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STRENGTHENING EFFECT OF FLOODING IN 3D PRINTED POROUS SOFT ROBOTICS SCAFFOLDS

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ABSTRACT

This study aims to design and 3D print porous elements for soft robotic applications and test the stiffness changes when the cavities are filled with liquids. When an elastic element has porous scaffolds, the stiffness can be controlled by filling the cavities with a liquid. A gyroid structure is selected for the design and evaluation of the characteristics of elements. The stiffness of the element in both non-filled and liquid-filled modes is analyzed using Finite Element Model (FEM) simulation Software in two modes where simple support with central loading and compressive uniform loading. A porous test structure is created and tested in these modes for observation of the stiffness change. In this project, employing a Fused Deposition Modelling (FDM) printer enabled us to make our thoughts into reality. The results show that liquid-filling can be used as a stiffening method for porous scaffolds in soft robotic applications.

Keywords: Soft Robotic. Flexible Filament. Porous. Stiffness. 3D Printing.

1. INTRODUCTION

3D printing is one of the fast-developing and trending topics in the science area. Among the seven methods of Additive Manufacturing, Fused Deposition Modelling (FDM) can be used to produce Computer-Aided Designed (CAD) parts by combining melted plastics layer by layer. Using 3D printing, many different parts can be produced from plastics with shore values around A65 to obtain desired softness.

Soft robotics applications are a proliferous topic among 3D printer researchers [1–3]. Soft robotics uses soft plastic filaments for producing robots with the capability of elastic transformability [4]. Scientists also use biomimetic science for developing the motioning and sensing ability of soft robots [5–10]. Totuk et al. [11] studied biomimetic, and they mentioned that bio-inspired additive manufacturing leveled up and became 4D printing. Owing the development of biomimetic and 3D printing technologies, robots have become more compatible with human-robot interactions [12–15]. Wang et al. [16] designed a soft mechanical grasper as part of these interactions. Besides, Selvi et al. [17] conduct an experiment for observing the usage ability of 3 different shapes as soft actuators or sensors. Moreover, Donatelli et al. [18] produced a caterpillar-like soft robot by using biomimetic techniques. On the other hand, soft robots have some possible problems, like preserving the shape during motions and unpredictable motion behavior of soft materials.

Scientists generally use foam structures to provide flexible structures without losing the robustness of soft plastic materials. Having wild numbers of different application chances, porous structures are often used on soft robotic research projects [19–28]. Porous foam structures act as flex as sponges; also, they can fill with liquids for enhancing stiffness and robustness [29, 30]. Although liquid filling can improve the stiffness of soft robotic parts, it can also change the elastic properties of the part. Therefore, Liu et al. [31] researched the effect of liquid filling on the elastic properties of porous materials. This critical work found that elastic properties change with liquid filling, and it directly depended on factors like liquid pressure and pore scales. Gyroid shape infill is one of the best suiting solutions for generating

porous structures. Gyroid shape provides both flexibility and porous structure simultaneously, filling liquids into the structure for changing stiffness [32–34].

Abueidda et al. [35] studied the mechanical properties of gyroid structures and made experimental and finite element studies. As a result, they found that the compressive strength of gyroid structures is one of the best compared to the other.

Varying stiffness is a rising topic in soft robotics studies [36–41]. Stiffness is an essential topic for enhancing the quality and safety of soft robotic applications [42]. Liquid filling operations and using different production materials are used to ensure the variety of stiffness for different situations [43–48]. The idea of observing the change in stiffness with the Liquid filling is the inspiration and motivation point of this study.

This study aims that, observing the strengthening effect of flooding in 3D printed porous soft robotics scaffolds. Two types of designs and two tests, which are associated with part types, were planned. Parts were 3D printed using shore A65 flexible filament, and FEM is used to analyze the parts. Results were obtained on Autodesk Inventor 2021 and discussed.

2. MATERIAL AND METHOD

The study observes stiffness change under pressure force and bending force by filling the part with the liquid. 3D designs of parts were created initially, and soft filament for 3D printing was selected. Parts were modeled to maximize the bending angle on the bending test and volume change in the pressure test and minimize required loads for conducting tests. Shore A65 filament, thermoplastic polyurethane, was selected for printing part due to its high flexibility capacity. Two types of soft parts were printed with the gyroid infill for two kinds of tests. Gyroid infill provides scaffold structure that was necessary for the experiment. Gyroid infill was represented in Figure 1a and Figure 1b.

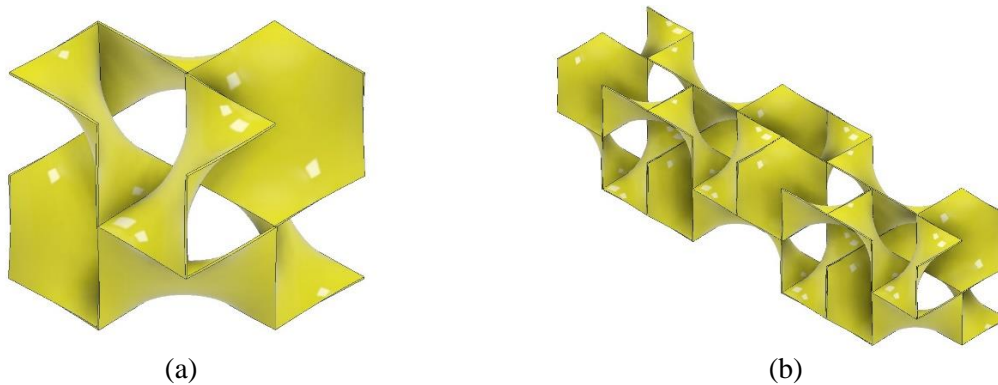


Figure 1. Figures of gyroid infill: (a) Single gyroid section and (b) Complete gyroid infill.

The rectangular prism-shaped part, presented in Figures 2a and 2b, was printed for the bending test, and the cylindrical-shaped part, shown in Figure 2c, for the pressure test. In the printing phase, the bed temperature was set to 60°C, and the nozzle temperature was set to 215°C. Layer thickness and nozzle diameter were selected as 0.2 mm and 0.4 mm, respectively. Finite element analyses were made with Autodesk Inventor Professional 2021. Non-linear finite element model was selected. Other papers were analyzed and used on deciding to model type. Zhang et al. conducted research that “Estimating the effective Young's modulus of soft tissues from indentation tests—nonlinear finite element analysis of effects of friction and large deformation” [49]. The research was used in deciding phase. Results of the analysis were obtained and discussed.

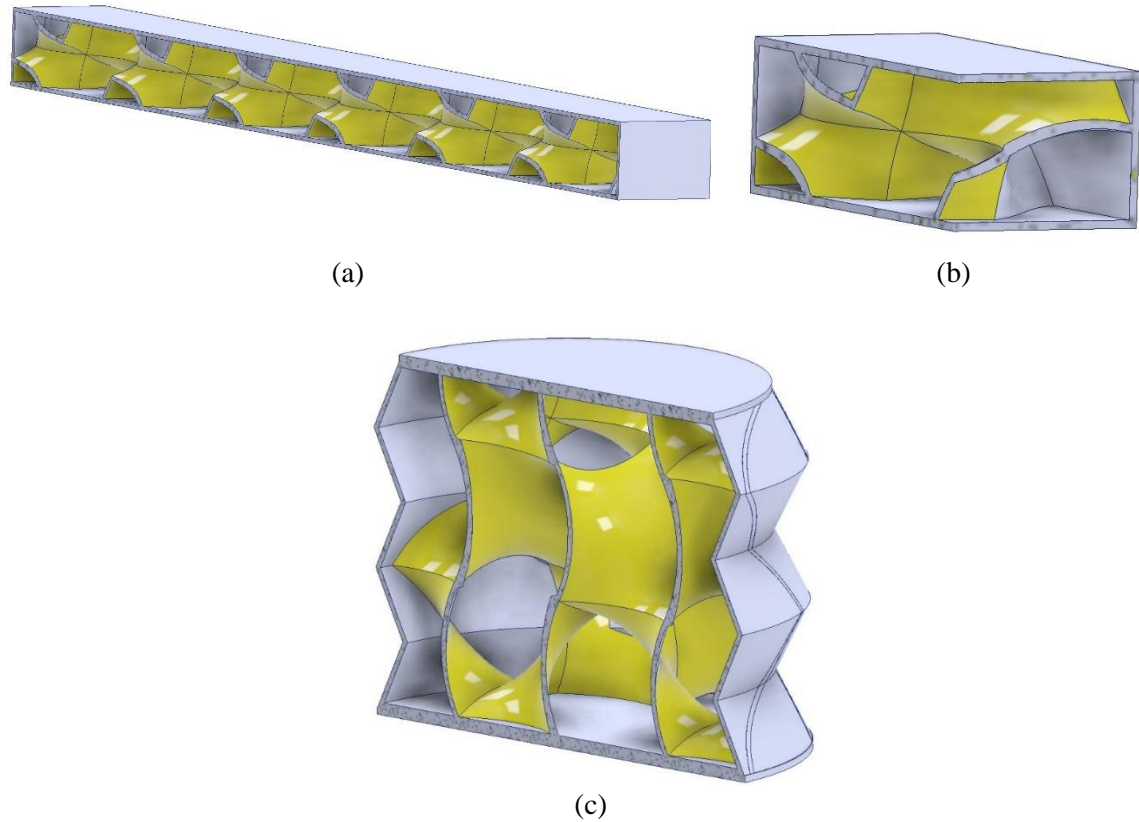


Figure 2. Figures of rectangular prism gyroid infill: (a) Half section view of rectangular prism (b) Quarter section view of the rectangular prism (c) Gyroid infill of the cylindrical-shaped part.

2.1. Bending Test

A rectangular prism-shaped beam was printed, and after an impermeability check, it was used to implement a bending test. The test was held by hanging 100 gr weights to be 1100 gr in total. Water was used as a filling Liquid, and it was applied by syringe. The test setup was presented below as Figure 3a no liquid applied test stage and Figure 3b liquid applied.

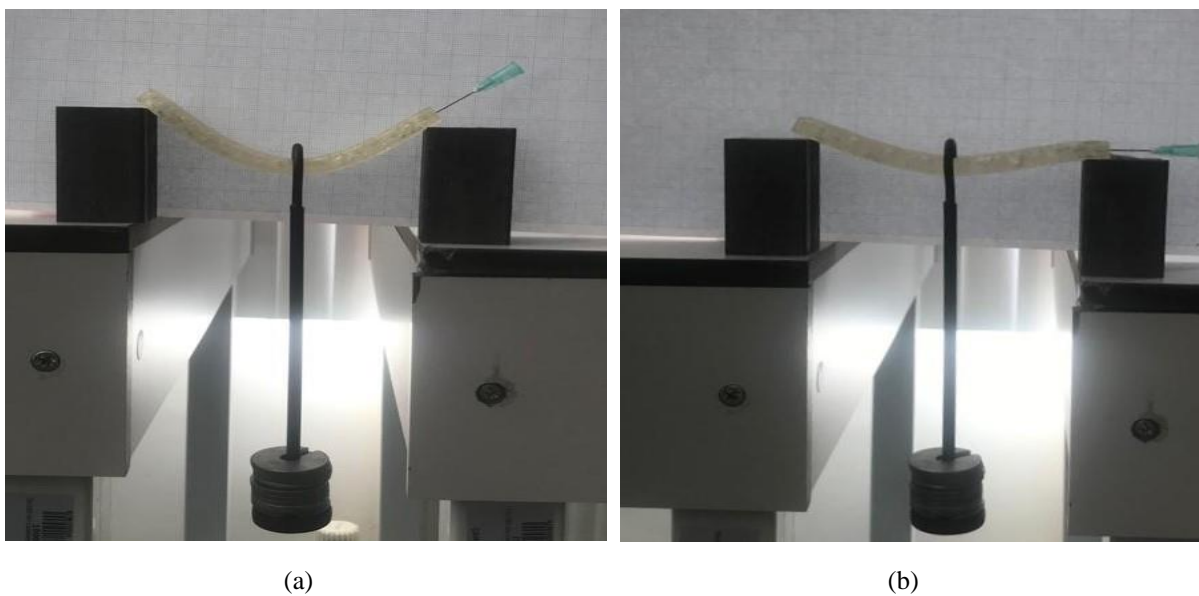


Figure 3. Figures of bending test: (a) No liquid applied test stage and (b) Liquid applied test stage.

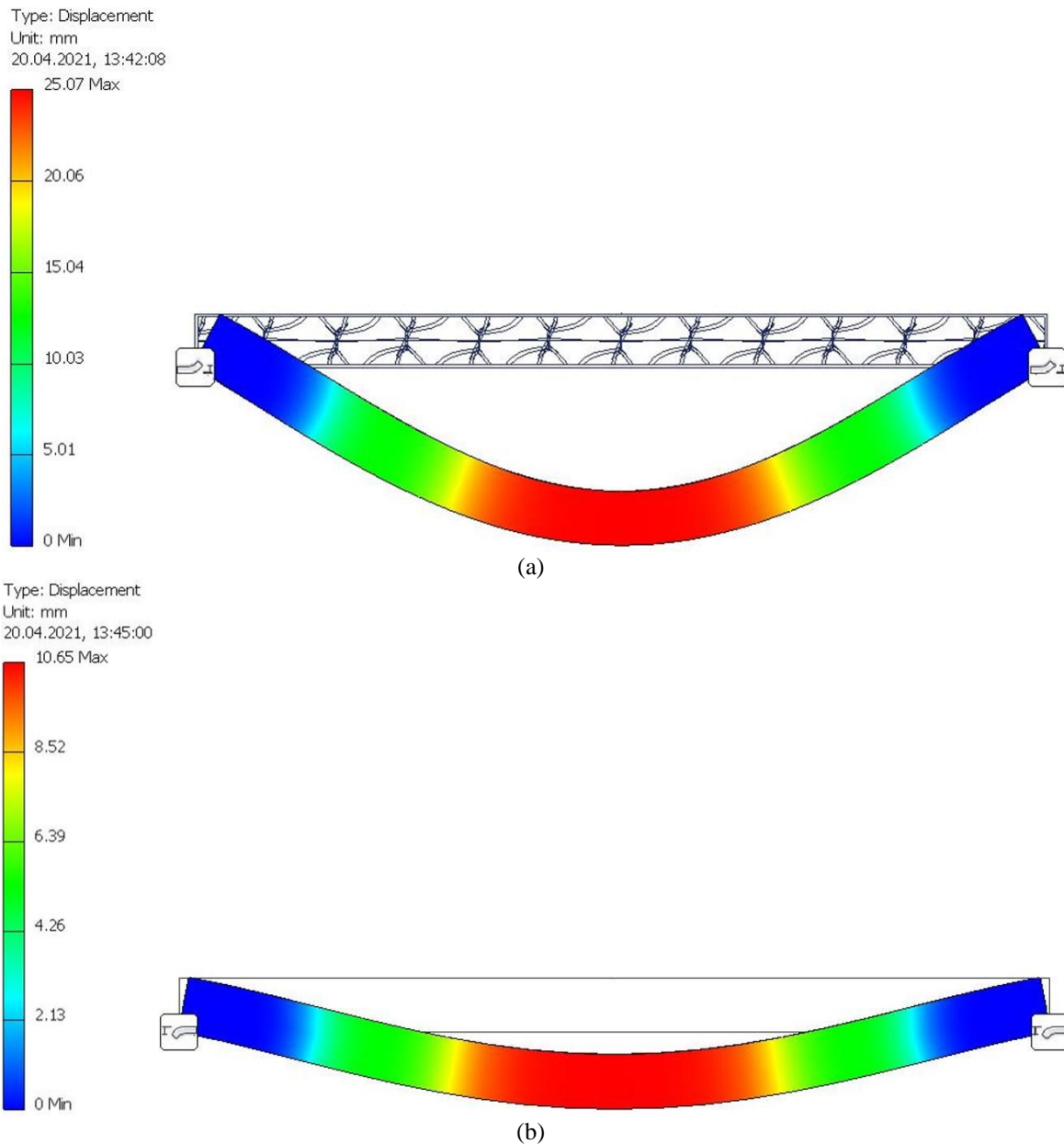


Figure 4. Figures of Finite Element Analysis (FEA) for bending test: (a) FEA of no liquid applied stage and (b) FEA of the liquid applied stage.

2.2. Pressure Test

The cylindrical-shaped part was used for the pressure test, and bellows were added along the side face of the cylinder to provide flexibility and support volume change without harming the thin sidewalls of the 3D printed soft part. An impermeability check for the liquid filling was made to part, and hereupon part was used to implement the pressure test. The test was held by putting 2000 gr weight as one solid part. Tap water was used as a filling Liquid, and it was applied by syringe. Setup for the test can be found below as Figure 5a no liquid applied test stage and Figure 5b liquid applied test stage.

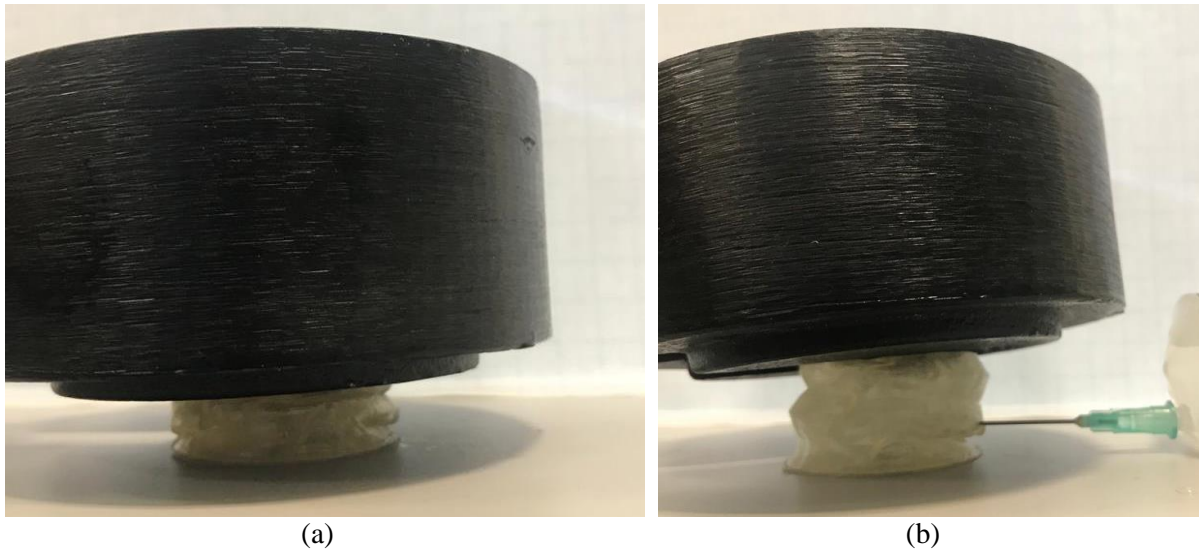


Figure 5. Figures of pressure test: (a) No liquid applied test stage and (b) Liquid applied test stage.

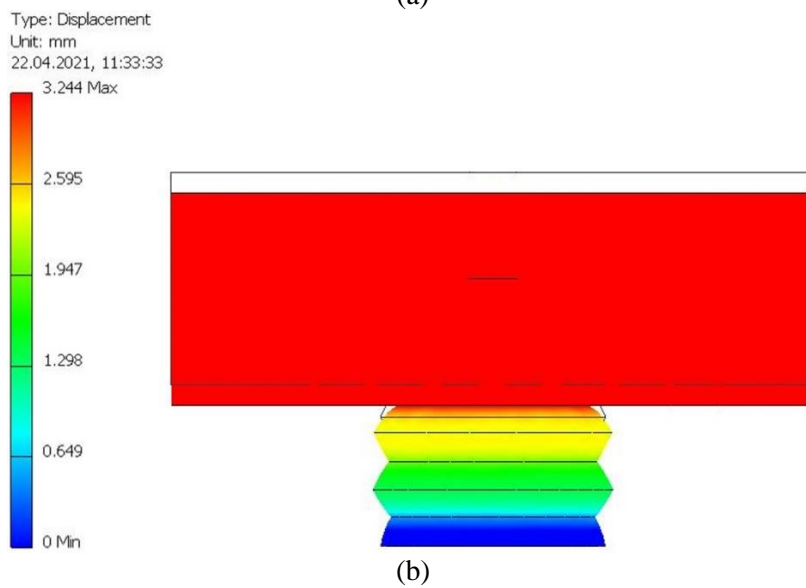
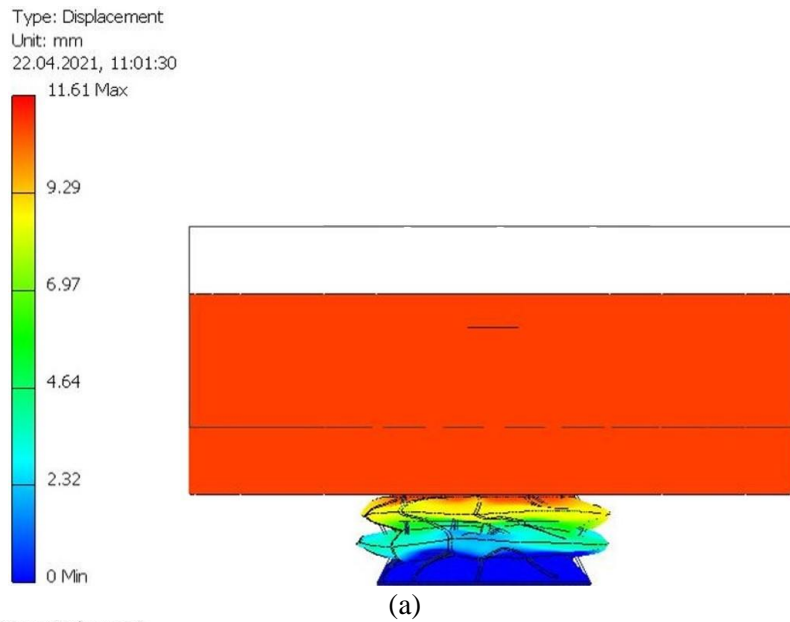


Figure 6. Figures of FEA for pressure test: (a) FEA of no liquid applied stage and (b) FEA of liquid applied stage.

3. RESULTS

The results obtained from the bending experiment, shown in Figures 3a and 3b, and from Finite Element Analysis (FEA), shown in Figures 4a and 4b, can be compared to understand the experiment's accuracy. The comparison indicates that bending FEA results have 25.07 mm displacement on no liquid filled the loaded and experimental results with 25.53mm displacement. The liquid-filled loaded stage result for FEA is 10.65, while the experimental result is 10.89 mm. Besides, a similar implication can be made for pressure test results. Non-filled stage results for pressure test is mm 11.35 while the result of FEA is 11.61 mm. The liquid-filled result for the test setup is 3.17 mm, while the FEA result is 3.24 mm. According to bending test results, change on height over part length for no liquid loaded stage and liquid-filled loaded stage can be calculated as 21.28% and 9.08%, respectively. In comparison, FEA results give 20.89% for no liquid loaded set and 8.88% for the liquid-filled loaded stage.

Moreover, displacement over height ratio can be calculated for no liquid loaded stage as 37,83%, and liquid-filled loaded stage as 10,57% for pressure test. Moreover, FEA results percentages can be found as 38,70% for no liquid loaded stage and 10,80% liquid-filled loaded stage. Accuracy of percentage results proves that soft robotics elements' stiffness can have improved by applying liquids inside the porous structure. On the other hand, printing parameters should be optimized for enhancing the quality and impermeability of the gyroid structure.

4. CONCLUSION

This study set out to assess the possibility of strengthening the effect of flooding in 3D printed porous soft robotics scaffolds. Two designs were examined on two different test setups organized specially for each of the parts. When results were compared with the literature, it is found that Yamada et al. provided a bending motion on the sponge-like structure [50]. Their structure was made out of foam, and the motion was provided by vacuuming air, which is also fluid like our filler. A similar bending motion was observed, except that the strengthening effect was not examined. Moreover, Chen et al. created a sponge-like structure from hyperelastic silicone foam to enhance the capacity of volume change [51]. Their compression ratio is similar to our gyroid-shaped model and proofs its validity. Again, no strengthening effect was examined, so a comparison could not have been made on that factor. In addition, Argiolas et al. conducted a similar experiment to ours [52]. They were used air as fluid and observed the strengthening effect by hanging weights to the part. Similar results were observed. Air improved the strength of the bent arm, and weight was carried due to this strengthening effect.

Findings are planned to strengthen soft robotics elements for enhancing the safety and quality of human-robot interactions. 3D printing parameters enhancement, experiments with different shapes and liquids can be accepted as future work on this topic. Moreover, different infill percentages and different gyroid types would change the strengthening results.

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