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CAPACITOR STRAIN SENSOR FOR ENHANCING FEEDBACK TO PATIENTS RECOVERING FROM A STROKE

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ABSTRACT
Embedded sensors in footwear are of interest for providing feedback on mobility and gait. The most sensitive location is within the sole, requiring development of new materials that have the required functional and mechanical properties. We are developing capacitive strain sensors. The performance of such sensorsis dictated by two fundamental materials properties: dielectric constant (ε) and hardness. The sensitivity is improved by a high dielectric constant and low hardness. This paper describes a novel material that combines a composite elastomeric polymer and single wall carbon nanotubes (SWCNTs). The optimum SWCNT loading in a polyurethane with 80A shore hardness was determined to be 0.1 vol% which delivered a high SNR and maintained its mechanical properties (hardness). Data collected from a shoe strain sensor array of this material can be used for automatic recognition of postures and activities, for characterization of extremity use, and to provide behavioral enhancing feedback to patients recovering from a stroke.

Keywords: capacitance sensor, composite material, dielectric constant, strain sensor, sensor array.

1. INTRODUCTION
Restoring the ability to walk after a stroke is a major objective of the rehabilitation process [1]. Rehabilitation strategies that are task oriented and intensive can drive cortical reorganization and increase activity levels in people after a stroke.

Strain-based sensors integrated into footwear can be used to monitor the body's interaction with the ground while the patient moves. A single sensor in the heel allows the detection of heel strikes and lifts, while a sensor array within an sole (as described in this study) enables examination of walking strategies and the center of pressure translations, and the estimation of vertical ground reaction forces throughout the step cycle. Schematic sketch of the device has been shown in figure 1.

State-of-the-art sensors are mostly composed of piezo-resistor-sensitive switches or force-sensitive resistors that characterize gait based on the configuration of the sensors. However, the use of these resistor-based sensors is limited due to their susceptibility to high mechanical stress, wear over time, potential drift due to humidity inside the shoe, and limited measurements during inactivity, which may all reduce data quality.

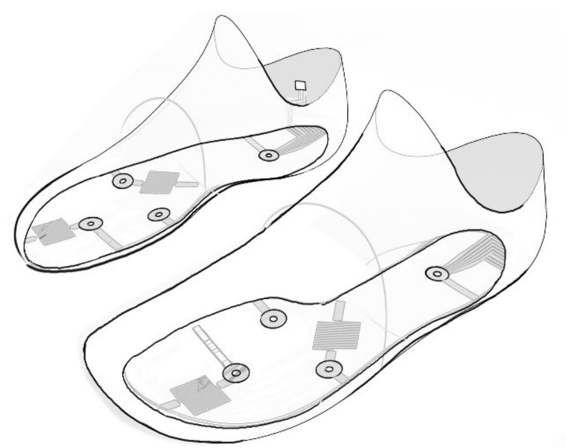

FIGURE 1: Capacitive sensing element integrated into sole provides a nonintrusive capture of biometric data

The novel sensing material described here is composed of single-wall-carbon-nanotubes (SWCNTs) dispersed in an elastomeric polymer [2,3]. The choice of material for a capacitor

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strain sensor used in footwear is dictated by two fundamental physical properties: dielectric constant (ε) and hardness. High dielectric materials are desired for capacitance application because they improve the Signal-to-Noise-Ratio (SNR). Current elastomeric materials used in shoe insoles have suitable hardness but a low dielectric constant (ε=2.6), making them inappropriate for capacitance materials due to relatively low SNR caused by a lack of sensitivity.

We have developed an elastomeric composite material for use in a capacitor-based strain sensor capable of retaining its compliance while having a higher capacitance than current state of the art.

2. METHODS

The elastomeric material with tuned dielectric constant was made from a dispersion of high purity SWCNTs in m-cresol. The dispersing media of SWCNTs was selected so it was compatible with commercial solvent-based polyurethane resins.

This dispersion was added to a polyurethane resin, PMC780, which offers superior tear and tensile strength suited for shoe application. The uniform dispersion of SWCNTs in this two-component resin is critical for achieving a high dielectric constant without impacting the mechanical properties of resin materials. Using a tape casting technique, the dispersion was cast into a highly robust, flexible freestanding composite film.

3. RESULTS AND DISCUSSIONS

The sensitivity and accuracy of the sensor is related to SNR. High dielectric materials are desired for capacitance application because it improves SNR. The dielectric constant is tailored by incorporating a filler (such as SWCNTs) with a high dielectric constant into the resin matrix.

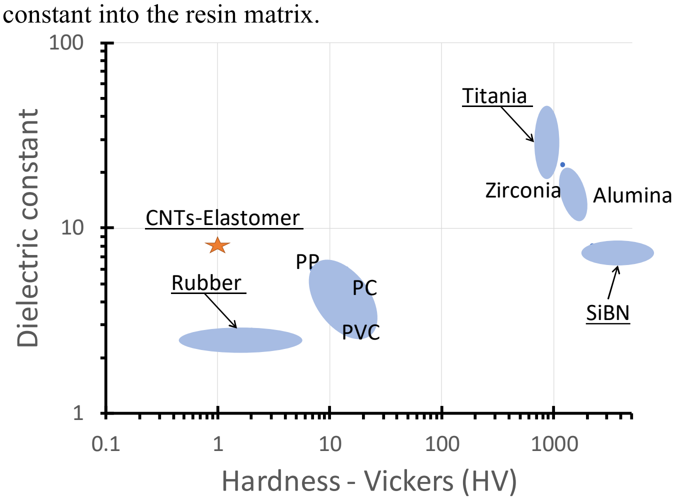

FIGURE 2: Dielectric constant vs. hardness for ceramic and polymeric materials

This novel elastomeric material has similar dielectric constant to alumina or zirconia but with lower hardness suited for shoe insole. The combined attributes exceeds the state of the art as shown in Figure 2.

Figure 3 shows the dielectric constant of the flexible sensing pad as a function of SWCNTs loading. The dielectric constant starts to increase near 0.1 vol% SWCNTs, associated with achieving the threshold value.

There are many theoretical approaches used to predict the effective dielectric constant of the polymeric composite material. The volume-fraction average is a simple but inaccurate method. A more realistic models is the Maxwell method [4]. This method, shown in Figure 2, is strictly valid only as the filler fraction goes to zero, i.e. infinite dilution. Every method used to estimate the dielectric constant of a composite material was developed for a single spherical discrete phase surrounded by a continues resin matrix. Therefore, they are inaccurate in describing the dielectric data obtained for filler with a length-to-diameter aspect ratio above 1,000.

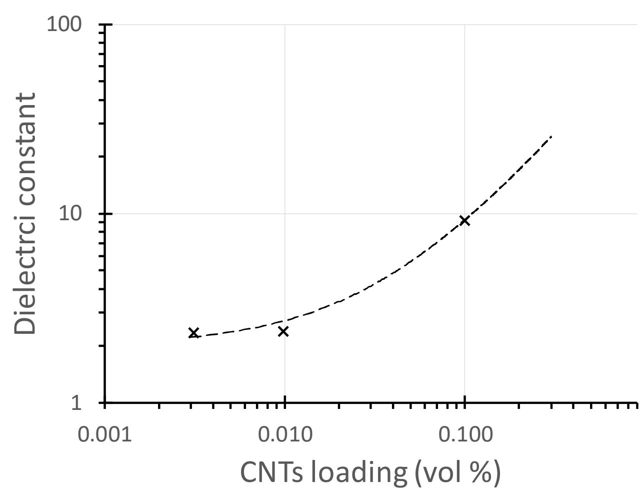

FIGURE 3: Effective dielectric constant vs. volume fraction of SWCNTs. Dash line present the Maxwell fitting line

In Figure 4, the sensing data for a device with a planar configuration are plotted as a function of the strain. According to this data we achieved a functional and highly sensitive sensor by building capacitors from composite material with 0.1 vol% SWCNTs. This threshold value depends on many factors such as

(i) Length-to-diameter ratio of SWCNTs
(ii) SWCNTs dispersibility

The elastic modulus of the SWCNTs-elastomer matrix used for these tests was 11.7 MPa. This value remains constant for SWCNT volume fractions up to 0.2 vol%.

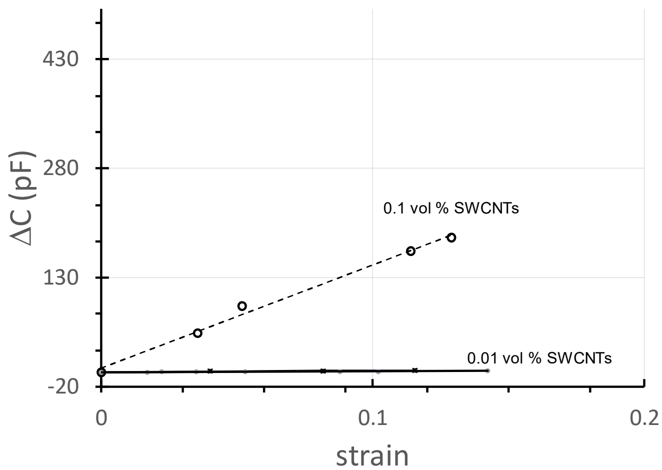

FIGURE 4: Strain dependence of capacitance change

Taber abrasion testing showed no mass loss or visual change associated with heavy traffic or underfoot wear indicating that the composite developed here can be placed on the outer portion of the shoe, where the system is most sensitive to complex changes in motion.

4. CONCLUSIONS

We developed a durable capacitor strain sensor with improved strain sensitivity and an increased dielectric constant, suitable for embedding strain sensors in shoe soles. This was enabled by a new SWCNT-filled elastome , which has the high dielectric constant required for function. The high aspect ratio of the SWCNT filler ensures that this function is achieved while retaining mechanical properties. Taber abrasion testing indicated that it was suitable for shoe applications.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Munoz-Organero, M., Parker, J., Powell, L., Mawson, S., 2016, "Assessing walking strategies using insole pressure sensor for stroke survivors," *Sensor*, 16, 1631, doi:10.3390/s16101631

[2] Yan, T., Wang, Z., Pan Z.J., 2018, "Flexible strain sensors fabricated using carbon-based nanomaterials: A review," *Current Opinion in Solid State and Materials Science* 22, 213-228, doi: 10.1016/j.cossms.2018.11.001

[3] Shuba, M.V., Paddubskaya, A.G., Kuzhir P.P., Maksimenko, S.A., Flahaut E., Fierro, V., Celzard, A., Valusis, G., 2017, "Short-length carbon nanotubes as building blocks for high dielectric constant materials in the terahertz range" J. Phys. D: Appl. Phys. 50, 08LT01 (6pp), doi:10.1088/1361-6463/aa5628

[4] Barber, P., Balasubramanian S., Anguchamy, Y., Gong, S., Wibowo, A., Gao H., Ploehn, H.J., zur Loye, H.-C., 2009, "Polymer composite and nanocomposite dielectric materials for pulse power energy storage," *Materials,* 2, 1697-1733, doi:10.3390/ma2041697