Toward a Smart Compliant Robotic Gripper Equipped with 3D-Designed Cellular Fingers

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Usual lightweight soft robotic bodies built with elastomer materials show lack of structural stiffness that limits their use in many practical applications. Herein, an architectured robotic body design with deformable cellular structures, which is easy to fabricate, lightweight, mechanically durable, and compliant while maintaining its resilience, is proposed. The cellular body design overcomes not only the stiffness limitation but also other drawbacks of most common soft bodies that may damage from high pressure or impact. An artificial cellular finger is printed together with embedded pressure sensors on the fingertip to form a functional system in a single-building process with the advantage of multmaterial 3D printing. The integrated architectured grippers, composed of cellular fingers with a repeatable, reliable bending profile, demonstrate maximum gripping force as 16 N on actuation, with gripping capability of various objects. 3D cellular designs open up new possibilities for architectured robotic bodies that can immensely widen their space of applications.

1. Introduction

Conventional robotic bodies made of rigid materials demonstrate great precision to perform heavy industry tasks, but their rigid components tend to compromise the robot's versatility by limiting them from certain operations, such as handling soft and fragile objects and/or dealing with natural or human-based environments. With the advancement in constituent materials of the robot bodies, inspired from the biological systems, there has been an increasing interest in the studies of “softness” in the materials for the emerging field of compliant robotics.[1] Novel elastomer-based technologies and integrated soft systems have been designed and demonstrated recently, which usher innovations for robotics, especially in the applications where elastic versatility is needed. The field of soft robotics focus to accomplish better compliance and deformability in the interaction with the environment, as well as exhibit physical robustness and a human-safe operation at potentially low cost. Most of these robots have taken inspiration from the animals that are capable of performing versatile tasks, such as the artificial snake skin with anisotropic frictional properties inspired by snake’s skin, that enables a single soft actuator to propel itself.[2] Among various elastomer materials used in soft robotic bodies, silicone rubber and highly stretchable hydrogel are popular choices for soft robotic body fabrication due to its availability in low modulus. But they face a challenge to incorporate mechanical durability in this soft body while retaining the softness of the body for interaction, such as robotic humanoid fingers, as previously reported,[3,4] where majority of them are fabricated with silicone rubber and foam[5] and are actuated pneumatically or by shape memory alloy (SMA) and are often prone to tears, punctures, and tensile failures when strained. The robot should be soft for safety, but it should not be so soft when performing tasks; therefore, it should have enough structural stiffness. These challenges open a room for research on soft robotic bodies that are lightweight as well as stiff enough to perform different tasks while maintaining their flexibility. A body whose deformation is in somewhat controlled way has high energy absorption to retain its original shape after deformation, such as silicone. To address this issue, other methods to integrate rigid components with soft material have also been adapted, which can enhance the forces that robots can exert on objects.[6] But these still have concerns for safety and can be used for limited applications. Also, since most control and power systems to control the robotic bodies in this system are electric, all fluid- or air-driven actuators require large compressors, pumps, and valves to convert electric power and signals to fluid flow. The overall bending motion profiles of these common soft bodies exhibit a circular configuration under actuation, which do not conform to the shape of the fingers during flexion, limiting the grasping of versatile objects.[7,8]

Adding architecture reduces the mass of materials and results in highly designed properties. Such modern materials with a complex architecture can achieve higher structural efficiency.[9] Mechanical metamaterials are rationally designed artificial materials, which have their properties delivered by designed structures rather than the bulk behavior of the materials. They have been intensively studied earlier in many robotic applications.[10,11] For designing a cellular structure, the layout of its struts is important, which decides the dominated failure
mechanism of that particular structure. Stretching-dominated cellular solids, such as octet, octahedral, and so on, show higher initial yield strength compared with bending-dominated foamed materials, which is due to their different layout of structural components and makes them better alternatives for lightweight structural applications. One such unique spatially arranged structure produces a negative Poisson’s ratio (NPR); these are called auxetics. Similar to other types of mechanical metamaterials, the NPR of auxetics is generally a direct consequence of the topology, where the joints rotate to move the structure.\(^{[12]}\) This property of NPR materials makes them undergo volumetric expansion and contraction when they are stretched and compressed, respectively, allowing them to show compliant-bending behavior. In this study, re-entrant hexagonal honeycomb auxetic structures are studied for their unique properties such as energy absorption as well as reliable bending properties. The classical re-entrant cell structure has been a focus for many years because of its well-established auxetic behavior. Unlike some of the 2D auxetic structures such as chiral honeycomb, the re-entrant honeycomb structures can be readily patterned into 3D structures with sufficient unit-cell connectivity and auxetic behaviors in multiple principal directions.\(^{[13]}\) 3D re-entrant hexagonal structure is greatly studied, which is more porous, hence lightweight, and shows NPR in all three directions.\(^{[14,15]}\) This 3D structure has been shown to exhibit an NPR at a small strain, with \(-1.18\) being the lowest value recorded.\(^{[16]}\) The 2D honeycomb unit cell is combined with another cell at 90\(°\), around the central axis, to form a 3D unit cell and is linearly patterned to form a 3D auxetic structure. By changing the geometric parameters of the re-entrant honeycombs, these auxetic cellular materials get a tunable deformation capacity. This work studies the effect of the geometric parameters of the re-entrant honeycombs, such as cell angle, thickness, and strut length ratio, on the durability and energy absorption performance of the materials. The consequence of this deformation is the simultaneous expansion of the cell faces, increasing cellular volume. It is known that the NPR of these structures depends not only on the re-entrant geometry but also on the simultaneous flexure, hinging, and stretching of the cell walls.\(^{[17]}\) Being subjected, for example, to a tensile load, the hinges in the corners rotate, forcing the structure to unfold on itself. Elastic metamaterials have been studied earlier to obtain high stretchability,\(^{[10]}\) which has produced completely elastic structures, but they do not include any expandable structures. Auxetic metamaterials that are explored in the field of soft robotics are largely based on 2D planar sheets of the re-entrant cells,\(^{[18]}\) and arrange the unit cells with different values of the Poisson’s ratio program their desired compliant lateral deformation upon deformation. We studied both 3D flexible auxetic structures and their variable parameters to achieve high deformability, durability, and energy absorption while maintaining their compliant nature.

Here, we propose to use porous cellular materials to make a lightweight and compliant robot body that overcomes the challenges of stiffness and bending curvature while retaining the flexibility and durability in an elastic robot, making them firm enough to lift heavy and fragile loads. This cellular body is further driven by micro motors that are still the most versatile, cost-effective, and efficient means of actuation. Compliant motor-driven transmissions generally fall into the categories of cable-driven tendons for which the actuation is transmitted through cables embedded in the structure.\(^{[19]}\) We combine several interdisciplinary perspectives in material science, manufacturing, and robotics using single-step 3D printing with triple materials for the integration of pressure-sensitive, cellular structure–based robotic body. As a demonstration of their potential, we used them in a humanoid finger model as well as a functional gripper, capable of grasping and manipulating objects. Each finger design is composed of cellular structures with three octet segments and two auxetic joints, inspired by bones and joints in human fingers, respectively, along with an integrated pressure sensor on the fingertip to form a functional system. These cellular materials are lightweight as a human bone, and their structure can be altered to achieve different deformation behaviors. Although integration of compliance in a robotic body is generally achieved by embedding elastic joints and soft elements, in case of our structured body, we use re-entrant honeycomb auxetic structures for finger joints that have high volume change capability with shock and vibration absorption properties and have a natural tendency to form dome-shaped double-curved surfaces under bending, called synclastic behavior. These properties make them suitable for joints\(^{[17,20]}\) and have shown applications in robotics.\(^{[9,21]}\) The re-entrant structures are designed with variation in their geometrical parameters to manipulate the deformation of the auxetic cells that will alter their Poisson’s ratio and energy absorption capacity. The distribution of flexible and stiff material is studied to get maximum possible strength and volume expansion in the auxetic structure, which is helpful to attain the joint’s durability and bendability, respectively. We then use these cellular materials to form prosthetic architected fingers to conduct multiple cycles of bending and sensing experiment, as well as develop an architected gripper to demonstrate its intelligent gripping capability.

2. Results and Discussion

2.1. Design of 3D-Printed Auxetic Structures

The 3D-printed cellular structures are studied to confirm their expected mechanical behaviors. Stretching-dominated structures, octet, and octahedral are studied for the stiffness, and their study is published in our earlier work.\(^{[22]}\) Here, we explored an expandable re-entrant-type auxetic structure and studies its mechanical behavior for different geometrical and material parameters. The unit-cell structure (Figure 1A) is formerly known as re-entrant hexagonal honeycomb, where the honeycomb compresses like conventional materials upon loading, and the re-entrant honeycomb shows an auxetic behavior, with NPR, and better energy absorption ability. By achieving higher NPR of the unit cell while maintaining its relative density, a higher volume deformation capacity can be achieved.\(^{[23]}\) The joints part of the gripper body needs to be durable and at the same time flexible enough to provide maximum expansion and shrinkage, on the outer and inner sides of the gripper finger while bending, to perform compliant grasping. With smaller Poisson’s ratio values (more negative), the fracture toughness of the auxetic structure is also found to increase due to the deformation of the re-entrant cell struts, which gives rise to a
significantly larger amount of dimensional change.\cite{24} The geometric parameters are selected to achieve a high NPR, which will result in maximum expansion and contraction in volume under loading conditions. To obtain high Young’s modulus, the structure is reinforced with a carbon fiber–based polymer while maintaining the flexibility of the re-entrant struts whose rotation is responsible for showing an auxetic behavior. The 3D re-entrant hexagonal structures, which show the best combination of high NPR, Young’s modulus, and energy absorption, are therefore best candidates to be used for adding curvature into the gripper body.

To create these complex structures, 3D printing is considered as the most promising technique.\cite{9} One of the most widely used 3D printing technology, fused filament fabrication (FFF) dispenses molten thermoplastic materials through an extrusion nozzle heated above glass transition temperatures of the plastics. The printed filament solidifies immediately after the extrusion. An object is built up with a print head moving with the designed trajectories layer-by-layer. In this report, an FFF-based 3D printing capable of 100 μm printed layer resolution was used with the SeeMeCNC Rostock Max 3D printer, which is equipped with four-nozzle-based multi-extrusion system. We used triple-material printing in a single-step building process using different kinds of materials, based on this cost-effective and less time-consuming 3D printing technique (Figure 1B).\cite{25} Dual-material-based auxetics have been reported by the Polyjet printing technique. But here, we used the FFF-based 3D printing technique to create cellular structures, because it has more broad range of printable materials that are easily available, and it consumes less time.\cite{22} Using multi-material printing technique, different compositions of complex structures are created by using both rigid and flexible materials. Thus, multi-material 3D printing enables multi-functional objects, where rigid sections can be combined with flexible ones, with high-strength or conductive sections, and all these different sections/elements can be printed in a single-step process with a multi-extrusion 3D printing equipment. Therefore, a desired mechanical behavior can be achieved to design robot bodies for different applications.

Apart from studying the usual design parameters of these structures, such as length of vertical struts, length of re-entrant struts, thickness of struts, and re-entrant angle to achieve the optimal auxeticity, new parameters such as material selections and distribution of flexible and stiff regions in the unit cell are studied as well to attain maximum stiffness without compromising in its auxetic behavior. 3D re-entrant honeycomb structure is a common auxetic structure, known for its superior properties among other auxetics, and is created by joining two 2D unit cells at 90°. These unit cells are arrayed 3 × 3 × 2 to form a
3D auxetic structure for joints. Different auxetic models with various $\theta$ (20°, 30°, 40°) and $\alpha$ (1, 1.5, 2) values are designed using Solidworks, where $\theta$ represents the re-entrant angle and $\alpha$ is the ratio of lengths of vertical strut to the re-entrant strut (h/l) (Table 1). These ranges of values are selected since further increase in a positive $\theta$ value would make it into hexagonal honeycomb structure, which is not auxetic, and the range of $\alpha$ value is to avoid the intersection of the re-entrant struts when the length ratio is less than 1.5. For example, when $\theta$ becomes very small, all the struts in the cell are either vertical or nearly vertical. This type of lattice has almost no room to collapse inward when subjected to a compressive load and will therefore behave more like a bulk solid than a lattice material. Six models were made from different combinations of these values (Figure 1C). Among them, three models ($\alpha = 1.5$, $\theta = 20^\circ$, $\alpha = 1.5$, $\theta = 30^\circ$, and $\alpha = 2$, $\theta = 30^\circ$) are further selected for compression study. These models are chosen because they have comparatively more space inside the unit cell to move inward under compressive loading that would result in larger volume change and also Young’s modulus and density is found to decrease once the structure became “less” re-entrant.[23] Multi-materiality serves as an extra dimension to design and control properties of 3D auxetics within a given design space. This can allow tuning the stiffness of the auxetic cellular structure with fixed geometrical parameters for enhancing its applications. Three materials were used in the experiments—SemiFlex as a flexible material, which is a thermoplastic polyurethane (TPU) material, polylactic acid (PLA), and carbon fiber reinforced PLA (CFRPLA) as rigid materials. Using the parameter of distribution of rigid and flexible materials, three designs were studied—single, dual 1, and dual 2. The single unit cell is made up of SemiFlex material, which makes it flexible throughout the unit cell (Figure 1D). To add stiffness to this structure, a rigid material is added to the struts. The movement of the re-entrant struts are majorly responsible to show the auxetic behavior; therefore in dual 1 design, the re-entrant struts are made with SemiFlex and the vertical struts are made with a PLA material (Figure 1E). The soft material serves as a hinge in the auxetic structure to facilitate opening and closing of the re-entrant cell during loading, which improves the auxetic behavior. Since the rotation at the joints causes the re-entrant struts to move inward and outward, and to minimize the stiffness of the re-entrant corners, the flexible region is confined to just the joints, and the rest of the part is made with CFRPLA in dual 2 design (Figure 1F). It should be noted that the percentage of stiff base material was kept same for all dual 2 models with the value, $f_s = (h_s/h_l) = 0.45$. From a previous study, CFRPLA has shown to have improved stiffness than PLA due to the alignment of included carbon fibers, so the dual 2 design uses CFRPLA such that the vertical struts have aligned carbon fibers to have the most stiffness.[22] In both the dual material designs, the overlapped regions are printed such that they have alternate layers of flexible and rigid materials, making a reliable connection.

### Table 1. Auxetic unit cell designs based on different $\alpha$ and $\theta$ parameters.

| Samples | Single mater | Double mater #1 | Double mater #2 |
|---------|--------------|----------------|-----------------|
| $\alpha = 1$  | $\theta = -20^\circ$ |                  |                 |
| $\alpha = 1.5$ | $\theta = -20^\circ$ |                  |                 |
| $\alpha = 1.5$ | $\theta = -30^\circ$ |                  |                 |
| $\alpha = 2$  | $\theta = -20^\circ$ |                  |                 |
| $\alpha = 2$  | $\theta = -30^\circ$ |                  |                 |
| $\alpha = 2$  | $\theta = -40^\circ$ |                  |                 |

#### 2.2. Mechanical Characterization of Auxetic Cellular Designs

To identify the changes in the mechanical behavior of different unit cell structures, compression tests were conducted. These tests help to study the energy absorption capability of the cellular materials and provide modulus information to choose the best auxetic structure capable of bending at the finger joints. Samples arrayed with $3 \times 3 \times 2$ unit cells were tested by uniaxial compression to see the stress–strain behaviors of distinctive designs and material compositions using Shimadzu EZ-LX Universal testing machine with a 5 kN load cell. The unstrained arrayed samples were compressed between flat steel plates at a constant strain rate of 2 mm min$^{-1}$ to the point of full densification and then unloaded. The compression tests were controlled and recorded using Trapezium X software. The deformation behaviors of all the auxetic models were recorded using a Canon EOS 700D camera with 24–105 mm lens. The displacement for each model was obtained, and their corresponding Poisson’s ratio, $\nu$, is calculated from the captured images. An image-processing tool is used to capture images from where the lateral displacement (perpendicular to the load) is measured from the center unit cell in the middle row. As the compression is applied at a controlled rate, the linear displacement values are known and are used to calculate the Poisson’s ratio value for each structure. The compression test results of single- and dual-material auxetic structures are shown for $\alpha = 1.5$, $\theta = 20^\circ$ model (Figure 2A) at different applied strain (0%, 20%, and 40%). For the single-material design, the structure buckled in all directions, but the dual-material structures deformed uniformly, with
even stress distribution when they are compressed, making them self-supported. The vertical stiffer struts do not suffer deformation as they are not in the loading direction.

The stress–strain behavior of all the auxetic structures is compiled in a graph (Figure 2B), and the legend reads as alpha–theta–material composition (e.g., $\alpha = 1.5$, $t = -20^\circ$, $\theta = -30^\circ$ for designs (single, dual 1, and dual 2). The legends read as “a” for alpha, “t” for theta, and S, D1, D2 for single, dual 1, and dual 2, respectively. C) Finite element analysis (FEA) simulation analysis of compressed auxetic unit cell to study the different stress distributions in the elastic region for the three different designs. The color code is kept constant and is defined next to each image. The corresponding elastic curves from experiment and simulation are compared for each case. D) The cellular finger is designed using the rigid stretching-dominated octet structure for the main body and using chosen auxetic structure ($\alpha = 1.5$ and $\theta = -20^\circ$) with dual 2 designs for the joints.

Figure 2. Characterization of 3D printed auxetic structures: A) Compressed samples from the design with $\alpha = 1.5$ and $\theta = -20^\circ$. Three different material distributions in the unit cell (single, dual 1, and dual 2 designs) are studied. Images were captured for each sample at 0%, 20%, and 40% strains. B) Stress–strain graph of three samples with different combinations of $\alpha = 1.5$, 2 and $\theta = -20^\circ$, $-30^\circ$ for designs (single, dual 1, and dual 2). The legends read as “a” for alpha, “t” for theta, and S, D1, D2 for single, dual 1, and dual 2, respectively. C) Finite element analysis (FEA) simulation analysis of compressed auxetic unit cell to study the different stress distributions in the elastic region for the three different designs. The color code is kept constant and is defined next to each image. The corresponding elastic curves from experiment and simulation are compared for each case. D) The cellular finger is designed using the rigid stretching-dominated octet structure for the main body and using chosen auxetic structure ($\alpha = 1.5$ and $\theta = -20^\circ$) with dual 2 designs for the joints.
the dual-material auxetic structures require higher stress for deformation and therefore have more energy absorption than single-material auxetic structures. The energy absorbed by a cellular structure during a compression is simply the area under the stress–strain curve, up to the strain to which it is compressed. Since little energy is absorbed in the linear region, a long flat plateau is desired for an efficient energy-absorbing structure, such that compressive energy can be absorbed at a constant load.\footnote{20}

In case of dual-material designs, dual 1 and dual 2, where dual 2 represents the flexible joints structure, the later shows tremendous improvement in energy absorption as well as a steep slope defining higher Young’s modulus. An improvement in Young’s modulus can also be understood to result from the aligned carbon fibers in the vertical struts made from the portion of CFRPLA. The same trend is shown by all three models, where the Young’s modulus, energy absorption, and strain sensitivity are in order, dual 2 > dual 1 > single designs, and $a = 1.5$, $\theta = 20^\circ$ model outperforms in all three designs as compared with the other three, making it the most optimized one. Table 2 lists the mechanical properties measured from the compression experiments. Young’s modulus values can be seen to follow the same order as seen in the graph mentioned earlier. As for the NPR, the dual 2 design structure shows enhanced values for majority of the structures. The NPR values measured from compression experiments ranged from $-0.1$ to $-0.4$, and a high value of $-0.47$ was observed in sample $\alpha = 1.5$, $\theta = 30^\circ$ dual 2, which has the large re-entrant angle as well as strut length ratio, thus allowing the maximum movement in the structure. The energy absorption for both single and dual 1 designs are comparable, where the NPR for single is more due to the higher flexibility of the whole structure in which the vertical struts also buckle toward densification, allowing more inward movement. Analyzing the results obtained from the compression testing, listed in Table 2, bar charts are made to compare three properties for each model visually as shown in Figure S2, Supporting Information. Dual 2 design models comparatively show higher performance in terms of Young’s modulus, energy absorption, and Poisson’s ratio. To make an expandable joint, a higher volume expansion cell is chosen, which in case of auxetic should have a higher NPR (more negative). On the basis of this selection criterion, model $\alpha = 2$, $\theta = -30^\circ$ shows the highest values of NPR among all three models. Between the other models, $\alpha = 1.5$, $\theta = -20^\circ$ shows 0.17 higher NPR than $\alpha = 2$, $\theta = -20^\circ$. To make these joints durable, it is important to have stiffness in the structure that will not be equivalent to that of the stiff structure but is enough to make a reliable joint structure. Therefore, comparing the Young’s modulus, model $\alpha = 1.5$, $\theta = -20^\circ$ is the stiffest, while $\alpha = 2$, $\theta = -30^\circ$ shows the least value. Thus, comparing all three models, $\alpha = 1.5$, $\theta = 20^\circ$ with dual 2 material distribution exhibits the optimal combination of higher Young’s Modulus (0.8 MPa), energy absorption (0.67 J), and a high NPR ($-0.35$), making it the candidate for the finger joints.

Finite element method (FEM) used to simulate auxetic unit cell’s linear elastic behavior using ANSYS 18.0 Workbench shows similar results as experiments. Material properties assigned to the simulation are listed in Table S1, Supporting Information. Meshing of the unit cells was done using hexagonal solid elements with default minimum edge length of $1.16 \times 10^{-4}$ mm (Figure 2C). Bonded contacts were formed at each joint that are checked for any slipping or detachment using contact tool analysis after performing simulation. The boundary conditions are applied to all the models, where the edges at the bottom are fixed and the top ones are loaded with controlled downward displacement, perpendicular to the vertical struts. The mesh quality was checked by a refinement study, in which meshes of assorted sizes were compared. When the results were same over a range of different-sized mesh analysis, the simulation results are confirmed and used further. The stress distribution contour for $\alpha = 1.5$, $\theta = -20^\circ$ auxetic unit cell is shown in three images for each design (single, dual 1, and dual 2). In contour scale, gray color represents least or zero stress and red represents the maximum stress value. The stress generated at the re-entrant struts was 6.7 MPa for single, 9.1 MPa for dual 1, and 19.5 MPa for dual 2 designs with the same 10% applied strain. This similar trend is noticed for multi-material auxetic cells in the compression results for elastic strains. The results show how the material gradient in cellular struts can affect the stiffness considerably. The stress distribution contours for all re-entrant cells demonstrate the localized stress concentration at the inner re-entrant joints and is highest for dual 2 design, which permits easy translation and rotation of struts, leading to structural flexibility. A very small and localized stress can also be observed at the interface of material change in case of dual 2 multi-material cell. Both the movement of re-entrant struts for improved auxetic behavior and the stress at the re-entrant joints follows the order, dual 2 > dual 1 > single, which aligns with the experimental compression test results. Reaction force and displacement results were used to plot the strain–strain curves for each design case and were compared with the experimental results. The simulation results were linearly fit and show similar slopes of Young’s modulus for single and dual-material designs similar to experimental results. The unique dual-material design allows structure to deform with

Table 2. Mechanical properties of the samples from compression test.

| Properties                  | $\alpha = 1.5$ | $\theta = -20^\circ$ | $\alpha = 2$ | $\theta = -20^\circ$ | $\alpha = 2$ | $\theta = -30^\circ$ |
|-----------------------------|----------------|----------------------|--------------|----------------------|--------------|----------------------|
| Young’s modulus [MPa]       |                |                      |              |                      |              |                      |
| Single                      | 0.33           | 0.24                 | 0.80         | 0.24                 | 0.21         | 0.72                 |
| Dual 1                      | 0.41           | 0.40                 | 0.67         | 0.37                 | 0.44         | 0.84                 |
| Dual 2                      |                |                      |              |                      |              |                      |
| Energy absorbed [J]         |                |                      |              |                      |              |                      |
| Single                      | 0.14           | 0.09                 | 0.35         | 0.27                 | 0.19         | 0.43                 |
| Dual 1                      | 0.41           | 0.40                 | 0.67         | 0.37                 | 0.44         | 0.84                 |
| Dual 2                      |                |                      |              |                      |              |                      |
| Expt. Poisson’s ratio (\text{\%}) 5% elastic strain |                |                      |              |                      |              |                      |
| Single                      | 0.42           | 0.23                 | 0.35         | 0.19                 | 0.2         | 0.18                 |
| Dual 1                      | 0.41           | 0.40                 | 0.67         | 0.37                 | 0.44         | 0.84                 |
| Dual 2                      |                |                      |              |                      |              |                      |
maximum possible volume expansion of the hexagonal cells, resulting in higher NPR.

2.3. Design of 3D Cellular Robotic Fingers

The design of cellular structural finger is made similar to a human finger, where the bones represent the stiff part and the joints represent the bendable part. As shown in Figure 2D, octet structures are used to make the stiff part and re-entrant auxetics are used to make the bendable part. The octet structure is a rigid stretching-dominating structure, which has superior mechanical properties compared with other cellular structures.[20] These are used for the rigid component of the finger, suitable due to their high strength and lightweight properties. Its joints are made using re-entrant auxetic structures with the selected model ($\alpha = 1.5$, $\theta = -20^\circ$), as discussed previously in Section 2.2, which shows the best combination of volume expansion, energy absorption, and Young’s modulus. The schematic also shows the enlarged designs of the auxetic used in the finger model, which undergoes bending when the finger actuates. To bend the finger easily in the inner side of the finger and limit its movement in the opposite outer side of the finger, the auxetic joint is designed by targeting specific positions of the single and dual 2 designs. As mentioned earlier, the single design uses flexible material throughout the auxetic unit cell, whereas the dual 2 design uses flexible material only at the joints and the rest of the part is comparatively stiff (Figure 1D,F). The blue color in the dual cells is printed with alternate layers of SemiFlex and CFRPLA materials, which reinforces the cell structure with higher stiffness. To relatively restrict the movement of the joint in the outer direction, a row of dual 2 design re-entrant cells are added in the $3 \times 3 \times 3$ cell block of re-entrant made from single flexible material. While bending the finger in the forward direction, the inner side of the joint area faces compression, whereas the outer side undergoes tension simultaneously. The auxetic joint is designed with the distribution of dual 2 cells in the middle of the outer side and rest with single flexible material, to completely bend the inner side, mimicking the 1 degree of freedom (DOF) of the finger joint. These auxetic structures add bending ability to the finger, as a finger made with just the stiff octet structures cannot readily bend by itself upon actuation. The high NPR of these structures allow them for maximum expansion and contraction in 3D, which ensures maximum surface contact with objects through compliant bending, while exerting minimum contact force due to its hollow structure. When observing the bending of a finger joint closely, the inner part compresses into the smallest area, whereas at the same time, the outer part stretches and expands. The auxetic effect of the structure complies well with this joint movement, where the cells shrink to the minimum size in the inner side of the joint under compression, and the cells in the outer side of the joint undergo maximum expansion, spreading the area while bending and allowing the finger to undergo a compliant and controlled bending motion. Therefore, the use of rigid joints with mechanical springs can be eliminated by using auxetic structures.

The fabricated finger is actuated using a nylon string that is woven into the middle front side of the finger, such that when the finger is pulled, it moves forward creating compression in the inner side of the finger. Since the finger body is entirely porous, no modifications to the structure need to be done to insert the string. Only one string is used to fully bend the finger and was secured by a knot at the top side, while it is attached to the horn of a 250:1 micro-gear direct current (DC) motor with 6–12 V voltage capacity and 110 rpm. This motor is further controlled by Arduino controller system, explained in Section 2.5, to pull and release the string. As a developed technology, the use of motors provides ease of integration with electronics and well-known control methods; therefore, it makes the integration and building of this system simpler. This will be demonstrated in the following section where capacitive sensing is also done using the same system.

2.4. Integrated Cellular Fingers with Pressure Sensors

The architectured cellular finger is further equipped with a pressure sensor on the fingertip. Figure 3A shows the computer-aided design (CAD) and the finger integrated with further designed pressure sensors. The capacitor with double metal plates filled with auxetic structure is embedded in the inner top side of the finger by in situ 3D printing. The auxetic structures have been used in stretchable sensors to increase sensitivity due to their bidirectional expansion.[27] Upon applying pressure on the tip of fingers, the capacitance between the plates gets changed. The octet structure behind the sensor, in the fingertip, provides a stiff support for the sensor to compress against it. Capacitive sensors offer excellent linearity and hysteresis performance, whereas their sensitivity might be low compared with resistive-type sensors.[28] The electrode plates are printed with a copper-based conductive filament, called Electrifi, from Multi3D, which is printed consequently with a third nozzle in the multi-material 3D printing system. The schematic of the finger (Figure 3A) shows the embedded sensor on the top with the octet structural finger body and thinner auxetic structures in between the plates for flexible bending. The enlarged inset of the sensor shows its four designs, which were composed of different auxetic designs to achieve highest sensitivity. The distance between the two plates was changed by reducing the $2\cos(\theta)$ length of re-entrant unit cell from 7 and 3.5 mm. Also, the strut diameter is reduced from 1.5 to 1 mm, which is the smallest that the FFF printer can reliably print. These factors change the area of the plate and distance between the plates, which affects the sensitivity of the capacitance change. These four models are evaluated for static structural simulation study using ANSYS 18.0 software. The samples are strained by fixed percentage as 5%, 10%, 20%, and 40% of displacement, and their resulting forces are measured. Also, the capacitance values of the sensors are calculated using the equation with combined dielectrics from air and the material ($K_{air} = 1$, and $K_{SemiFlex} = 6$). Thus, the following relation is used for total capacitance ($C$)

$$C = \varepsilon_0 b (K_{air} X_{air} + K_{SemiFlex} X_{SemiFlex}) \div d$$

(1)

where $b$ is the width of the plate, $X_{air}$ and $X_{SemiFlex}$ are volume ratio of each dielectric material, and $d$ is the distance between the electrode plates. The capacitance change is plotted against the pressure change to determine the sensitivity.
(sensitivity = \( \Delta C/\Delta P \)) in Figure 3B. It is seen that model #1 has the highest slope corresponding to the highest sensitivity among other designs. The cellular finger is assembled together with the actuation system, where a motor is used to pull a string passing through the finger and connected at the top. Therefore, the 3D printed architectured robotic system is built with auxetic joints and octet cellular body made and equipped with a sensitive pressure sensor.

2.5. Compliant Bending with Pressure Sensing

The fabricated robotic finger body takes advantage of using cellular materials to enhance its mechanical properties. Its bending performance is measured reliably by repeated bending tests more than 1000 times. To allow fingers to demonstrate feedback by sensing capacitance, a pressure sensor was 3D printed together with cellular structures composed of double conductive plates as a capacitor, located on the fingertip, separated by the auxetic unit cell, to allow easy compression when force is applied. The sensor design (model 1) is used for the cellular finger, whose metal plates have an area of 520 mm\(^2\) and a compressible gap of 6 mm between the plates. The sensor is simultaneously printed with the rest of the finger. The human touch sensing system (Figure S3, Supporting Information) consists of an Arduino UNO, a H-Bridge, an external battery supply of 6 V for the motor, a second external battery supply of 6 V to supply the Arduino board, a 1M\(\Omega\) resistor. A high-speed DC motor is used for actuation, which provides enough force to bend the finger completely at its joints. For actuation, a nylon string with 200 \(\mu\)m in diameter is used that acts as a tendon for winding and unwinding the finger bodies.

A capacitive sensing library from Arduino is used to sense the electrical capacitance, where we have an output that transmits a pulse and an input that receives the pulse and compares it to the
transmitted pulse. Although the finger is at rest in an upright position, when a plastic object is touched against the sensor on the fingertip, there is a slight change in the capacitance, which is below the threshold, so the finger stays at rest (Figure 3C). Here, the graph reads a capacitance of 3 pF when the plastic object is pressed against the fingertip sensor, thus reducing the distance between the plates. But if the sensor detects human touch, then the motor is actuated to pull the string in the finger, subsequently bending it (Figure 3D). The graph in this case shows that when a conductive object or human touch (which has a very high charge) is pressed against the sensor, the capacitance quickly shoots up to around 42 pF, which is much higher than the set threshold of the capacitance. This triggers the motor to actuate the finger, making an electromechanical output based on the capacitance derived by the change in environment. The bending trajectory is very compliant to an actual human finger. The auxeticity of metamaterial forms similar curvature and flexibility of a finger joint, making this architectured finger durable to withstand more than 1000 bending cycles. It also shows reliable bending profiles at the auxetic joints, without compromising the overall elastic properties of the robot itself. Bending and sensing capabilities of the cellular robotic fingers are demonstrated (Movie S1, Supporting Information), along with a graph showing the change in capacitance signal when an object and finger is pressed against the sensor. The graph is plotted with Arduino plot that shows arbitrary capacitance values on the y-axis against time. The finger is flexible and compliant enough to have safe interaction in the human environment while capable of sensing its surroundings. This experiment demonstrates the advantages of architectured robotic finger, integrated with metamaterial joints, which allows compliant bending, and offers to sense and distinguish targets in an unstructured environment. Also, it is robust and able to withstand impacts with its stiff body at the same time.

2.6. Pressure-Sensitive Architectured Robotic Gripper

To demonstrate the utility of the cellular fingers in robotic application, three fingers are assembled to produce an architectured robotic gripper. The gripper is mounted on a delta robot platform that enables the target objects to move in all three axes. Details of the robotic gripper are shown in Figure 4A, where the three cellular fingers are distributed periodically along the rigid holder. Each finger is assembled with dimensions as \( \theta = 45^\circ \) and \( r = 22 \text{ mm} \) to maximize the dimensional range of the manipulable objects. During the grasping test, all fingers are actuated simultaneously by the 110 rpm micro motors connected to each finger and placed right above them in the red holder. Given the current design of the gripper, the maximum size of a spherical object it can accommodate is about 90 mm under ideal bending and actuation conditions. The movement of the architectured fingers while gripping is shown in Figure 4B, where the fingers start bending at the joints and eventually pinch at the fingertips upon full actuation.

Mechanical stimuli such as pressing, bending, and stretching are shown to be measured with precision to provide information about the surrounding environment. Many haptic or touch sensors used in wearables are therefore based on strain measurement. A grasping test is performed with the structural gripper, which shows that it can manipulate a large variety of objects indicated in Figure 4C. The demonstration includes both delicate objects such as fruits, disposable cup, egg, as well as heavy objects such as pliers and metal piece. The gripper can grasp different objects of various shapes, stiffness levels, and sizes reliably, benefiting from the high strength of the cellular design and flexibility from the elastic multi-materials. This structural gripper can be applied in industrial lines or for harvesting fruits. It is therefore possible to obtain high forces by choosing suitable high-torque motors. As a developed technology, the use of motors provides ease of integration with electronics and well-known control methods; therefore, it makes the integration and building of this system simpler. The gripper’s grasping force is also evaluated to measure the maximum force exerted by the gripper when fully actuated. The structural gripper was tested for its grasping capability by grasping a 3D-printed fixed spherical shape object, and its capacitance change was measured by the pressure sensors on fingertip. Figure 4D shows the open and closed position of the gripper while grasping spherical objects. The supplementary video (Movie S2, Supporting Information) shows the grasping and manipulation capability of the gripper.

Insulated 24 American wire gauge (AWG) wires are connected to the top and bottom plates of the sensor, and the connection is made by using Electrifil filament. For each test trial, the structural gripper grasped the object firmly when the motor is supplied with 12 V to actuate its maximum capacity; then, the capacitance was recorded before and after grasping the object. The capacitance and applied pressure stress \( (\sigma) \) are related by using Hooke's law

\[
\frac{C}{C_0} = (1 - s/E)^{-1}
\]

where \( E \) is the Young's modulus of the auxetic structure (0.33 MPa) between the plates for our case. The grasping test is repeated for ten consecutive cycles and the average of maximum force is calculated. Forces were calculated using Equation (2) for each cycle, and the maximum force that the fingertip sensor measured was about 16 N, which proved sufficient to perform gripping of multiple objects (Figure 4E), and readily tunable depending on the tension of the pulled string, controlled by the torque of the motors. The normalized capacitance response is shown in Figure S4, Supporting Information, which was acquired to analyze the repeatability and the drift of the pressure sensor. The consistent change in capacitance over multiple cycles shows the repeatability of the capacitive sensing. Although the capacitance values of all three sensors in each finger were not exactly the same, it ranged from 2 to 5 pF capacitance with no pressure applied.

To demonstrate the intelligent sensing of the gripper, it is further explored to distinguish among different objects based on their size. Similar to the sensing capability shown earlier in Section 2.5, a threshold is set up to perform mechanical actuation when the value larger than the threshold is detected. In the same way, thresholds for capacitance change value represented as a characteristic for each size of the ball can be set up, and intelligent gripping and manipulation can be demonstrated. Three spherical objects are 3D printed with different sizes as
The capacitance change is measured while gripping each object at complete actuation of the motors. The measured change in capacitance is plotted against the diameter of each sphere object in Figure 4F. The graph shows a linear response, where the capacitance change is the highest for the smallest object and vice versa. The motors are actuated with the same voltage to give the same gripping force on each finger, and the objects are placed such that the sensors are in complete contact with the object's surface. The grasping sequence involves applying voltage to all motors to enable bending of fingers, while touching the objects in their path of bending. The pressure applied from the smallest sphere is the highest. Thus, it moves the capacitance plates closer and causes a higher capacitance change. This capacitance change reduces with the increase in size of the object being touched due to the reduced pressure change, as shown in Figure 4F. By grabbing objects with different sizes that create higher contact pressures, the capability of the sensor-equipped gripper is demonstrated as a functional robotic system, to distinguish between different sized objects and perform required action on the same.

3. Conclusions

We present the design and fabrication process of an architected robotic finger based on 3D printed metamaterials in this article. The finger design features compliant auxetic joints, octet body, and an embedded pressure sensor. In our design, we use the structural skeleton that improves the mechanical stiffness while being flexible, and the auxetic joints enable compliant bending of the finger by undergoing expansion on the outer side and compression on the inner side. The metamaterial body conforms to the finger profile during actuation with touch/pressure sensing capability. This cellular robotic finger is lightweight and stiff, thanks to its designed porosity, mechanical behaviors, and mechanical robustness from octet and auxetic structures, as well
as resiliency with its material composition. Unlike other soft robotic fingers that are mostly composed of silicone, our cellular finger overcomes their mechanical weakness. Another demonstration of architectured gripper composed of three compliant fingers can manipulate various objects.

An appropriate design of the finger geometry with compliant joints allows the fingers to adapt to the shape of the object with tunable mechanical properties. An embedded pressure sensor on the fingertip allows to actively interact with its environment through sensing. We believe that the sustainable manufacturing, cost-efficiency, mechanical durability, and high repeatability of the developed cellular robotic body will benefit the field of robotics. In addition, the demonstrat cellular finger can have tunable flexibility and robustness to be adapted in customized prosthetic hand with controlled pressure-sensing functions. The structures can also be miniaturized for use in small-scale systems.

Our architectured robotic finger is a starting point of cellular design concept. Therefore, there is a lot of room for further research in this topic. Design of other mechanical metamaterials has lots of opportunities, so other lattice structures can be investigated to tune additional mechanical deformation functionality in the robotic finger. The optimization of sensor design and addition of other sensors can also be investigated to achieve its ubiquitous performance. This compliant robotic design with metamaterial body can prove to enhance the functionality and durability of robotic bodies for prosthetic or industrial applications, thus developing new generation of robotic systems with better performance and greater adaptability in a variety of tasks.

4. Experimental Section

Fabrication of Auxetic Metamaterials and Cellular Robotic Finger. Multi-material FFF-based 3D printing fabrication method was used, thanks to its large design freedom to fabricate complex structures with high precision. The multi-material 3D printing fabrication process takes advantage of several emerging technologies, such as molding, laser cutting, etc. Rostock max SeeMeCNC printer equipped with 4 nozzle extruder system was used to fabricate all the lattice structures and a cellular robotic finger using three materials in one step. Printing speed was 15–20 mm s⁻¹ on average with a printing temperature ranging from 220 to 235 °C for nozzle and 30 °C for bed. A 0.4 mm aluminum nozzle for metal printing and 0.25 mm brass nozzle for thermoplastic filaments were used with 100 μm printed layer resolution. For characterization of the auxetic structure designs, three samples of each model were fabricated with same printing conditions. While printing the overlapped joint areas in the structures, two materials were printed in alternate layers to make a bed. The re-entrant struts were inclined to the building direction. This ensured that the carbon fibers were aligned to the vertical struts, thus reinforcing the structure. The diameter of these chopped carbon fibers was in the range of 5–10 μm and was compounded of 15 wt% with CFRPLA resin. These carbon fibers experienced shear from the nozzle during extrusion, which led to their alignment along the printing direction. The embedded sensor on the tip of the finger to form a functional system was 3D printed with careful control over its design. The dimensions of the printed finger had a length of 130 and 15 mm in width. Lastly, the palm/holder was printed using SemiFlex filament for the integration with the motor. A hole with 1 mm diameter was designed in the finger to insert a nylon string with 200 μm diameter through the porous structures and fixed at the top of the fingertip, which allowed the finger to bend when it was pulled.

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

auxetic, cellular materials, grippers, multi-material 3D printing

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