Evaluation of Textile-Based Wearable Force Sensors for Functional Clothing Applications

Crystal Compton, Alireza Golgouneh, Brad Holschuh, Lucy E. Dunne
University of Minnesota – Twin Cities, Wearable Technology Lab

Keywords: Soft sensors, wearable technology, body sensing, force sensing, functional clothing design

Introduction: On-body force sensing can provide beneficial information used in garment design and performance evaluation for functional clothing and wearable technology applications. However, not all sensors are alike or suitable for wearable and body sensing scenarios. Some sensors are not suitable due to wearability factors such as being conformable to the body's shape and size (complex geometry) or do not meet the force or pressure profile requirements for on-body sensing.

Tactile force sensors are used for a variety of applications such as measuring forearm surface deformations (Castellini & Ravindra, 2014), respiration monitoring (Hoffmann et al., 2011), and gait analysis (Tao et al., 2012). Despite the usage of these sensors in many contexts, there is not a systematic approach to assess sensor performance on the body. Most studies focus on the application of force sensing rather than reporting typical sensor performance characteristics, which can be useful information for selecting a sensor for a specific use. In this study, we investigate and report the performance of two textile-based force sensors intended to be used for on-body sensing scenarios, to better inform sensor performance and selection for specific application requirements for improved wearable sensing accuracy.

Methods: Two types of entirely textile-based sensors (Figure 1 a-b) were fabricated for evaluation. Three samples were made of each sensor type to assess intra-sensor repeatability. Each sensor consisted of the same 3-layer fabric configuration with a different middle sensing material layer: *'Pressure Sensing'* fabric (SparkFun Electronics ®, n.d.-b), and *'Conductive'* fabric (SparkFun Electronics ®, n.d.-a), both by Eeonyx/EeonTex. Sensors were evaluated using a tensile testing machine (Instron, model #3365) to apply a controlled dynamic force. A 3D printed flat bottom platform and top applicator were held in place by pneumatic side-action grips. Each sensor type and sample were lightly taped to the platform (avoiding the sensing area) to hold in place while the applicator applied 5 N of force to each sensor during 4 (1 conditioning pre-cycle, 3 cycles) cyclic repetitions. For static drift testing, a constant 10 N of force for 20 minutes was applied. Saturation test ranged from 0-50 Newtons (N). All sensors were connected to the Instron Analog to Digital Conversion (ADC) sensing unit and a voltage divider circuit to collect sensor data.

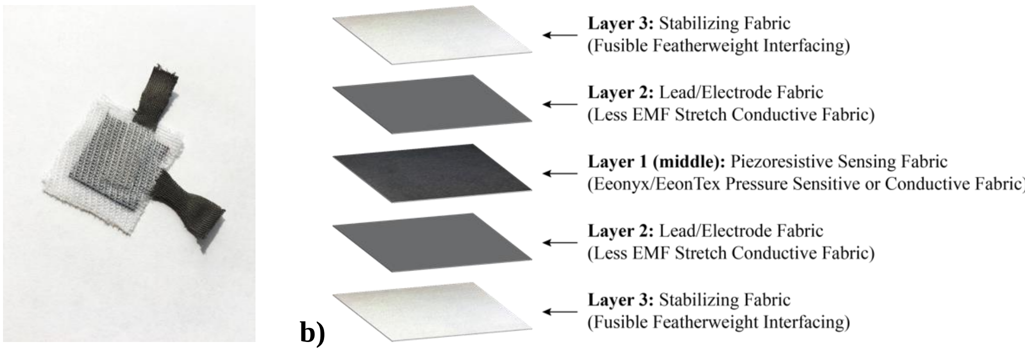

Figure 1: Textile-based sensors used: a) fabricated sensor, b) expanded view of layers.

Results and Discussion: Data was analyzed using MATLAB and a summary of the sensor performances based on standard sensing metrics is described in Table 1. Overall, the Eeonyx Pressure Sensing fabric sensor had better performance and outperformed in 4 out of 5 sensor metric categories compared to the Eeonyx Conductive fabric sensor.

Table 1: Quantitative summary of sensor metric results (* indicates better sensor performance).

Sensor Type	Repeatability	Linearity	Static Drift	Saturation	Hysteresis
Eeonyx Pressure Sensing	10% *	0.76 *	1.22% *	7.62 N *	5.50%
Eeonyx Conductive	18%	0.68	1.54%	4.82 N	2.56% *

Repeatability is an important sensing factor, which demonstrates how much a sensor's response will vary given all testing conditions are equal. Therefore, lower rates of repeatability are better as there are smaller variations between sensor measurements. To calculate the repeatability, the actual difference between consecutive testing cycles was normalized to the saturation range. Linearity shows the correlation coefficient between force and the sensor response. A value closer to 1 has a stronger linear relationship and is ideal. Static drift is the stability of a sensor response under the stable conditions (no strain, loading, etc. (Golgouneh et al., 2019) and is an important factor which can affect the sensor calibration and lead to measurement errors. A lower static drift indicates higher sensor stability. Saturation indicates the dynamic force sensing range (measured here in Newtons) of the sensor, meaning a higher saturation affords use in various sensing applications. Hysteresis is the difference between the area-under-curve of sensors during the loading and unloading cycles. Low hysteresis is essential for improved measurement reliability.

These sensors are completely textile-based, which is advantageous compared to traditional force sensors commercially available, such as commonly used force sensitive resistors (FSRs) made from films, which may introduce wearability issues, such as being rigid/stiff and uncomfortable on the body or against the skin. Commercial sensors are also typically limited to certain sizes and shapes available, and are not customizable. Textile-based sensors offer great advantages in terms of customization, fabrication, and wearability. Sensors can be tailored to different sizes and shapes based on sensing requirements, are more comfortable and conformable on the body, and can be easily integrated into clothing for wearable-based force sensing.

Conclusions and Future Work: This study evaluated two different textile-based sensors that may be used for on-body sensing and reported sensing performance metrics. This evaluation and the results may be used to inform sensor selection for specific on-body sensing scenarios that have certain requirements for wearable technology and functional clothing applications.

This study was limited to one specific sensing area size for both sensors, which was relatively small (~0.5 cm). The size of the sensing area may perform differently under different conditions (e.g., different force surface areas applied to the sensor) and may afford different sensor capabilities (e.g., with a larger sensing size, it is possible that pressure, not just force, could be measured if using a pressure sensing fabric – when the sensing area is this small the sensor is typically completely saturated, which does not allow a detectable force-pressure distinction). In future work, we have increased the sensing area and are investigating additional conductive materials and fabrication methods using this sensor configuration. We are currently evaluating: 1) the pressure sensing capability of the textile-based sensor types here, as well as other in-lab fabricated and commercial sensors, and 2) metrics on the sensor performance with on-body like conditions (e.g., surface curvature and tissue stiffness). Additional future work has focused on the development of a textile-based force sensing array using this sensor configuration to sense larger surface/body areas (Compton et al., 2020).

References

Castellini, C., & Ravindra, V. (2014). A wearable low-cost device based upon Force-Sensing Resistors to detect single-finger forces. *5th IEEE RAS/EMBS International Conference on Biomedical Robotics and Biomechatronics*, 199–203. https://doi.org/10.1109/BIOROB.2014.6913776

Compton, C., Golgouneh, A., Holschuh, B., & Dunne, L. (2020, July 31). Towards Large-area On-body Force Sensing Using Soft, Flexible Materials: Challenges of Textile-Based Array Sensing. *International Conference on Environmental Systems (ICES)*. International Conference on Environmental Systems (ICES). https://ttu-ir.tdl.org/handle/2346/86441

Golgouneh, A., Molla, Md. T. I., & Dunne, L. E. (2019). A comparative feasibility analysis for sensing swelling with textile-based soft strain sensors. *Proceedings of the 23rd International Symposium on Wearable Computers - ISWC '19*, 60–65. https://doi.org/10.1145/3341163.3347739

Hoffmann, T., Eilebrecht, B., & Leonhardt, S. (2011). Respiratory Monitoring System on the Basis of Capacitive Textile Force Sensors. *IEEE Sensors Journal*, *11*(5), 1112–1119. https://doi.org/10.1109/JSEN.2010.2082524

SparkFun Electronics ®. (n.d.-a). *EeonTex Conductive Fabric—COM-14110—SparkFun Electronics*. SparkFun. https://www.sparkfun.com/products/14110

SparkFun Electronics ®. (n.d.-b). *EeonTex Pressure Sensing Fabric—COM-14111—SparkFun Electronics*. SparkFun. https://www.sparkfun.com/products/retired/14111

Tao, W., Liu, T., Zheng, R., Feng, H., Tao, W., Liu, T., Zheng, R., & Feng, H. (2012). Gait Analysis Using Wearable Sensors. *Sensors*, *12*(2), 2255–2283. https://doi.org/10.3390/s120202255