Towards the Development of Soft Force and Pressure Sensors for Robot Safety Applications

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***Abstract*—When collaborative robots impact humans, their body parts deform which can cause surface and deep pain. Onset of pain has been determined as an acceptable injury threshold in human-robot impacts and has been related to pressure. Therefore, it is necessary to measure pressure on deformable human body parts contacted by a robot. A pressure sensor appropriate for this purpose should deform with the body part and not introduce local stiffness. In this paper, we present the design and fabrication of a soft pressure sensor. We demonstrate that the sensor matches the biomechanical response of the human forearm and that its capacitance changes linearly with applied force. In the near future, we intend to embed this sensor in a biofidelic dummy arm, with long-term goals of designing a fully sensorized dummy to measure pain caused by impact with collaborative robots.**

***Index Terms*—force sensor, pressure sensor, soft materials**

I. Introduction

During human-robot collaborative tasks, it is important to ensure humans are not harmed by their robot collaborators. Towards this safety effort, ISO/TS 15066 provides a list of biomechanical limits on force and pressure for various body parts in case of human-robot impact [1]. For manufacturing environments, ISO/TS 15066 defines four operation modes, one of which allows contact between the robot and human operator known as power and force limiting (PFL). When deploying a PFL-based collaborative robot application, a risk assessment is performed which identifies worst case robot-to-human contacts. Currently, a biofidelic test device with a stiff pressure sensor is then to test these scenarios under both quasi-static and transient conditions. The pressure sensors used by these systems do not mimic deformations seen in compressed flesh and thus may not be sufficient for properly measuring the pressure from the contact.

Efforts are being made to improve measurements of human-robot contact. Pungrasmi *et al.* proposed a dummy arm to test personal care robots where they utilized two commercial flexible pressure sensor arrays to explore superficial and deep pain [2]. This work was expanded in [3] to include a comparison of the dummy's force-displacement response against human forearm responses as well as identifying pain thresholds from human trials.

It would be beneficial if a pressure sensor embedded within a dummy arm was inexpensive, simple to manufacture, and manufactured of similar materials to a biofidelic dummy arm. Through advancements in soft sensing technology, researchers have demonstrated numerous examples of soft material capacitive pressure sensors [4]–[10]. Depending upon the specific manufacturing processes, soft pressure sensors can meet the three criteria of being (1) inexpensive, (2) simple to manufacture, and (3) materially soft and, thus offer a good alternative to traditional pressure sensors and pressure sensor arrays.

This paper describes the design, fabrication, and quasi-static performance of a soft capacitive pressure sensor that (1) has the same force-displacement characteristics of the human forearm (for future inlay in a biofidelic test dummy) and (2) is capable of measuring within the pressure range required for human-robot collision. The dummy arm being developed will have a rubber base with a foam skin designed to mimic the human subject response. The test setup for the sensor prototype incorporates a foam skin layer and an elastomeric layer to mimic the properties of the dummy arm region under investigation. We limit our analysis of the sensor to force and pressure since those are the metrics outlined in ISO/TS 15066. Biofidelity of the sensor deformation under static loads was demonstrated by comparing sensor deformation to human arm deformation in static tests [3]. We show that our sensor responds linearly with respect to pressure from 0-250 kPa. Additionally, we show that the sensor behavior is consistent across multiple sensors and there is good agreement between calculated pressure and measured pressure from our sensors. Thus, the results prove that this is a reasonable sensor to integrate into a dummy arm that can be effective for measuring biomechanical limits in collaborative robots.

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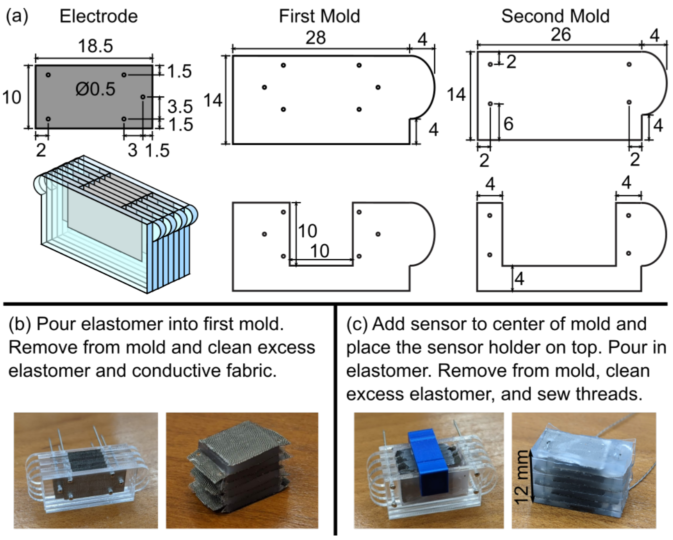

Fig. 1. (a) Side views of the electrode, first and second molds, and a graphic of the first mold. Dimensions are in mm. (b-c) The two-step molding process.

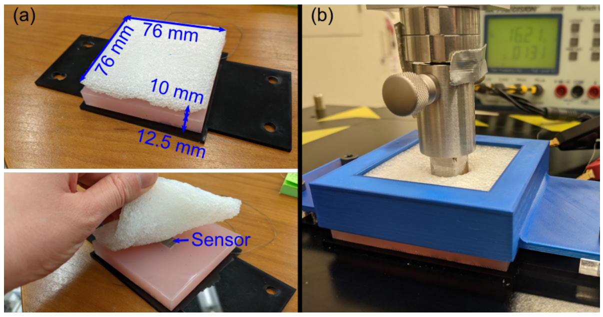

Fig. 2. (a) Dimensions of materials in the test structure and the sensor placement within the test structure. (b) Full test setup with the materials test machine pressing into the test structure with the skin.

II. Fabrication

The development of this sensor was adapted from existing literature on pressure sensors that utilized commercially-available conductive materials [8]–[10]. In this paper, we demonstrate modular molds for fabricating a pressure sensor of any thickness with multiple electrode and dielectric layers in a two step molding process that enables us to cast all the dielectric layers simultaneously. The electrodes, which are made from conductive fabric (Nora Dell, Shieldex)[1], and molds, which are made from 1.5 mm thick acrylic sheets, were cut with a laser cutter (Universal Laser System). The dimensions for the electrodes and molds are given in Fig. 1a.

The first mold was assembled by placing electrodes between the sheets of the acrylic molds. The mold was held together with six sewing pins that fit through the holes in the electrodes and molds, shown in Fig. 1b. For this paper, we manufactured sensors with seven electrodes (i.e., a thirteen-layer sensor with six dielectric layers). An elastomer, EcoFlex 00-10 (Shore Hardness: 00-10, Smooth-On, Inc.), was poured into the mold to serve as the dielectric. Note that each dielectric layer should be approximately the same thickness as the acrylic sheet (1.5 mm). Once the elastomer was fully cured, the mold was disassembled, excess elastomer was removed, and the conductive fabric was trimmed such that there were alternating tabs.

The second mold ensured that the conductive fabric was fully encapsulated in elastomer preventing delamination. The sensor was held in place in the mold, as shown in Fig. 1c, and elastomer was then poured around the sensor. Once cured, the mold was disassembled. The final step of sensor assembly was to sew conductive thread (Stainless Thin Conductive Thread, Adafruit, Inc.) through either side of the sensor connecting alternating layers together.

[1]Certain commercial materials are mentioned in this paper to specify the experiment adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material is necessarily the best available for the purpose.

III. Test Methodology

Sensor testing was conducted using a test structure that held a sensor within a bulk elastomer (P-10, Silicones, Inc.). We also utilized a foam sheet (Soma Foama 15, Smooth-On, Inc.) as a skin that covered the elastomer and sensor, shown along with dimensions in Fig. 2a. Tests were run using an aluminum 14 mm square probe, the same dimensions used during human subject testing [3], shown in Fig. 2b.

The force, displacement, and capacitance of the sensor were collected during testing. The force and displacement were collected with a materials testing machine (eXpert 5600, Admet Solutions), which was operated manually. The materials testing machine was driven down at 1 mm intervals. The test was ended when the force measurement exceeded 70 N. The capacitance was measured with an Inductance-Capacitance-Resistance (LCR) meter (B&K Precision 889B). The displacement, force, and capacitance were recorded three times at each interval. This data set was collected three times on three different sensors.

IV. Results & Discussion

For this sensor, we demonstrated that (1) we chose materials that achieve an appropriate force-displacement curve that falls within the human range and (2) the sensor is linearly responsive to the force/pressure region required for human safety applications.

A. Material Behavior

We were able to replicate a human-like force-displacement curve with a combination of our sensor and soft silicone foam skin, shown in Fig. 3. The Soma Foama skin lowers the force curve during initial compression which falls closely inline with the response of the human forearm. Once the foam is compressed, we see a greater increase in force as the sensor and P-10 silicone compress. When we compare the dummy arm presented in [3] to our sensor response shown in Fig. 3, we see that our sensor response falls within the human range and is close to the center of the human range. We believe this data

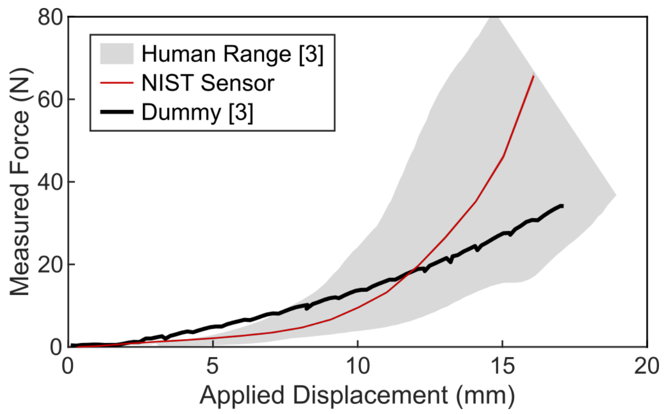

Fig. 3. Force-displacement results for our sensor compared to the reported human range for a forearm and dummy arm presented in [3]. The shaded region around the NIST sensor response shows two standard deviations.

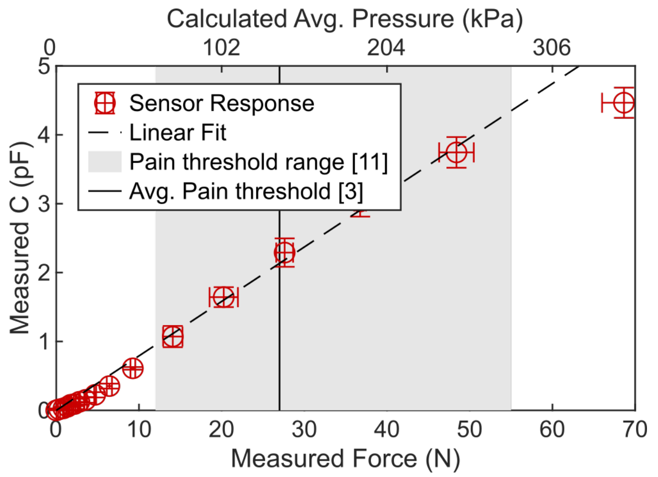

Fig. 4. Mapping between force, calculated pressure, and change in capacitance across the average response of a single sensor. The error bars show two standard deviations.

demonstrate that the proposed sensor is capable of replicating a human-like force-displacement response under quasi-static loading when coupled with the surrounding elastomer and foam skin of a dummy arm.

B. Force/Pressure Response

To understand the behavior of the sensor, we have analyzed the data in two manners. First, we average the results of three trials from a single sensor and calculate a linear fit through the force-capacitance data ($C = 0.079F$, where C is the capacitance in pF and F is the measured force in N, with an R^2-value of 0.9935 when the point around 70 N is removed), shown in Fig. 4. The reported capacitance removes the zero offset. Second, we apply that linear fit to the averaged response of all three sensors and present a comparison of the calculated average pressure ($P = F/A$ where A is the cross-sectional area of the probe) against the reported pressure from the sensors, shown in Fig. 5.

From Figs. 4 and 5, we can see that the sensor has a linear response to force and average pressure up to about 50 N and

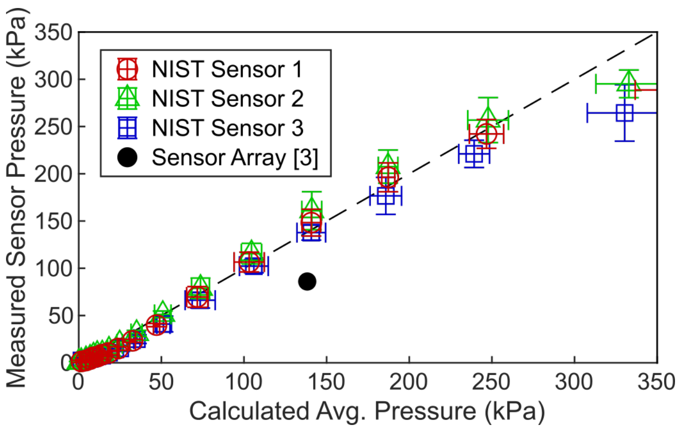

Fig. 5. Comparison of sensor pressure measurements against the calculated pressure. The error bars show two standard deviations.

250 kPa, respectively. The average human pain threshold is about 27 N of force according to [3]. Muttray *et al.* reported pain thresholds between 12 N for the 5th percentile and 55 N for the 95th percentile [11]. These reported pain thresholds both fall in-line with the linear range of our proposed sensor which we believe demonstrates that the sensor is appropriate for measuring the forces and pressures exerted by robots during human-robot interaction.

Fig. 5 shows that responses from sensors 2 and 3 are very close to that of sensor 1. Since we used the linear fit from a single sensor (sensor 1) shown in Fig. 4 for all three sensors, this demonstrates the consistency and reliability of the manufacturing process within the sensor responses. We believe that calibrating the sensors *in situ* helps achieve high accuracy between the calculated and measured average pressure. Our proposed sensor is a suitable candidate for integration with a dummy arm at the forearm location given the pain threshold limits defined in [3] and [11].

V. Conclusion

In this paper, we have demonstrated a capacitive sensor manufactured from conductive fabric and elastomer that has a force-displacement curve within the range of human forearm responses and has a linear capacitive response to force within our desired range. The sensor is linear within the range identified in human pain threshold studies for the forearm [3], [11]. Our tests indicate that it is possible to reproduce the sensor using the fabrication methodology described. The modular design of the sensor makes it feasible to build sensors of varying sizes as well as stiffness to match various parts of the human body. The manufacturing of the sensor is simple which enables those unfamiliar with traditional sensor fabrication techniques to build their own sensors in-house. In the future, we plan to embed this sensor into a dummy arm artifact that could be used in measuring human-robot safety.

Acknowledgment

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References

[1] International Organization for Standardization (ISO), ISO/TS 15066, "Robots and robotic devices - collaborative robots," 2016.

[2] T. Pungrasmi, Y. Shimaoka, T. Okamoto, and R. Watanabe, "A Human-Inspired Pain Sensing System to Recognize Difference between Superficial and Deep Pain for Personal Care Robot Safety," in *35th Annual Meeting of JCSS*, pp. 934–938, Aug. 2018.

[3] T. Pungrasmi, Y. Shimaoka, T. Okamoto, and R. Watanabe, "Contact Area Effects on Superficial and Deep Pain Threshold for Service Robot Safety Design using a Pain-sensing System," *Panasonic Technical Journal*, vol. 65, no. 1, p. 6, 2019.

[4] P. Roberts, D. D. Damian, W. Shan, T. Lu, and C. Majidi, "Soft-matter capacitive sensor for measuring shear and pressure deformation," in *2013 IEEE International Conference on Robotics and Automation*, pp. 3529–3534, May 2013. ISSN: 1050-4729.

[5] H. Vandeparre, D. Watson, and S. P. Lacour, "Extremely robust and conformable capacitive pressure sensors based on flexible polyurethane foams and stretchable metallization," *Applied Physics Letters*, vol. 103, p. 204103, Nov. 2013.

[6] B.-Y. Lee, J. Kim, H. Kim, C. Kim, and S.-D. Lee, "Low-cost flexible pressure sensor based on dielectric elastomer film with micro-pores," *Sensors and Actuators A: Physical*, vol. 240, pp. 103–109, Apr. 2016.

[7] E. L. White, M. C. Yuen, J. C. Case, and R. K. Kramer, "Low-Cost, Facile, and Scalable Manufacturing of Capacitive Sensors for Soft Systems," *Advanced Materials Technologies*, vol. 2, p. 1700072, Sept. 2017.

[8] M. Totaro and L. Beccai, "Electromechanical behavior of soft porous capacitive sensors," in *2018 IEEE International Conference on Soft Robotics (RoboSoft)*, pp. 233–238, Apr. 2018. ISSN: null.

[9] O. Atalay, A. Atalay, J. Gafford, and C. Walsh, "A Highly Sensitive Capacitive-Based Soft Pressure Sensor Based on a Conductive Fabric and a Microporous Dielectric Layer," *Advanced Materials Technologies*, vol. 3, no. 1, p. 1700237, 2018.

[10] F. Pizarro, P. Villavicencio, D. Yunge, M. Rodríguez, G. Hermosilla, and A. Leiva, "Easy-to-Build Textile Pressure Sensor," *Sensors*, vol. 18, p. 1190, Apr. 2018. Number: 4 Publisher: Multidisciplinary Digital Publishing Institute.

[11] A. Muttray, M. Melia, B. Geissler, J. King, and S. Letzel, "Final scientific report on project fp-0317: Collaborating robots - determination of pain sensitivity at the human-machine interface," *Universitatsmedizin, Institut fur Arbeits, Sozial and Umweltmedizin, Mainz. Project FP-0317 Final Report*, 2014.