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Fully 3D Printed Tactile Pressure Sensor

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***Abstract*—With continuous advancements in additive manufacturing and an expanding selection of printable materials, the range of products manufactured via Fused Deposition Modelling (FDM) 3D printing continues to grow. One of the most promising applications of additive manufacturing is the production of tailored, custom-fit prosthetic components, where precise adaptability is crucial for comfort and function. Conductive filaments enable the 3D printing of electronics, and multi-material printing allows for fully 3D-printed sensors with practical applications such as pressure sensing and monitoring. This study investigates a strain gauge-like pressure sensor designed for its integration into prosthetic sockets, where pressure monitoring is critical for comfort and fit. The sensor operates by leveraging the deformation of a conductive material under applied pressure, altering its length and cross-sectional area and thereby changing its electrical resistance. This resistance change correlates with mechanical stress, enabling pressure measurement. The sensor design utilizes Multi3D's Electrifi conductive filament as the pressure-sensitive material, polylactic acid (PLA) for rigid structural components, and thermoplastic polyurethane (TPU) for flexible support where needed. Multiple sensor prototypes were 3D-printed and tested to evaluate performance. Changes in electrical resistance were measured using a Wheatstone Bridge circuit. The circuit also includes an instrumentation amplifier and a low-pass filter for better signal resolution. The sensor prototypes were tested in compression using a mechanical force applicator up to an equivalent stress of 500(kPa) at a loading rate of 800(N/s). This simulates the loading conditions within a prosthetic socket, the proposed application for these sensors. The results confirmed the design's ability to detect continuous changes in applied mechanical stress, demonstrating its viability for continuous pressure monitoring in sensor arrays.

***Keywords-component*—3D printing, pressure sensor, fused deposition modeling, additive manufacturing, biomedical applications**

I. INTRODUCTION

Additive manufacturing (AM) has become an integral part of modern technologies due to their quick, accurate and cost-effective fabrication of designs and more recently functional structures [1]. The development of conductive filaments has facilitated the 3D printing of electronic components, which when combined with multi-material printing, enables the fabrication of fully 3D-printed devices such as pressure sensors. 3D printing offers rapid manufacturing of these pressure sensors as well as the ability to embed these sensors during the printing of other devices, such as lower-limb prosthetics. This allows for a one-step manufacturing method to simultaneously print a prosthetic socket and pressure sensors within the socket walls. In 2021, the rejection rate of lower limb prosthetics ranged from 24% - 70%, and over 50% of users who rejected expressed pain while using their prosthesis [2], [3]. The use of embedded pressure sensors within these prosthetic devices would allow for monitoring of stress levels around the socket while the prosthesis is in use, and the collected data could be used to further improve the design of the device to better meet the user's needs. Additionally, embedding these sensors into a 3D printed prosthetic socket during the printing process would significantly reduce manufacturing times and costs compared to embedding the sensor after socket manufacturing. The use of this technology can also be later expanded to a variety of 3D-printable wearables and surfaces that are in contact with skin and soft tissue.

Fused Deposition Modelling (FDM) 3D printing has been explored as a method to produce accessible sensors. The technique functions by heating and extruding thermoplastics in the form of filaments. Lee and So [4] developed a pressure sensor which utilizes a circular concentric pattern printed from 3D printed PLA to create a pressure-sensitive surface. The PLA pattern was printed and coated with PEDOT:PSS to give the PLA electrical conductivity. The design showed great sensitivity to various applied forces and distinct measurement levels for different applied pressures. While the design did prove successful, the design required extensive post-processing to achieve pressure measurements which is not suitable for an embedded sensor design.

Other 3D printing techniques have also been explored, such as direct ink writing (DIW). In comparison to FDM 3D

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printing which uses thermoplastics, DIW utilizes viscoelastic inks as printing materials [5]. DIW printers also use pressure to feed inks through the nozzle as opposed to mechanical drives. Using DIW printing, Binelli [6] developed a 3D printed sensor that could be embedded. The design utilizes various inks such as cellulose nanocrystals and MTMS to achieve a flexible and pressure-sensitive device, and was successful in measuring forces within an insole. Another example of DIW printed sensors comes is Mogli [7], who successfully developed a DIW-printed capacitive pressure sensor. The sensor was composed of an in-house manufactured hydrogel which allowed for the sensor to be flexible and stretchable. They tested the sample under various conditions such as finger bending, swallowing, and muscle motion along the forearm. While these sensors did exhibit good sensitivity and repeatability to various applied pressures, the use of DIW 3D printing leads to a significant increase in manufacturing cost as DIW printers range in cost from $10,000 up to $200,000 [8].

Many different materials suitable for FDM printing pressure sensors have also been explored. Huiying [9] investigated a one-step fabrication process for a fully printed pressured sensor using fused deposition modelling. Their design utilizes polyvinylide fluoride (PVDF) mixed with multi-walled carbon nanotubes (MWCNTs) as a piezoelectric layer for measuring changes in resistance. Their design successfully demonstrated changes in voltage as pressure was applied to the sensor. However, PVDF required an enclosed heat chamber in order to print, leading to increases in manufacturing cost. Lee [10] explored a polylactic acid-carbon black (PLA-CB) filament called Proto-pasta as the electrode in their capacitive pressure sensor design. Their design was tested from 5(kPa) up to 50(kPa) and proved capable of detecting changes during dynamic loading conditions. In order to enhance the conduction of their electrode, they performed a post-annealing process on the PLA-CB filament. This post-processing is not ideal for our design, as post-processing is not viable when embedding the design into a 3D printed structure during its print.

This paper demonstrates a fully 3D printed tactile pressure sensor design with potential application for pressure monitoring in various systems, such as in prosthetics. The design of the sensor is reviewed, including the selected materials and working principles. The methodology for realizing this design is discussed, including the 3D printer and data collection system used for manufacturing and measurement recording respectively. The sensors were tested with loading conditions set to partially simulate applied pressures during gait in lower-limb prosthetics, and its response and sensitivity were assessed.

II. Sensor Design

Our goal was to design a sensor that required as little post-processing as possible, allowing for embedding the design into other 3D-printed designs while being printed. These sensors could be used in biomedical applications, such as monitoring pressures occurring within prosthetics. Additionally, FDM 3D printing was selected over other manufacturing methods as it allows for an affordable design for consumers.

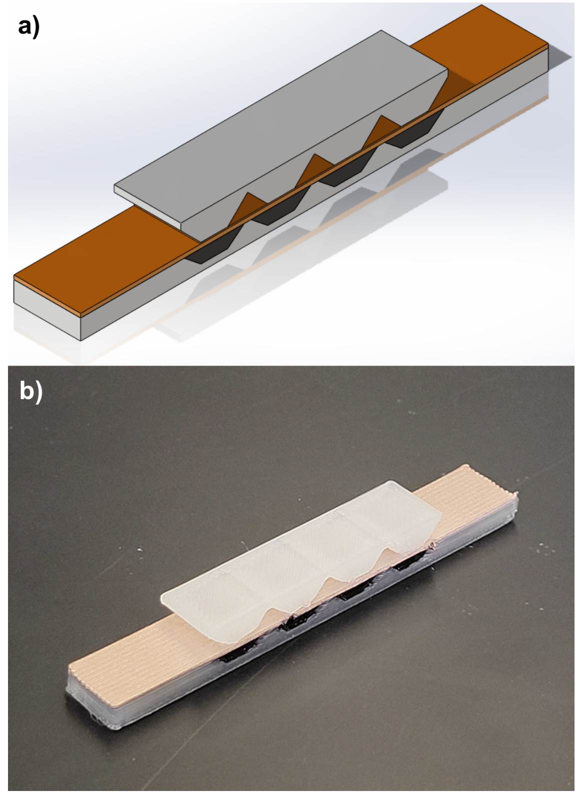

Figure. 1. Developed sensor design. The materials are colored coded as follows; PLA in white, TPU in gray/black, and Electrifi in Orange. a) Computer-aided design model. b) Printed sensor design.

A. Materials

The design consists of three materials as seen in Figure 1. Multi3D's Electrifi (Multi3D, USA) conductive filament is used as the pressure-sensitive material. Clear PLA (Elegoo, CN) is used for the structural components of the sensor that are required to be rigid. TPU with a Shore hardness of 85A (Siraya Tech, TW) is also used as a flexible support material where needed and to fill any gaps in the sensor structure.

B. Design

Figure 1 highlights the chosen design configuration of the pressure sensor. The design uses the working principles of strain gauges to detect changes in mechanical stress. As a force is applied to the upper surface of the sensor, the deposited conductive material deforms into a soft polymer region (TPU). From this deformation, the measured resistance through the sensor will change according to Equation 1.

$$R = \frac{\rho L}{A} \tag{1}$$

where R is the resistance of the material, ρ the resistivity of the material, A the cross-section area of the electrical path, and L the length of the electrical path. As the conductive material is elongated from the applied force, its cross-sectional area decreases according to its Poisson ratio, resulting in an increase in measured resistance as the applied force increases. The resistivity of the conductive material is a material property, and does not change throughout the testing.

III. Methodology

A. Data Collection

To collect resistance measurements, the sensor is connected to an Adafruit Feather Express M0 through a Wheatstone bridge configuration. The Wheatstone bridge is connected to an instrumentation amplifier with a gain of 10, as well as low-pass filters set to 30(Hz). From the testing conditions, a sampling frequency of 25(Hz) was chosen, allowing for a sufficient resolution to measure the rapid changes in applied force.

B. 3D Printing

A Jubilee 3D printer was used and assembled in-house to print the design. This 3D printer utilizes a tool-changing mechanism to swap materials when needed. This mechanism allows for the utilization of multiple materials during printing, while preventing cross-contamination. With the utilization of multi-material printing, each material requires its own printing parameters to achieve a good quality print with strong adhesion between materials. Printing parameters were determined based on visual inspectionI.

TABLE. I
Printing Parameters

Parameter	PLA	TPU 85A	Electrifi
Temperature ($^{\circ}C$)	205*	205	150

C. Sample Preparation

Male jumper terminal connections were selected to form an electrical connection with the samples as they provided the most consistent results. Heat set inserts were considered due to their low nominal resistance readings, however, the difficulties in connecting these to a data collector and its wiring harness were the deciding factors to not use them. Female jumper terminal connections were also tested, however the results were not consistent and thus not considered.

D. Testing Procedure

A mechanical force applicator (TA ElectroForce DMA3200) was used to test the design and determine the correlation between the applied force and the resistance changes. Compression plates with a diameter of 50mm were used, as well as a 500(N) load cell, which provided a wide range of force to test the sensor. The testing procedure begins at an applied pre-load of -25(N). The force applicator is then set to ramp up to a force -250(N) at a loading rate of 800(N/s). These parameters were chosen to approximate the typical loading conditions between a prosthetic socket wall and the residual limb of the user during normal walking gait [11], [12]. Once the set force level is reached, the force is set to hold at -250(N) for 15 seconds. Once this hold is complete, the force applicator is set to ramp down to the initial loading condition of -25(N) where it holds for another 15 seconds. This process repeats for a total of 20 cycles to evaluate the consistency of the measurements over a prolonged duration. The total testing procedure occurs over a duration of 10 minutes.

IV. Results

From the cyclic testing, the resistance and force were plotted versus time to visualize the behaviour of the sensors, which can be seen in Figure 4. The left axis shows the change in resistance from the nominal resistance of each sensor in ohms, while the right axis shows the applied force on the sample in newtons. These are plotted against the test duration, shown in seconds. A total of 6 samples were tested. These results indicate that as the applied force increases, the change in resistance from the nominal also increases. Inversely, as the applied force decreases the measured resistance also decreases.

Initially, there is a large change in resistance, and as the samples undergo a larger number of cycles the total change in each cycle gradually attenuates. This behavior is expected

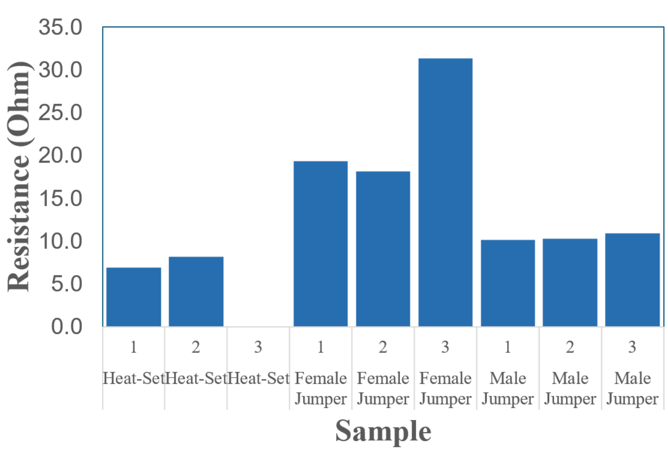

Figure. 2. Average resistance readings of terminal test samples

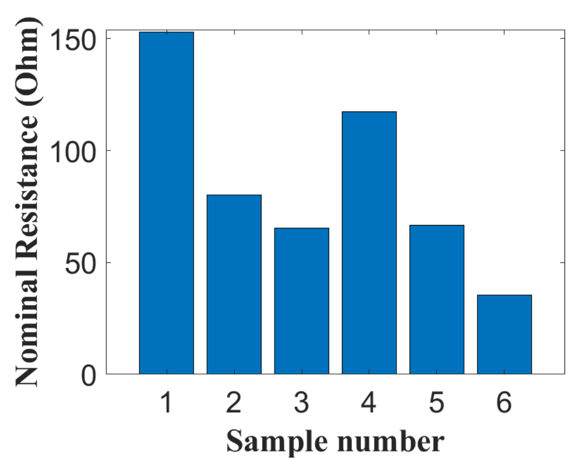

Figure. 3. Nominal resistances

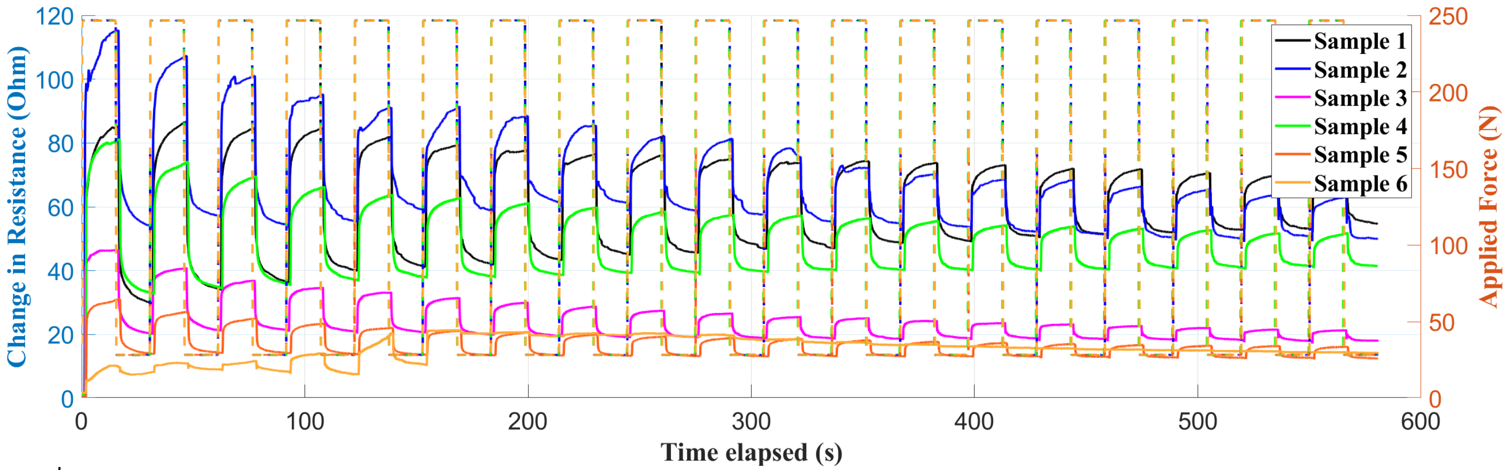

Figure. 4. Normalized testing results

for this type of sample, as initial testing serves to compact the printed materials and reduce the number of voids and gaps between the deposited traces of materials. Towards the end of the testing, it can be see that the samples are more stable and the total change between cycles is more consistent, indicating that the sensor measurements are consistent and repeatable over long durations. The overall change in resistance ranges from 5(Ω) - 20(Ω). It can be seen during the first cycles that the sensor exhibits a non-linear response at the peaks and valleys, and some lag is present. This is resolved as the design undergoes additional cycles, leading to a more rapid response.

A notable outlier in these results is Sample 6. The samples exhibits very little and inconsistent readings during initial testing, and reaches a state of insensitivity to change in applied force. This deviation from the anticipated results can be due to poor print quality or inconsistent printing results, leading to the samples undergoing plastic deformation. The variation in results between 3D prints can be noted by observing the nominal resistances of each sample seen in Figure 3.

The results indicate that the design is capable of detecting and measuring changes in applied pressures over a prolonged duration of loading. The sensor exhibits rapid response to these changes and shows repeatable responses after initial test cycles.

V. Conclusion

This study developed and manufactured a fully 3D printed pressure sensor to detect mechanical stresses to be used and embedded within lower limb prosthetic sockets. The design was verified using a mechanical force applicator for sensitivity to applied mechanical stresses and repeatability over multiple loading cycles. The sensor was tested between 25(N) and 250(N) in compression at a loading rate of 800(N/s). The results indicate that the sensor successfully measures changes in applied pressure and can be used for pressure monitoring in systems that experience frequent changes in applied pressure, such as lower limb prosthetic devices during gait.

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References

[1] H. Pan et al., ”Sandwiched-resistive sensors based on the 3D printing of TPU/CNTs–ILs”, Composites & nanocomposites, J Mater Sci, vol. 57, p. 9187-9201, 2022. doi: 10.1007/s10853-022-07226-4.

[2] E.C. Baars, E. Schrier, P.U. Dijkstra, J. H.B. Geertzen, ”Prosthesis satisfaction in lower limb amputees,” Systemic Review and Meta-Analysis, vol. 97, no. 39, 2018. doi: 10.1097/MD.0000000000012296.

[3] D. Piscitelli et al., ”Prosthesis rejection in individuals with limb amputation: a narrative review with respect to rehabilitation,” Luglio-Agosto, vol. 56, no. 4, 2021. doi 10.1708/3654.36344.

[4] J. Lee, H. So, ”3D-printing-assisted flexible pressure sensor with concentric circle pattern and high sensitivity for health monitoring,” Microsystems & Nanoengineering, vol. 9, no. 44, 2023. doi: 10.1038/s41378-023-00509-z

[5] M. Wei et al., ”3D direct writing fabrication of electrodes for electrochemical storage devices,” Journal of Power Sources, vol. 374, p. 134-147, 2017. doi: /10.1016/j.jpowsour.2017.04.0420378-7753

[6] M.R. Binelli et al., ”Digital manufacturing of personalised footwear with embedded sensors,” Scientific Reports, vol. 13, 2023. doi: 10.1038/s41598-023-29261-0

[7] G. Mogli, I. Roppolo, A. Chiappone, S. Stassi, ”Multi-responsive 3D printable organohydrogel for the fabrication ofdurable and low-hysteresis flexible sensors,” Applied Materials Today, vol. 44, 2025. doi: 10.1016/j.apmt.2025.102675

[8] J.D. Weiss et al., ”A Low-Cost, Open-Source 3D Printer for Multi-material and High-Throughput Direct Ink Writing of Soft and Living Materials,” Advanced Materials, vol. 37, no. 10, 2025. doi: 10.1002/adma.202414971.

[9] Z. Huiying et al., ”One-step fabrication of highly sensitive pressure sensor by all FDM printing,” Composites Science and Technology, vol. 226, 2022. doi: 10.1016/j.compscitech.2022.109531.

[10] S. Lee et al., ”Pressures monitored by 3D printed capacitive pressure sensor embedded on prosthetic upper-limb socket; a case study,” Journal of Biomechanical Science and Engineering, JSME, vol. 16, no. 3, 2021. doi: 10.1299/jbse.21-00077

[11] M. Matray, X. Bonnet, P.-Y. Rohan, L. Calistri, H. Pillet, ”Evaluating interface pressure in a lower-limb prosthetic socket: Comparison of FEM and experimental measurements on a roll-over simulator,” Journal of Biomechanics, vol. 180, 2025.

[12] E.R. Esposito, J.M.A. Whitehead, J.M. Wilken, ”Sound limb loading in individuals with unilateral transfemoral amputation across a range ofwalking velocities,” Clinical Biomechanics, 2015. doi: 10.1016/j.clinbiomech.2015.09.008