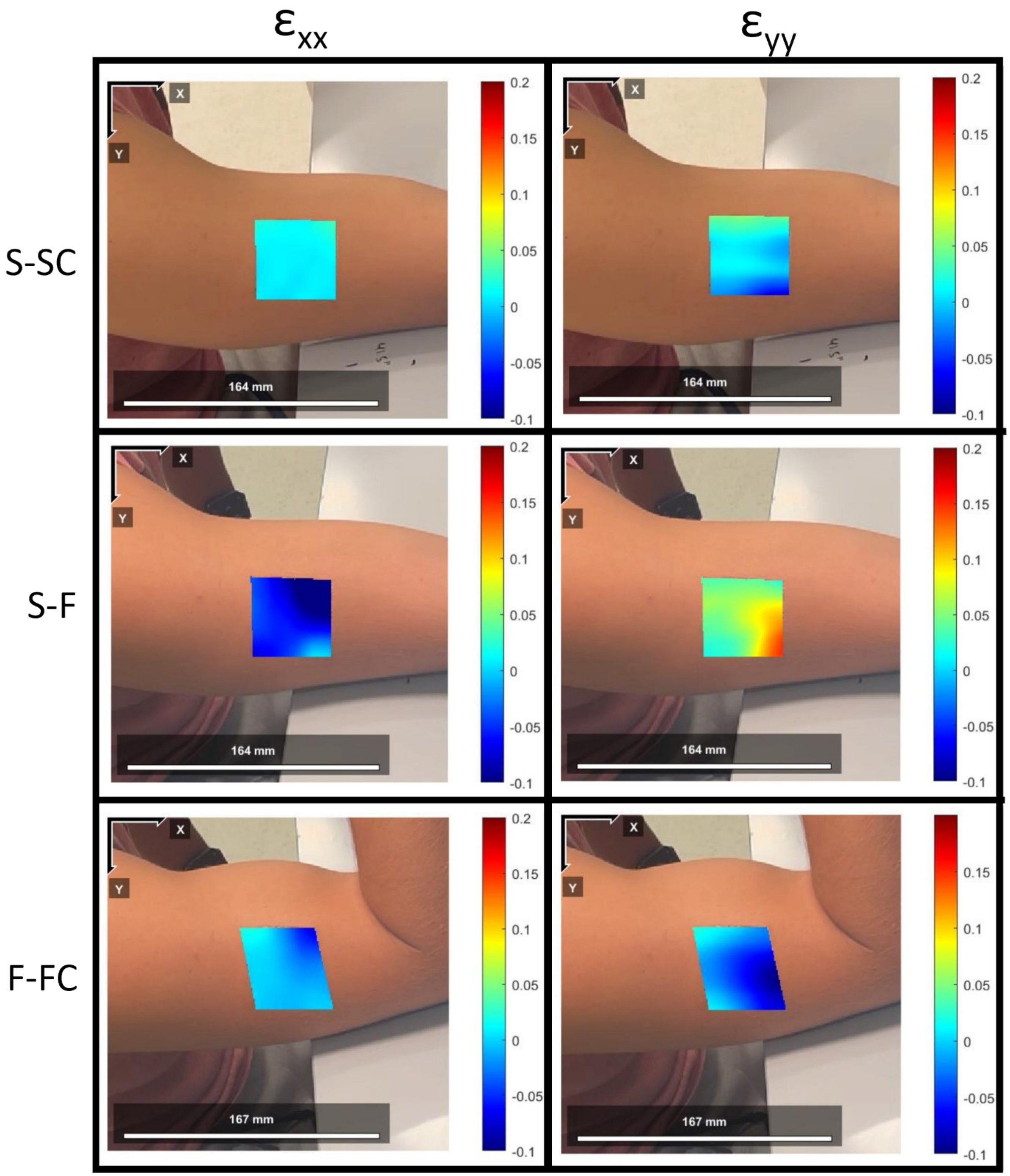
1. Supplementary Figures



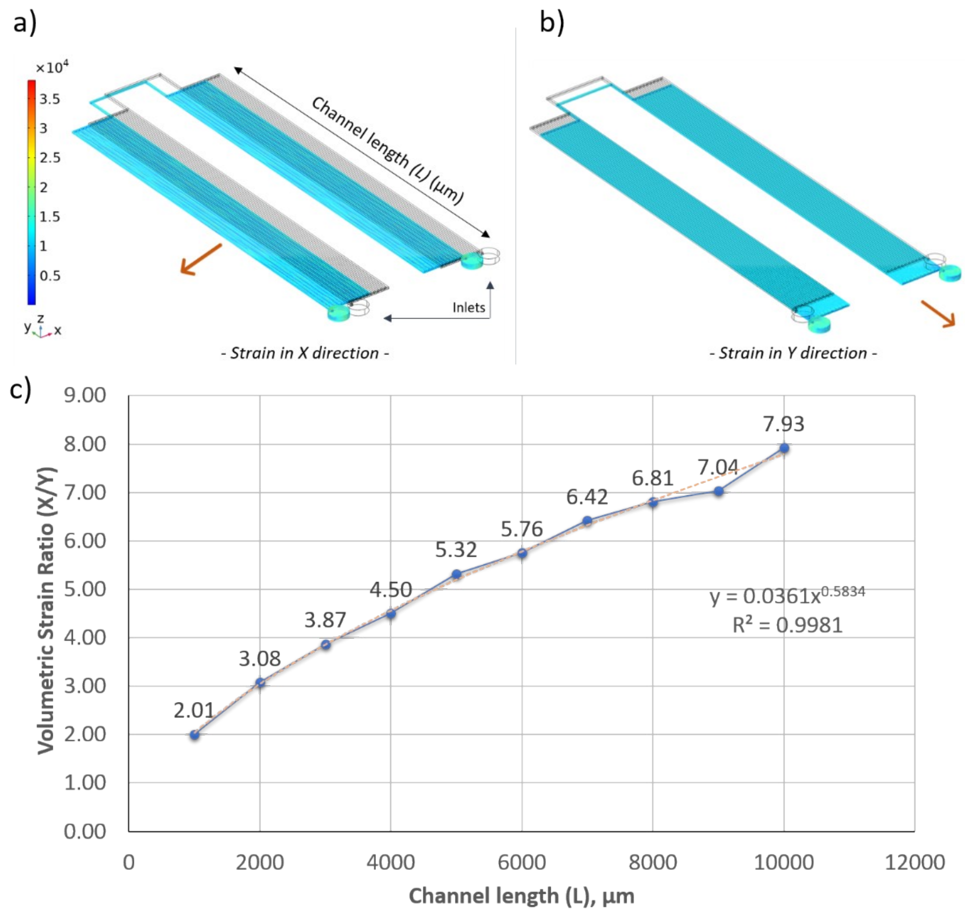
Suppl. Figure 1 Schematic of the Strain Field Generator (SFG) that is used as the mechanical test module. The device was fabricated for testing the sensors under prescribed strain generated from four actuators. To apply the strain to the sensor, a PDMS base was fabricated and clamped to the SFG. The SFG is comprised of a 250 x 250 mm aluminum plate, four Actuonix linear actuators, 8 clamps (four of them fixed, four of them attached to the arm of the actuators), and a 40 x 40 mm PTFE block was used to provide support under the sensor location and to provide contrast for the DIC speckle pattern.



Suppl. Figure 2 ε_{xx} and ε_{yy} strain field Images of the inner upper arm during the three different movements: straight-armed bicep contractions, arm flexion at the elbow, and arm flexion at the elbow with bicep contraction. The strain field exhibits positive values in the y-direction (tension) and small positive values in the x-direction on the right side of the sample during flexion and flexion plus contraction. Here the strain field during flexion plus contraction with respect to straight position can be calculated by adding S-F and F-FC strain fields together.



Suppl. Figure 3 ε_{xx} and ε_{yy} strain field Images of the outer upper arm during the three different movements: straight armed bicep contractions, arm flexion at the elbow, and arm flexion at the elbow with bicep contraction. The strain profile exhibits positive values (i.e., tension) in the y-direction and negative values (i.e., compression) in the x-direction, for flexion and flexion plus contraction) indicating a more uniaxial profile.



Suppl. Figure 4 COMSOL Multiphysics is used to model the capillaric strain sensor using the Solid Mechanics Module. A square frame with dimensions of 50 x 50 mm^2 in area and 1130 μm in thickness is defined from a PDMS material, which has a density of 1000 kg/m^3, Young's modulus of 1 MPa, and Poisson's ratio of 0.49. Inside the square of PDMS, fluid channels with a height of 50 μm are established, and the solid material inside the channels are defined with a Young's modulus of 1 μPa, and a Poisson's ratio of 0.49 to represent a liquid filled channel. Identical to the experimental case, a 50 μm wide sensing channel connects two blocks of fluidic channels, each consisting of 12 channels and one inlet. With a magnitude of 1 mm in each direction, a prescribed displacement in X and Y is applied. On the boundaries that run opposite to those set for a prescribed displacement, fixed constraints are defined. The volumetric strain readings of the capillaric strain sensor are recorded for the X and Y directions, using a stationary study and a fine mesh with physics-controlled mesh element size. The volumetric strain values in the X direction are divided into volumetric strain values in the Y direction (X/Y) to determine the volumetric strain ratio that indicates the directionality in this study. The 3D schematic of the COMSOL model deformation and its Von Mises stress color map under strain a) in X direction and b) in Y direction. c) The directionality with respect to the channel length.

2. Supplementary Analysis

2.1. Theoretical gauge factor calculations for orthogonal and parallel direction

The measured gauge factor is used to find the theoretical individual contributions of the orthogonal and parallel strain components, $GF'_{\perp}, GF'_{\parallel}$, respectively. As shown in Fig. 1, a single liquid reservoir under uniform uniaxial strain has two measured GF values in two different applied strain directions as,

$$GF^{Measured}_{\perp} = \frac{\frac{\Delta R_{\perp}}{R}}{\varepsilon^{applied}_{\perp}} = \frac{74}{2} \qquad Eq.1$$

$$GF^{Measured}_{\parallel} = \frac{\frac{\Delta R_{\parallel}}{R}}{\varepsilon^{applied}_{\parallel}} = \frac{26}{2} \# Eq.\,2$$

Here $\Delta R_{\perp,\parallel}$ is the measured resistance change in response to the applied strain, $\varepsilon^{applied}_{\perp,\parallel}$, for the associated direction. To simplify the analysis of the direction dependent sensor response, we have always applied the strain in parallel or in orthogonal direction to the reservoir orientation. The subscripts show this direction. When strain in a uniaxial direction is applied to a thin film, this induces a strain in the lateral direction with respect to the applied strain direction. Using Poisson's ratio for an incompressible material,

$$\nu = -\frac{\varepsilon^{induced}_{lateral}}{\varepsilon^{applied}_{\perp,\parallel}} = 0.5 \# Eq.\,3$$

we calculate this lateral strain as:

$$\varepsilon^{induced}_{lateral} = -0.5\ \varepsilon^{applied}_{\perp,\parallel} \# Eq.4$$

The volumetric strain is simply sum of individual linear strains for isotropic materials under small strains ($\frac{\Delta V}{V} = \varepsilon^{applied}_{\perp,\parallel} - 0.5\ \varepsilon^{applied}_{\perp,\parallel}$). Here the strain component in Z-axis is omitted, as the thin film system is assumed two-dimensional. Therefore, the measured gauge factors in Eq. 1 and 2 are due to the addition of individual volume expansion contributions from the applied and induced strain. If we decouple the effect of the two strain components on the volumetric strain, we obtain two theoretical volumetric strains; $\frac{\Delta V_{\perp,\parallel}}{V} = \varepsilon^{applied}_{\perp,\parallel}$, $\frac{\Delta V_{\parallel,\perp}}{V} = -0.5\ \varepsilon^{applied}_{\perp,\parallel}$ due to the applied and induced strains, respectively. Each of these components will cause a proportional sensor response. Consequently, the measured resistance response will be the addition of two theoretical sensor responses that have orthogonal and parallel components.

$$\frac{\Delta R_{\perp}}{R} = \frac{\Delta R'_{\perp}}{R} - 0.5\frac{\Delta R'_{\parallel}}{R} \# Eq.\,5$$

$$\frac{\Delta R_{\parallel}}{R} = \frac{\Delta R'_{\parallel}}{R} - 0.5\frac{\Delta R'_{\perp}}{R} \# Eq.6$$

Here, $\Delta R'_{\parallel,\perp}$ shows the theoretically calculated resistance change solely in response to the volume change in the associated strain direction. Plugging Eq. 5 and 6 into Eq. 1 and 2;

$$GF_{\perp}^{Measured} = \frac{\frac{\Delta R'_{\perp}}{R} - 0.5\frac{\Delta R'_{\parallel}}{R}}{\varepsilon_{\perp}^{applied}} \#Eq.7$$

$$GF_{\parallel}^{Measured} = \frac{-0.5\frac{\Delta R'_{\perp}}{R} + \frac{\Delta R'_{\parallel}}{R}}{\varepsilon_{\parallel}^{applied}} \#Eq.8$$

Assuming that $\varepsilon_{\perp}^{applied} = \varepsilon_{\parallel}^{applied} = \varepsilon^{applied}$, Equation 7 and 8 gives us two equations with two unknowns, and allows us to find the individual direction dependent Gauge factors, $GF'_{\parallel,\perp}$, for single reservoirs as:

$$GF'_{\parallel} = \frac{\frac{\Delta R'_{\parallel}}{R}}{\varepsilon_{\parallel}^{applied}} = 43 \; and \; GF'_{\perp} = \frac{\frac{\Delta R'_{\perp}}{R}}{\varepsilon_{\perp}^{applied}} = 59 \#Eq.9$$

2.2. Theoretical calculation of the sensor response based on the DIC results

To demonstrate how the theoretical procedure described in Methods section is used we are providing two examples here.

Example 1: HHVV OR with X1 strain profile

First, the strain values in both X and Y directions at each of the liquid reservoirs are found by averaging the strain under each reservoir.

Reservoir	ε_{xx}
A	0.0029
B	0.0026
C	0.0411
D	0.0426
	ε_{yy}
A	0.000758
B	0.0011
C	-0.0222
D	-0.0195

The X (Y)-direction strain is orthogonal to B(A) and D(C) on the HHVV design. Therefore, the sensor response is calculated with the following equation;

$$\frac{\Delta R}{R_0} = 43 * \left(\varepsilon_{XX}^{A} + \varepsilon_{XX}^{C} + \varepsilon_{YY}^{B} + \varepsilon_{YY}^{D}\right) + 59 * (\varepsilon_{XX}^{B} + \varepsilon_{XX}^{D} + \varepsilon_{YY}^{A} + \varepsilon_{YY}^{C} - 0.01)$$

$$\frac{\Delta R}{R_0} = 43 * (0.0029 + 0.0411 + 0.0011 - 0.0195) + 59 * (0.0026 + 0.0426 + 0.000758 - 0.0222 - .01)$$

The strain threshold of 0.01 is used for the OR configuration as there are twice as many liquid reservoirs connected to the sensing channel.

$$\frac{\Delta R}{R_0} = 1.87$$

$$Predicted\ Sensor\ Response = \frac{\frac{\Delta R - R_0}{R_0}}{Max\ Strain}$$

$$1.87 / 0.05 = 37.4$$

$$Measured\ Response = 40.2$$

Example 2: HHVV AND with an XXYY strain profile

Reservoir	ε_{xx}
A	0.0318
B	0.0598
C	0.06
D	0.0315
	ε_{yy}
A	0.0528
B	0.0347
C	0.0249
D	0.0368

Here, since there are essentially two independent sensors (i.e., AB and CD) that are connected in parallel (i.e., AB // CD) electrically, their individual responses are found with the same approach demonstrated above and then the overall response is found using the parallel resistor formula.

$$\frac{\Delta R_1}{R_{0,1}} = 43 * (\varepsilon_{XX}^{A} + \varepsilon_{XX}^{D}) + 59 * (\varepsilon_{YY}^{A} + \varepsilon_{YY}^{D} - 0.01)$$

$$\frac{\Delta R_1}{R_{0,1}} = 7.4$$

$$\frac{\Delta R_2}{R_{0,2}} = 59 * (\varepsilon_{XX}^{B} + \varepsilon_{XX}^{C} - 0.01) + 43 * (\varepsilon_{YY}^{B} + \varepsilon_{YY}^{C})$$

$$\frac{\Delta R_2}{R_{0,2}} = 9$$

The strain threshold of 0.01 is used in this case, as the strain profile is biaxial.

$$R_{1,TOT} = \frac{\Delta R_1}{R_{0,1}} * R_{0,1} + R_{0,1} = 34.6 \text{ M}\Omega$$

$$R_{2,TOT} = \frac{\Delta R_2}{R_{0,2}} * R_{0,1} + R_{0,1} = 41.4 \text{ M}\Omega$$

, where $R_{0,1}$ is 4.1 MΩ

$$\frac{1}{R_{TOT}} = \frac{1}{R_{1,TOT}} + \frac{1}{R_{2,TOT}}$$

$$R_{TOT} = 18.9 \text{ M}\Omega$$

$$Predicted\ Sensor\ Response = \frac{\frac{\Delta R_{TOT}}{R_{0,TOT}}}{Max\ Strain} = 127.9$$

$$Measured\ Response = 125.2$$