Development of Fully Shielded Soft Inductive Tactile Sensors

Hongbo Wang, Massimo Totaro, Lucia Beccai
Center for Micro-BioRobotics, Istituto Italiano di Tecnologia (IIT), Pontedera, PI, 56025, Italy
E-mails: hongbo.wang@iit.it, massimo.totaro@iit.it, lucia.beccai@iit.it

***Abstract*— Tactile sensors should be immune to electromagnetic interference (EMI), to provide repeatable and accurate signal of the physical touch for real-world applications. Soft Inductive Tactile Sensors (SITS) can achieve high performance, but could be affected by EMI. Here, we present the development of fully shielded (FS-) SITS using conductive textile both for sensing target and electromagnetic shielding. By grounding the conductive textile cover, parasitic capacitance effect is also minimized. The FS-SITS can measure pressure lower than 30 Pa, with a sensing range over 150 kPa. The proposed sensor is scalable, customizable, low-cost and robust for robotics and wearable systems.**

Keywords*— *soft tactile sensors; electromagnetic interference (EMI); eddy-current effect; inductance; flexible coils

I. INTRODUCTION

Force and tactile sensors [1] play an increasingly important role in robotics [2-4], human-robotic interaction (HRI), wearables [5], and biomedical engineering [6]. In the past decade, various materials and transducer mechanisms have been explored to develop tactile sensors and skins [5, 7-9], to provide the sense of touch for control and interactions, particularly benefiting soft robotics [10, 11] and wearables [12]. Capacitive [13] and inductive [14] sensors can achieve high performance, but electromagnetic interference (EMI) and proximity effects can introduce errors or even impair the functionality. Thus, EMI shielding strategies are needed to tackle this issue. For example, a fully shielded capacitive strain sensors for wearable applications is developed [15].

In 2017, Wang et. al. [14, 16, 17] developed single and tri-axis soft inductive tactile sensors (SITS) based on the eddy-current effect. The SITS can detect forces less than 1 mN and also measure large forces (over 20 N, 1 kSPS), and it is robust to operate in harsh environment (e.g. underwater). However, potential issues of electromagnetic coupling between the sensing coil and conductive objects other than the sensing target could cause errors. On the other hand, the rigid conductive films in the SITS design [14] would limit its applications when conformable contact is desirable (e.g. HRI).

In this paper, we present a new design of a fully shielded SITS (FS-SITS) by wrapping the sensor core parts (i.e. sensing coil and the elastomer) with compliant conductive textile. Such outer layer has a double role: it represents the sensing target and the electromagnetic shielding "box". The proposed FS-SITS results in a high-performance soft tactile sensing solution that can operate robustly in various application scenarios.

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 799773 ("3D-SITS" Project).

II. DESIGN METHODOLOGY

A. Working Principle

As illustrated in Fig. 1a, a SITS consists of a planar coil, a conductive film as sensing target, and an elastomeric block. The elastomer is deformed when pressure is applied, which reduces the distance x, thereby decreasing the effective inductance [14]. Figure 1b shows the normalized response of inductance to distance curve of an eddy-current system [18]. A SITS is equivalent to a variable resistor (R_x) and a variable inductor (L_x) connected in series, with a parasitic capacitor connected in parallel. For ultra-stable, high-resolution inductance measurement, a well-balanced AC bridge can be used to demodulate the signals of extremely small inductance variation [19]. LC oscillator-based inductance measurement circuit has been widely used to measure inductance, as illustrated in Fig. 1c. The oscillation frequency of a LC tank varies with the inductance when the capacitance is constant.

B. Electromagnetic Interference

Given that the SITS is operating through AC magnetic field coupling at a specific frequency (typical 0.1 MHz to 10 MHz) [14], it is not affected by magnetic field noise like tactile sensors based on magnetic field sensing [20]. Since the AC magnetic field can generate eddy-currents in any nearby conductive object, the measurement will be affected when conductive objects other than the sensing target are coupled with the coil's magnetic field. A 2D symmetric FE model

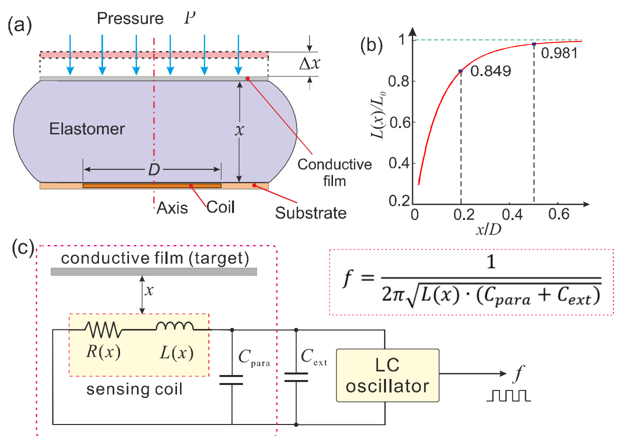

Fig 1. Schematic sketch of the SITS system (a) Working principle of a SITS; (b) Curve of normalized inductance to distance between the coil and the target; (c) Equivalent circuit of the SITS and LC oscillator based inductance measurement.

(using COMSOL® Multiphysics v. 5.4) was developed to investigate the magnetic field distribution of a double layer planar coil with different conductive target configurations. As highlighted in Fig. 2a, the conductive film can act both as the sensing target and as a shielding layer when the SITS interacts with conductive or ferromagnetic objects. However, the magnetic field is extending to a distance beyond the coil diameter [21] in all other directions (Fig .2a), which introduces a risk of interference from other nearby conductive objects. Figure 2b-c shows the magnetic field of a SITS with double-side target and fully closed target, respectively. Obviously, when a closed target around the planar coil is used, there is no magnetic field outside the target "box", which provides a fully shielded solution to make the SITS immune to any interference. On the other hand, this FS-STIS design also ensures better EMI compatibility to other nearby devices.

As discussed in [14], the design of the SITS can be divided into two independent steps: (1) design of the eddy-current displacement transducer; (2) choice of the stiffness of the elastomer to meet the requirements of sensing range and resolution. Here, we focus on the characteristics of the eddy-current transducer, using the same elastomer of previously developed SITS. For a double layer coil (inset of Fig. 2d) with the same design of [14], we calculate the normalized inductance curves with respect to distance of SITS with these three target configurations shown in Fig. 2a-c. As shown in Fig. 2d, the inductance verse distance curves of SITS with target at double side and fully shielded target are almost overlapped, with much larger inductance variation compared to the SITS with single target, due to larger magnetic field coupling area. However, the sensitivity (slope of the curves in Fig. 2d) for the FS-SITS only increased by 18.7% compared to the single target SITS.

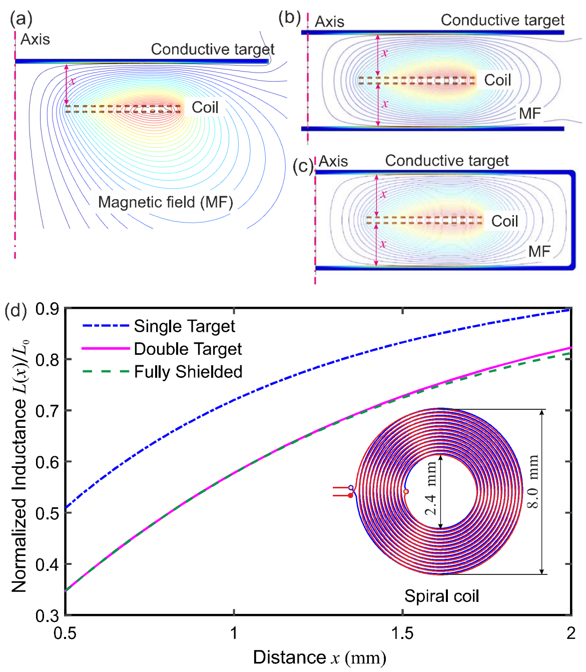

Fig 2. Magnetic field distribution of a SITS with (a) Single target; (b) Double target; (c) Fully shielded target; (d) Normalized inductance to distance response of a SITS with different target configurations.

C. *Conformable sensing target materials*

As discussed above, a conformable sensing target would be much more attractive for several applications in robotics and wearables. In order to achieve effective EMI shielding and maintain high sensitivity, the thickness of the conductive films should be larger than the penetration depth δ [22] of the eddy-current inside that material at the specific working frequency. Metal conductors can be very flexible at tens of micrometer thickness (e.g.: aluminium foil), but not stretchable, and can easily encounter plastic deformation. Liquid metal (mostly refer to Eutectic Gallium-Indium (EGaIn) [23]) can be embedded in elastomers to form highly stretchable and highly conductive material, which has been extensively exploited for stretchable strain sensors [24]. However, the complex fabrication of micro-channels makes it not ideal to be used as "shielding box" for the FS-SITS. Another solution is to use magnetorheological elastomers (MRE) as soft sensing target [25, 26], but MRE cannot provide the shielding effect.

Here, we propose to use conductive textile [27] (4712, Holland Shielding Systems BV, Dordrecht, NL) as the sensing target of FS-SITS, which is conformable, and has relatively high conductivity (0.05 Ω/sq at 0.1 mm, 0.28% of Copper). The eddy-current penetration depth of this conductive textile is 505 μm at 5 MHz, and 356 μm at 10 MHz. Therefore, 0.5 mm thick conductive textile (5 layers of the 4712 textile) should be used for FS-SITS to work between 5 and 10 MHz.

III. Experiments and Discussions

A. *Prototyping*

The flexible coil (Fig. 3a) has an outer diameter of 8 mm, consisting of two layers of 14 turns trace connected in series. A

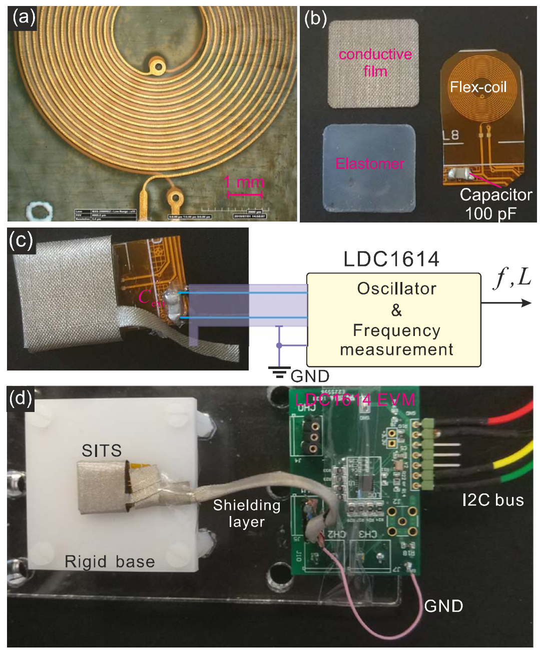

Fig 3. (a) Magnified view of the double flexible coil; (b) Photo of the square-shape elastomer, conductive textile, and the flexible coils with 100 pF capacitor connected in parallel; (c) Schematic diagram of the FS-SITS prototype and signal conditioning system; (d) Photo of a FS-SITS prototype on a rigid base and the electronics for experiments.

FS-SITS is made of a flexible coil, and two silicone elastomers, and multi-layer conductive textile, as shown in Fig. 3b. A 1.5 mm thick, 10 mm × 10 mm square elastomer block was made of ultra-soft silicone rubber (Ecoflex 00-10, Smooth-on, USA) through laser cutting from a casted silicone sheet. Conductive textile with 0.1 mm thickness was cut into the same size. Two elastomers were glued to the top and bottom sides of the flexible coil, respectively, with a thin layer of silicone adhesive (SilPoxy, Soomth-On, USA). Four layers of conductive textile were stacked together through the self-adhesive, and glued to the elastomers on both side. Finally, another textile with conductive adhesive (4713) was cut to a shape that can be folded to cover all surfaces of the elastomer-coil block.

A fully integrated digital inductance converter evaluation board [28] (LDC1614 EVM, Texas Instruments, USA) was used to measure the inductance based on LC oscillation frequency. A 100 pF NP0 capacitor is used as C_{ext} to form the oscillation network with a resonance frequency around 8 MHz. The parasitic capacitance (C_{para}) is negligible. However, additional stray capacitance can be created between conductive parts of the FS-SITS and other conductive objects nearby, increasing the total capacitance of the LC network and affecting the measured frequency (inductance). Therefore, the textile cover is connected to the ground through the textile shielding of the wires to eliminate this effect (Fig. 3d). The digital output of the LDC1614EVM is sent to a controller (NI MyRIO 1900, National Instruments, USA) via I^2C protocol.

B. Characterization

To characterize and compare the performance of the FS-SITS and regular SITS, another prototype with single-side textile target was fabricated (Fig. 4a). The experimental setup used to characterize and evaluate the FS-SITS in this paper is similar to [25]. A LabVIEW program is developed to acquire data from the FS-SITS and a commercial force/torque sensor (Nano17-E, ATI, USA), and to control the motorized micro-positioning stages (M-111.1DG, Physik Instrumente, Germany). Both the regular SITS and the FS-SITS prototypes were fixed on rigid base (Fig. 4a-b), and compressed by 0.8 mm. Figure 4c shows that the FS-SITS and the SITS have similar stiffness. The inductance variation of the FS-SITS is slightly smaller than the regular-SITS (Fig. 4d) as the distance variation between the coil and the textile of the FS-SITS is only $0.5\Delta x$. Both prototypes have a significant hysteresis (22%), which is much higher than the SITS with rigid target (5.4%, Fig. 8a in [14]). High hysteresis is a common issue for soft sensors using conductive textile due to its interlocking and plastic deformation, was reported for textile-based capacitive pressure sensor [29] as well. Figure. 4d shows that the FS-SITS has an almost linear response from 0 to 150 kPa, with a sensitivity of 1.25 nH/kPa. The standard deviation of the inductance measurement electronics at 100 Hz sampling rate is about 3.4×10^{-5} µH, which indicates pressure sensing resolution of 27 Pa. It should be noted that the pressure sensing range can be much higher since there is no saturation of this type of sensor. The ultimate limit of the pressure sensing range is the break strength of the elastomer in the FS-SITS. Finally, the sensitivity can be easily tuned through the elastomer material.

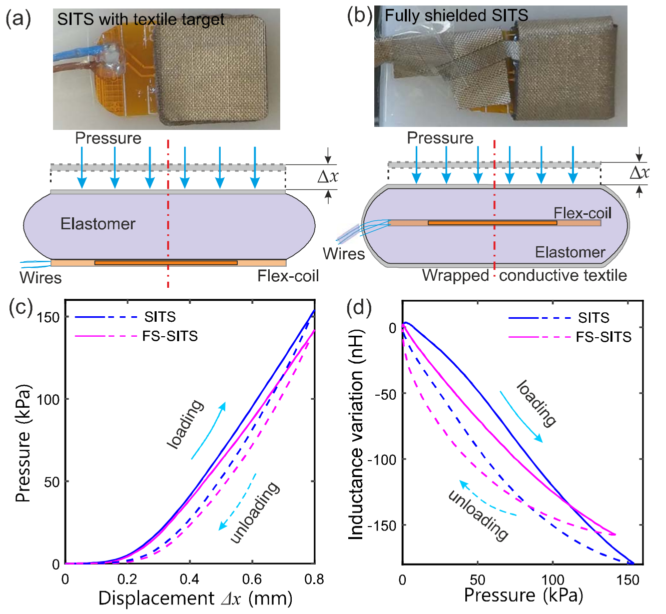

Fig 4. Prototypes characterization. Photo and schematic drawing of the SITS under pressure loading (a) with single-side textile target; (b) with fully shield textile target; (c) Pressure to displacement curves of the regular SITS and FS-SITS with 0.8 mm maximal compression; (d) Inductance variation to pressure curves of the two types of SITS (solid lines for loading phase, dashed lines for unloading phase).

C. Demonstrations

Figure 5a shows the inductance variation of the FS-SITS under gradually increased compression from 0 mm to 0. 6mm with 0.2 mm step. The pressure value from the load cell was plotted (scale on the right Y axis) as reference. The inductance variation curve is synchronized with the pressure curve, indicating rapid response of the FS-SITS. To evaluate the shielding effect, simple finger tapping (insets of Fig. 5b)

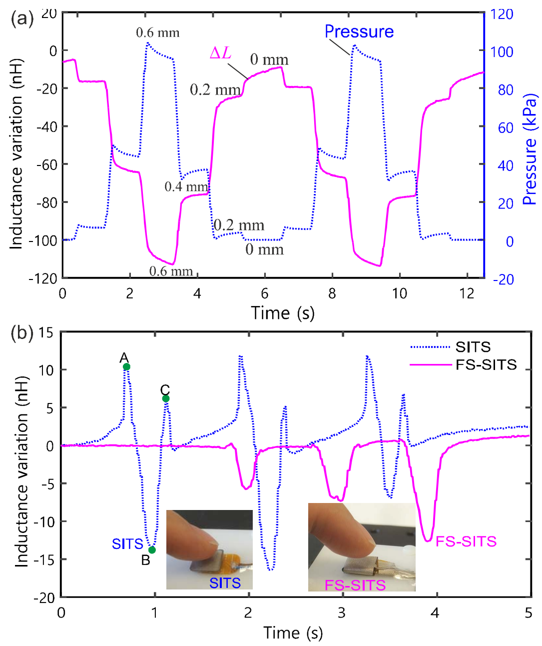

Fig 5. (a) Response of the FS-SITS under Step loading at 0 mm, 0.2 mm, 0.4 mm and 0.6 mm compression, with pressure value from the load cell as a reference; (b) Responses of regular and FS-SITS when they were tapped by an index finger.

experiments were performed with both the regular SITS and the FS-SITS. As shown in Fig. 5b, the inductance increased when the finger is approaching the surface of the regular SITS (before point A). Once the contact occurred (point A), the inductance starts decreasing due to the increase of the pressure (point A to B). When the finger is moving away from the regular SITS, the inductance value gradually goes back to the unloaded level. This proximity effect will cause errors in pressure measurement. In contrast, the FS-SITS only responded when actually pressure is applied to the surface (compressed by the finger), and the inductance value goes back to the unloaded level immediately once the finger is lift away from the sensor surface.

IV. CONCLUSION

In summary, we presented the design methodology and preliminary characterization of a fully shielded soft inductive tactile sensor (FS-SITS), which shows high resolution and large dynamic range. The results show that the FS-SITS have a sensitivity and hysteresis similar to the regular SITS, with pressure sensing resolution (RMS) of 27 Pa. The demonstration highlights that the FS-SITS is not sensitive to nearby conductive objects by wrapping the conductive textile on all surface of the SITS and connecting to the ground of the electronics. Utilization of conductive textile as the sensing target for SITS provides conformable contacts between the sensor surface and the objects, but also introduce significant hysteresis (22%). Further investigation is needed to find a solution to minimize the hysteresis or exploiting it as a positive feature in the control system. Finally, the presented FS-SITS is scalable, and can be easily customized to meet the specific requirements of diverse applications.

REFERENCES

[1] M. R. Cutkosky, R. D. Howe, and W. R. Provancher, "Force and tactile sensors," in Springer Handbook of Robotics: Springer, 2008, pp. 455-476.

[2] C. Bartolozzi, L. Natale, F. Nori, and G. Metta, "Robots with a sense of touch," Nature Materials, vol. 15, no. 9, pp. 921-925, 2016.

[3] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—from humans to humanoids," Robotics, IEEE Transactions on, vol. 26, no. 1, pp. 1-20, 2010.

[4] P. S. Girão, P. M. P. Ramos, O. Postolache, and J. M. D. Pereira, "Tactile sensors for robotic applications," Measurement, vol. 46, no. 3, pp. 1257-1271, 2013.

[5] T. Yang, D. Xie, Z. Li, and H. Zhu, "Recent advances in wearable tactile sensors: Materials, sensing mechanisms, and device performance," Materials Science and Engineering: R: Reports, vol. 115, pp. 1-37, 2017.

[6] M. I. Tiwana, S. J. Redmond, and N. H. Lovell, "A review of tactile sensing technologies with applications in biomedical engineering," Sensors and Actuators A: physical, vol. 179, pp. 17-31, 2012.

[7] Z. Kappassov, J.-A. Corrales, and V. Perdereau, "Tactile sensing in dexterous robot hands—Review," Robotics and Autonomous Systems, vol. 74, pp. 195-220, 2015.

[8] R. S. Dahiya, P. Mittendorfer, M. Valle, G. Cheng, and V. J. Lumelsky, "Directions toward effective utilization of tactile skin: A review," IEEE Sensors Journal, vol. 13, no. 11, pp. 4121-4138, 2013.

[9] Y. Huang, X. Fan, S. C. Chen, and N. Zhao, "Emerging Technologies of Flexible Pressure Sensors: Materials, Modeling, Devices, and Manufacturing," Advanced Functional Materials, p. 1808509, 2019.

[10] C. Majidi, "Soft robotics: a perspective—current trends and prospects for the future," Soft Robotics, vol. 1, no. 1, pp. 5-11, 2014.

[11] H. Wang, M. Totaro, and L. Beccai, "Toward perceptive soft robots: Progress and challenges," Advanced Science, vol. 5, no. 9, p. 1800541, 2018.

[12] J. Heikenfeld et al., "Wearable sensors: modalities, challenges, and prospects," Lab on a Chip, vol. 18, no. 2, pp. 217-248, 2018.

[13] L. Viry et al., "Flexible three‐axial force sensor for soft and highly sensitive artificial touch," Advanced Materials, vol. 26, no. 17, pp. 2659-2664, 2014.

[14] H. Wang et al., "Robust and High-Performance Soft Inductive Tactile Sensors based on the Eddy-Current Effect," Sensors and Actuators A: Physical, 2017.

[15] M. Totaro et al., "Soft smart garments for lower limb joint position analysis," Sensors, vol. 17, no. 10, p. 2314, 2017.

[16] H. Wang, J. Kow, G. d. Boer, D. Jones, A. Alazmani, and P. Culmer, "A Low-cost, High-Performance, Soft Tri-axis Tactile Sensor based on Eddy-Current Effect," presented at the IEEE Sensors 2017, Glasgow, Scotland, UK, October 30 - November 1, 2017.

[17] H. Wang et al., "Design and characterization of tri-axis soft inductive tactile sensors," IEEE Sensors Journal, vol. 18, no. 19, pp. 7793-7801, 2018.

[18] H. Wang and Z. Feng, "Ultrastable and highly sensitive eddy current displacement sensor using self-temperature compensation," Sensors and Actuators A: Physical, vol. 203, pp. 362-368, 2013.

[19] H. Wang, Y. Liu, W. Li, and Z. Feng, "Design of ultrastable and high resolution eddy-current displacement sensor system," in IECON 2014-40th Annual Conference of the IEEE Industrial Electronics Society, 2014, pp. 2333-2339: IEEE.

[20] H. Wang et al., "Design Methodology for Magnetic Field-Based Soft Tri-Axis Tactile Sensors," Sensors, vol. 16, no. 9, p. 1356, 2016.

[21] H. Wang, W. Li, and Z. Feng, "A Compact and High-Performance Eddy-Current Sensor Based on Meander-Spiral Coil," IEEE Transactions on Magnetics, vol. 51, pp. 1-6, 2015.

[22] Z. Mottl, "The quantitative relations between true and standard depth of penetration for air-cored probe coils in eddy current testing," NDT international, vol. 23, no. 1, pp. 11-18, 1990.

[23] R. C. Chiechi, E. A. Weiss, M. D. Dickey, and G. M. Whitesides, "Eutectic gallium‐indium (EGaIn): a moldable liquid metal for electrical characterization of self‐assembled monolayers," Angewandte Chemie International Edition, vol. 47, no. 1, pp. 142-144, 2008.

[24] D. M. Vogt, Y.-L. Park, and R. J. Wood, "Design and Characterization of a Soft Multi-Axis Force Sensor Using Embedded Microfluidic Channels," IEEE Sensors Journal, vol. 13, no. 10, pp. 4056-4064, 2013.

[25] H. Wang, M. Totaro, A. A. Blandin, and L. Beccai, "A Wireless Inductive Sensing Technology for Soft Pneumatic Actuators Using Magnetorheological Elastomers," in 2019 2nd IEEE International Conference on Soft Robotics (RoboSoft), Seoul, Korea, 2019, pp. 242-248: IEEE.

[26] T. Kawasetsu, T. Horii, H. Ishihara, and M. Asada, "Flexible tri-axis tactile sensor using spiral inductor and magnetorheological elastomer," IEEE Sensors Journal, vol. 18, no. 14, pp. 5834-5841, 2018.

[27] Conductive textile. Available: https://hollandshielding.com/content/Filemanager/4711-Conductive-textile-Technical-Datasheet.pdf_December-27-2016-1029am.pdf

[28] LDC1614 Evaluation Module. Available: http://www.ti.com/product/LDC1614/technicaldocuments

[29] J. Meyer, P. Lukowicz, and G. Troster, "Textile pressure sensor for muscle activity and motion detection," in 2006 10th IEEE International Symposium on Wearable Computers, 2006, pp. 69-72: IEEE