Soft robots are ideal to interact safely alongside humans when compared to rigid-bodied robots. These robots require robust soft sensors that can sustain large deformations. Novel soft pneumatic sensing chambers (SPSCs) that can be directly 3D printed using a low-cost 3D printer and an off-the-shelf thermoplastic poly(urethane) (TPU) are presented. The SPSCs are responsive to four main mechanical input modalities of compression, bending, torsion, and rectilinear displacement, and all of these cause a pressure change in the SPSCs. The SPSCs have several advantages including fast response, linearity, negligible hysteresis, repeatability and reliability, stability over time, long lifetime, and very low power consumption. The SPSCs are optimized using finite element modeling (FEM) simulations to obtain a linear relationship between the input mechanical modalities and the output pressure. With the hyperelastic material model developed for the TPU, the FEM simulations accurately predict the experimental behavior. These SPSCs are generic and can be tailored to diverse soft and interactive human–machine interfaces including soft wearable gloves for virtual reality applications and soft adaptive grippers control, soft push buttons for science, technology, engineering, and mathematics (STEM) education platforms, haptic feedback devices for rehabilitation, soft game controllers and soft throttle controllers for gaming, and soft bending sensors for soft prosthetic hands.

1. Introduction

Recently, the development of soft actuators, sensors, and structures for soft robotic applications has led to an enormous growth and interest in the soft robotics field where several soft untethered robots were established. Soft robots are made of highly deformable and compliant materials, which make them suitable and attractive candidates for operating in unstructured environments. Compared to conventional robots that are made of stiff and rigid components, soft robots are safer to operate in highly dynamic environments and to interact directly with humans. A fully soft robot should be composed of a passive or active soft structure, soft actuators, soft sensors, compliant power sources, and soft electronics. One key challenge in the soft robotics field is the development of robust flexible and stretchable soft sensors. Soft robots require robust and stable soft sensors that can sustain large deformations repeatedly while providing useful and reliable data about their own state and their environment.

These sensors are essential for soft robots to develop reliable feedback control systems.

Our aim is to directly 3D print soft robots with integrated actuation and sensing capabilities using low-cost and open-source 3D printers that use soft and flexible materials. Soft pneumatic actuators are compatible with our aim, and recently various 3D-printable soft pneumatic actuators based on multiple additive manufacturing technologies were developed. In the present study, we introduce 3D-printable soft pneumatic sensors to complement 3D-printable actuation concepts based on pneumatics and other actuation methods for soft robots.

While several types of soft sensors have been developed, most require several fabrication steps prior to their integration in soft robotic systems. Resistive strain sensors including flex sensors, conductive inks, ionic conductive liquids, liquid metals, fabrics and textiles, resistive 3D printable thermoplastics, and ultrathin piezoresistive sensors combined with 3D-printable soft monolithic structures were developed to sense large deformations in soft robotic structures. Capacitive soft sensors were also established as pressure sensors, tactile sensors, and strain sensors for various soft robotic applications including commercial wearable soft sensors. Optical sensors were also developed for use in soft prosthetic hands as strain, curvature, texture, and force sensors.
Pneumatic sensors based on soft deformable structures have also been developed for numerous soft robotic applications including human gait monitoring systems, soft grippers, tactile sensors, force and pressure sensors, soft interactive robotic structures, and active controls. Kong and Tomizuka[38] developed an air bladder that can be embedded in a shoe to monitor and detect human gait phases. The air bladder was formed by winding a soft silicone tube that is connected to a pressure sensor. Yang et al.[39] fabricated a pneumatic soft sensor to measure the contact force and curvature in a soft gripper. The soft sensor was fabricated using conventional molding and casting techniques that use commercial silicone rubbers. Choi et al.[40] designed a soft three-axis force sensor based on radially symmetric pneumatic chambers. The sensor was also fabricated by casting silicone rubber. Gong et al.[41] demonstrated a tactile soft sensor for cooperative robots. The sensor was fabricated using a commercially available latex tube that is connected to a pressure sensor. Slyper and Hodgins[42] presented a method for rapidly prototyping interactive robot skins using 3D printing and analog pressure sensors. Several building blocks were designed to offer different modes of deformation such as bending and twisting. Similarly, Vásquez et al.[43] developed 3D-printed pneumatic controls based on the same printing method that can be used for haptic feedback applications.

In these previous studies, the 3D-printed soft pneumatic structures were fabricated using high-cost 3D printers and flexible materials with limited performance in terms of deformation. The other pneumatic soft structures were fabricated using either conventional casting and molding techniques to develop soft robots[44] or using commercially available flexible and stretchable silicone tubes. The other types of sensors integrated in soft robotic structures are usually limited by hysteresis, drift over time, short life time, or slow response.

In this study, we present airtight soft pneumatic sensing chambers (SPSCs) that are directly 3D-printed, without requiring any support material or post-processing, using a low-cost and open-source fused deposition modeling (FDM) 3D printer that uses an off-the-shelf soft and flexible thermoplastic poly(urethane) (TPU). The SPSCs have multiple advantages such as very fast response to any change to their internal volume under four main mechanical input modalities of compression, bending, torsion, and rectilinear displacement; favorable linearity; negligible hysteresis; stability over time; repeatability and reliability; long lifetime and very low power consumption. The SPSCs as the soft and interactive interfaces between humans and machines (Figure 1) can be used as soft pneumatic push buttons (SPPBs), soft pneumatic linear sensors (SPLSs), soft pneumatic bending sensors (SPBSs), and soft pneumatic torsional sensors (SPTSs). The soft TPU used to 3D print the SPSCs was characterized to extract and study its stress-strain data. Accordingly, a hyperelastic material model was developed based on the data obtained for use in finite element modeling (FEM). The performance of the SPSCs was optimized and predicted using FEM to obtain a linear relationship between the input mechanical deformations and the output pressure. These soft pneumatic structures can be rapidly designed, customized, and 3D-printed to target various applications including soft wearable gloves for virtual reality applications and telecontrol of soft adaptive grippers, soft touch buttons for interactive soft robotic platforms for science, technology, engineering, and mathematics (STEM) education and haptic devices for rehabilitation, soft controllers and throttles for gaming applications, and soft bending sensors for soft prosthetic fingers tracking and control.

2. Results

2.1. SPSC Characterization Experiments

2.1.1. Linearity and Hysteresis

We activated all the SPSCs to obtain a relationship between the mechanical inputs (i.e., deformations) applied on each type and

Figure 1. Schematic illustration of the SPSCs responsive to four mechanical modalities and their dimensions and design as sensors. A) SPPB, B) SPLS, C) SPBS, D) SPTS, and E) SPPB dimensions: $d_{PB} = 20.0$, $h_{PB,1} = 8.0$, $t_{PB,2} = 22.8$, $t_{PB} = 0.80$. F) SPLS dimensions: $d_{LS} = 10.0$, $h_{LS} = 21.0$, $t_{LS,1} = 0.80$, $t_{LS,2} = 3.0$, $\delta_{LS} = 90.0^\circ$. G) SPBS dimensions: $h_{BS} = 34.0$, $R_{BS} = 15.0$, $\theta_{BS,1} = 0.80$, $f_{BS,2} = 2.0$, $f_{BS,3} = 3.0$, $w_{BS,1} = 15.6$, $w_{BS,2} = 4.35$. A triangular groove with a base of 4.0 mm and height of 1.0 mm is added to obtain a local bending joint. H) SPTS dimensions: $h_{TS} = 38.0$, $t_{TS,1} = 0.80$, $t_{TS,2} = 2.8$, $w_{TS,1} = 7.8$, $w_{TS,2} = 12.8$. The top wall of the SPTS is twisted by an angle of 90° with respect to its base. All dimensions are in mm.
the corresponding output pressure. In each case, the mechanical deformation applied was ramped up and down to assess the hysteresis exhibited by each structure. Figure 2 shows that all the SPSCs have a linear relationship between the mechanical deformations applied and the corresponding output pressure and that they exhibit negligible hysteresis. The linearity and negligible hysteresis exhibited by the SPSCs make them ideal to be used directly in diverse soft robotic applications without requiring complex control approaches.

2.1.2. Repeatability and Reliability

All the SPSCs were activated repeatedly to assess their reliability and consistency over time. Figure 3 shows that all the SPSCs generated a consistent output pressure signal under the same mechanical load applied repeatedly. These results prove that the SPSCs are repeatable and generate a reliable pressure signal without any noticeable drift. In addition, these results confirm that the SPSCs are airtight. This repeatability is crucial in soft robotic applications involving repeatable movements that need to be monitored or controlled.

2.1.3. Lifetime

The SPSCs were activated repeatedly to assess their durability. A single SPPB sustained 60,000 activation cycles prior to failure. The remaining SPSCs sustained 150,000 activation cycles without any noticeable failure. All the SPSCs showed a relatively long lifetime. The SPPBs, SPLSs, and SPBSs were activated with a frequency of 1.0 Hz. The SPTS was activated with a frequency of 0.5 Hz, which was the maximum value the servo motor used could handle. The main reason for the difference between the lifetime of the SPPB and the other SPSCs is that the SPPB topology involves overhangs, which resulted in thinner curved walls.

2.1.4. Stability Over Time

The SPSCs were activated for a period of 30 min continuously to assess their stability over time. The internal pressure of the SPSCs remained unchanged during the activation period, as shown in Figure 4. This result proves that the SPSCs are very stable and do not experience any drift over time. Therefore, the SPSCs can be used reliably in soft robotic applications for extended periods of time.

2.2. SPSC Applications in Soft Robotics

Here we demonstrate that the SPSCs can be tailored to various soft and interactive robotic applications including virtual reality, telecontrol of soft robotic systems, STEM education, haptic feedback devices and rehabilitation devices, gaming controllers, and prosthetic hands.
2.2.1. Soft Wearable Glove for Virtual Reality Applications

A soft glove composed of five SPBS was developed to track the motion of a human hand, as shown in Figure 5A–D and Movie S1, Supporting Information. Each soft bending chamber of the soft glove was connected to a separate pressure sensor to track the position of a distinct finger. The position of each finger was directly tracked and visualized using a 3D virtual hand simulation model. The soft glove can be useful for virtual reality applications to track the movements of the various human body parts.

2.2.2. Soft Glove as a Remote Controller for Soft Adaptive Grippers

The same soft glove was used to drive a three-finger soft gripper using a servo motor, as shown in Figure 5E–L. The glove can be used to directly drive the gripper to pick and place fruits, vegetables, and other objects with various weights, shapes, textures, and stiffnesses. The position of the fingers can be precisely controlled using the glove directly without requiring any control algorithms to grasp the objects and to finely manipulate them, as shown in Movie S2, Supporting Information. With this very simple and direct implementation, the glove proved to be robust and reliable to drive the gripper with a relatively high precision and stability. These soft gloves can be used to telecontrol other soft robotic structures with precision using very minimal control.

2.2.3. Soft Interactive Piano for STEM Education

A piano keyboard composed of six keys printed in different colors was developed. The SPPBs used were directly connected to separate pressure sensors. The soft piano keys can generate six different musical notes including Do (C), Re (D), Mi (E), Fa (F), Sol (G), and La (A). When a specific key is activated, a buzzer generates a corresponding note with a specified frequency, as shown in Figure 5M–P. The piano can be used to play a music piece interactivity, as shown in Movie S3, Supporting Information. An interactive screen shows the changes in pressure of each key and the key being activated. The sensitivity of the soft keys to any mechanical deformation can be directly changed by changing the pressure threshold.

2.2.4. Haptic Soft Push Button for Rehabilitation

A simple and effective soft haptic device was developed based on a single SPPB that activates a vibration motor disk, as shown in Figure 5Q–S and Movie S4, Supporting Information. The vibration level of the motor varies linearly with the linear increase in the pressure when the SPPB is activated. The amount of pressure applied, which is directly related to the level of vibration, was displayed graphically using a bar graph that changes its height and color depending on the pressure applied by a user to provide a visual feedback in addition to the mechanical feedback provided by the vibration motor. This application can be useful for rehabilitation applications requiring training to gain back a sense of
touch where the vibration motor disk can be placed on different body parts (Figure 5T).

2.2.5. Soft Joystick for Gaming Applications

A soft joystick was fully printed and assembled based on four SPLSs, as shown in Figure 6A–D. Each SPLS was connected to a separate pressure sensor. Ten different possible states can be achieved based on the number of SPLSs activated simultaneously. The ten possible states include forward, forward-left, forward-right, backward, backward-left, backward-right, left, right, brake, and idle, as shown in Movie S5, Supporting Information. The advantage of these game controllers is that they can be customized, designed, and manufactured easily and rapidly to meet specific requirements such as shape, curvatures, size, and the number of sensors.
2.2.6. Soft Throttle Controller for Gaming Applications

A soft throttle controller based on a SPTS was developed, as shown in Figure 6E–H. The throttle controls the rotational speed of a servo motor. The speed of the motor is proportional to the amount of twist generated by the user using the handle, as shown in Movie S6, Supporting Information. The speed of the servo motor was displayed graphically and numerically. This type of throttle controllers can be used in interactive gaming applications and control of robotic systems.

2.2.7. Master/Slave Soft Monolithic Prosthetic Fingers

A master soft monolithic prosthetic finger integrated with a SPBS was developed to control a tendon-driven slave monolithic prosthetic finger, as shown in Figure 6I–L. The slave finger connected to the servo motor imitated the master finger movements by articulating it to the same position in space when it was deformed, as shown in Movie S7, Supporting Information. This result proves that these bending sensors can be used with merely no control to drive soft structures with reasonable accuracy. These SPBS can be integrated in various soft structures as bending sensors.

3. Discussion

3.1. SPSC Hardware

The 3D-printed SPSCs presented in this study are not by themselves pressure sensors. However, these soft chambers were used in conjunction with commercially available solid air-pressure sensors. The hardware required to operate these...
SPSCs in soft robotic applications include a data acquisition system and solid air-pressure sensors to sense their internal volume due to the mechanical input modalities (Figure S1, Supporting Information). The solid air-pressure sensors that require a power of 13.5 mW have a response time of 1.0 ms.\cite{ref1}

### 3.2. Limitations

Since the SPSCs are based on pneumatics, their operating pressure range decreases when very long connecting tubes are used between their output and their input due to pressure losses in the tubes. However, this limitation can be alleviated either by placing the pressure sensors next to the SPSCs or by manufacturing the SPSCs with a larger internal volume. Placing the pressure sensors adjacently or within a short distance (<50 cm) to the SPSCs, especially for untethered devices, will automatically eradicate this limitation. A larger internal volume will result in higher air-pressure range.

In addition, thicker walls will affect the sensitivity of sensors. The sensitivity of the structures will decrease with an increase in the thickness of the walls for the same dimensions. Similarly, the stiffness of the structures will increase with an increase in the thickness of the walls, which in turn will affect the experience of the users, as larger forces are required to deform the structures.

### 4. Conclusions and Future Work

We developed airtight SPSCs that can be directly 3D printed in one manufacturing step without requiring any support material and postprocessing using a low-cost and open-source fused FDM 3D printer that requires a commercially available TPU. The SPSCs can sense four main mechanical modalities of push, bending, torsional, and rectilinear displacement. These SPSCs have multiple advantages including fast response, linearity, negligible hysteresis, stability over time, repeatability and reliability, and long lifetime. The TPU used to fabricate the SPSCs was characterized to understand its behavior, and a hyperelastic material model was developed for use in FEM. Based on this material model, the performance of the SPSCs was optimized using FEM to obtain a linear relationship between the change in the internal volume and the input mechanical deformations applied. The SPSCs were tailored to diverse soft robotic applications and human–machine interfaces including soft wearable glove for virtual reality applications and soft grippers, soft interactive devices for STEM education, soft haptic feedback devices for rehabilitation applications, soft game controllers and throttles for gaming applications, and soft bending sensors for master/slave soft robotic systems. These low-cost SPSCs can be manufactured easily and rapidly using FDM 3D printing, which makes them ideal for hobbyists, engineers, scientists, and communities interested in STEM education and soft robotics. Also, since these soft chambers are linear, repeatable, stable over time and exhibit insignificant hysteresis, they can be directly implemented in diverse robotic applications that require very small power consumption without requiring complex control approaches. Finally, since these SPSCs are based on pneumatics, they are ideal for integration in soft robotic applications based on pneumatic actuation concepts. The future work includes evaluating the scalability of the SPSCs and quantifying the effect of the internal volume on their performance.

### 5. Experimental Section

The Research Objective and Design: The objective of this study is to design and develop multipurpose and robust 3D-printable soft pneumatic functional SPSCs using NinjaFlex.

**Table 1. Optimal printing settings in Simplify3D for printing airtight and functional SPSCs using NinjaFlex.**

| Parameter                  | Value | Unit |
|----------------------------|-------|------|
| Resolution settings        |       |      |
| Primary layer height       | 0.1   | mm   |
| First layer height         | 0.09  | mm   |
| First layer width          | 0.125 | mm   |
| Extrusion width            | 0.4   | mm   |
| Ooze control               |       |      |
| Coast at end               | 0.2   | mm   |
| Retraction settings        |       |      |
| Retraction length          | 4     | mm   |
| Retraction speed           | 40    | mm s⁻¹|
| Speed settings             |       |      |
| Default printing speed     | 10    | mm s⁻¹|
| Outline printing speed     | 8     | mm s⁻¹|
| Solid infill speed         | 8     | mm s⁻¹|
| First layer speed          | 8     | mm s⁻¹|
| X/Y axis movement speed    | 50    | mm s⁻¹|
| Z-axis movement speed      | 20    | mm s⁻¹|
| Temperature settings       |       |      |
| Printing temperature       | 240   | °C   |
| Heat bed temperature       | 32    | °C   |
| Cooling settings           |       |      |
| Fan speed                  | 50    | %    |
| Infill settings            |       |      |
| Infill percentage          | 100   | %    |
| Infill/perimeter overlap   | 30    | %    |
| Thin walls and movements behavior | | |
| Allowed perimeter overlap  | 25    | %    |
| External thin wall type    | Perimeters only |
| Internal thin wall type    | Allow single extrusion fill |
| Avoid crossing outline     | ENABLED |
| Detour factor              | 100   | –    |
| Additional settings        |       |      |
| Extrusion multiplier       | 1.15  | –    |
| Top solid layers           | 5     | –    |
| Bottom solid layers        | 5     | –    |
| Outline/perimeter shells   | 25    | –    |
| Wipe nozzle                | DISABLED |
| Support material           | DISABLED |



sensors that have multiple advantages such as fast response, linearity, negligible hysteresis, stability over time, long lifetime, and low power consumption, using a low-cost FDM 3D printer that uses a commercially available soft TPU. The objective was achieved by optimizing the soft chambers developed using FEM simulations that predicted their performance. The main reason for developing such chambers as pressure sensors was to provide a new class of robust soft sensors that can be easily manufactured and directly integrated in diverse soft robotic systems as shown in this study.

3D Printing Optimization: The SPSCs were designed and modeled in Autodesk Fusion 360 (Autodesk Inc.). The SPSCs were modeled with a minimum wall thickness of 0.8 mm to ensure that the 3D-printed prototypes were airtight. The 3D computer-aided design (CAD) models were sliced in Simplify3D (Simplify3D Inc.). The printing parameters were optimized to obtain functional airtight prototypes. The stability of the SPSCs over time is highly dependent on the degree of their airtightness. The optimized 3D printing parameters are listed in Table 1. The SPSCs were printed using a low-cost and open-source FDM 3D printer (FlashForge Inventor, FlashForge Corporation) and a commercially available TPU known as NinjaFlex (NinjaTek, USA).

Herein, the optimized printing parameters are explained briefly and some guidelines to obtain 3D-printed airtight and functional SPSCs using FDM 3D printing are suggested. The layer height was set to the minimum value supported by the 3D printer, which was ideal for obtaining airtight structures and high-quality exteriors. The Coast at End option was activated to ensure that no blobs accumulate at the end of each printed layer that might cause air gaps in the structures. The values of the retraction settings were set to ensure that no excess material is extruded due to excess pressure in the nozzle that might cause uneven printed layers and printed plastic residuals on the thin walls. The print speed was set to ensure that a consistent and continuous flow of plastic is preserved throughout the printing process. High speeds might lead to under-extrusion since the printed material is soft. The first layer speed was set to a lower value compared to the actual printing speed to ensure that the first layer adhere to the heated bed. The first layer is the most important layer in the print, and its quality affects the whole printed part. Therefore, the bed must be accurately leveled, and the speed of printing must be adequate to obtain a consistent and complete first layer. The horizontal movement speed of the extruder was reduced to ensure that the printed material was well bonded and fused together to prevent any air gaps from developing between two consecutive ones. The heated bed temperature was set to ensure that the first layer adhered to the bed. High bed temperatures might lead to melting or softening of the first few printed layers. The cooling load was set to ensure that the extruded layers cooled down and solidified immediately to prevent any sagging. When overhangs are presented in a CAD model, the cooling load should be increased to prevent any thin walls or overhangs from sagging. The infill overlap value was dramatically increased so that the shells and the infill could be well fused together. The Perimeter Only option for External Thin Wall Type was activated to account for any thin walls printed. The value of the Perimeter Overlap was also increased to avoid any separation and air gaps between two printed shells. The Avoid Crossing Outline option was also activated to prevent the

Figure 7. Finite element modeling results. The relationship between the input mechanical load and the corresponding change in the volume of the pneumatic chamber for a) SPPB, b) SPLS, c) SPBS, and d) SPTS.
nozzle from moving above and over the extruded outer shells where it might possibly leave some plastic residuals that result in air gaps. Finally, the extrusion multiplier was increased to account for inconsistencies in the diameter of the TPU filament.

**Pressure Sensors and Data Acquisition System:** Analog pressure sensors (SSCDANN100PGA5, 0–100 psi Gauge, 0.25% accuracy, Honeywell International Inc.) were used to detect any volume change in the 3D-printed SPSCs. An Arduino UNO microcontroller was used to characterize the SPSCs and to demonstrate their use in various soft and interactive robotic applications.

TPU Characterization: The stress–strain relationship of the 3D-printed TPU was experimentally obtained by performing a uniaxial tension test on the material. The tensile tests were conducted on the TPU samples according to the ISO 37 standard, where all the samples were stretched by 800% at a rate of 100 mm s⁻¹ using an electromechanical Instron Universal Testing machine (Instron8801). Two different infill patterns, crosswise and longitudinal, were used to print the test samples to assess the effect of the infill pattern on the behavior of the TPU. The infill pattern had an insignificant effect on the behavior of the TPU, as shown in Figure S2, Supporting Information. The TPU was modeled as a hyperelastic material where a 5-Parameter Mooney–Rivlin material model was identified using the average experimental stress–strain data. The parameters of the hyperelastic material model are listed in Table S1, Supporting Information. The model is implemented in ANSYS Workbench (Release 19.1, ANSYS, Inc.) for use in finite element simulations. ANSYS provides various hyperelastic material models and curve fitting tools.

Finite Element Modeling: Finite element simulations were performed on various SPSCs to optimize their topology in order to obtain a linear relationship between the applied mechanical loads and the change in their internal volume and to predict their behavior under such mechanical loads. The FEM simulations were performed in ANSYS Mechanical where a Static Structural Analysis was implemented. The CAD models are meshed using higher-order tetrahedral elements. Contact pairs were defined between thin walls that come into contact when large mechanical deformations are applied on the SPSCs. In terms of boundary conditions, Fixed Support was defined on one side of each structure, and an Appropriate Displacement Support was imposed on their opposite ends to simulate the mechanical deformations applied for each mode of deformation. The FEM simulations proved that a linear relationship exists between the applied mechanical loads and the change in the internal volume of each SPSC, as shown in Figure 7. Ideally, a relationship exists between the change in the internal volume and the actual pressure change obtained experimentally when the mechanical loads are applied on the various SPSCs. Therefore, FEM can be used to predict the behavior of the SPSCs and to optimize their topology to meet specific design requirements quickly and efficiently without wasting potential 3D printing resources.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

3D printing, human–machine interfaces, soft robots, soft sensors

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