Teaching 2D to 3D design: Integrating a Pneumatic Cushion Simulation Tool into a Soft Robotics Course

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Abstract

This paper describes the integration of a pneumatic cushion simulation tool into an undergraduate and graduate elective course in soft robotics within a biomedical engineering curriculum. While hands-on fabrication is central to soft robotics education, physical prototyping can be time-intensive, difficult to scale for large classes, and often relies on trial-and-error iteration. One area of soft robotics focuses on inflatable structures for wearable and healthcare technologies. These designs are commonly designed and fabricated on planar sheets of plastic before inflation. When introduced to a new technology or fabrication technique, students often struggle to predict how two-dimensional (2D) actuator geometries translate into three-dimensional (3D) inflation behavior. To address these challenges, we introduced a simple simulation tool to support predictive design and reduce barriers to engaging with modeling. This tool allows students to upload 2D cushion drawings composed of air bladder units and visualize the resulting 3D inflation height maps for user specific seat cushions. Rather than replacing fabrication or providing high-fidelity analysis, a simulation was designed to build intuition around geometry-driven actuation and expose students to modeling as a design aid. The simulation activity was completed near the end of the semester, following foundational instruction in pneumatic actuation and soft actuator fabrication. Students completed an iterative design assignment in class during which they modified cushion geometries based on simulation feedback and reflected on their design decisions. Evaluation of the activity included post-assignment surveys and written reflections. Results indicate that the simulation supported geometry-informed iteration, enabled rapid design exploration, and improved students' understanding of how two-dimensional design choices influence soft pneumatic system behavior. This work demonstrates how accessible simulation tools can complement hands-on fabrication in soft robotics education and support scalable, design-centered learning in upper-level engineering courses.

The tool described in this paper is available from:
The SEAT project website: https://publish.illinois.edu/seat-team/education-resources/
Corresponding author's website: https://www.hollygolecki.com/teaching

Introduction

Soft robotics is a rapidly growing discipline that combines materials science, mechanics, and robotics to design compliant devices capable of safe interaction with the human body [1], [2]. Soft robot technologies have gained significant traction in biomedical engineering due to their compatibility with soft tissues, ability to distribute contact forces, and adaptability in complex anatomical environments [3], [4]. Recent work has explored the use of novel, biocompatible soft materials for robotic actuation, enabling new inflation modes and improved integration with biological tissues [5]. Additionally, hybrid material fabrication strategies for compliant actuation integrate additive manufacturing with soft actuators to enable precise motion while preserving overall compliance [6]. Soft robotics courses provide a unique opportunity for biomedical engineering students to engage with a design-based research field, allowing them to explore both fabrication and innovation pathways [7].

Wheelchair seat cushions represent a clinically relevant application for soft robotic systems. Air-cell based cushions play a critical role in redistributing pressure concentrations and reducing the risk of pressure injuries for individuals who rely on seated mobility [8]. Prior work has shown that cushion geometry may help with pressure redistribution characteristics, significantly decreasing pressure hotspots at high-risk anatomical locations such as the ischial tuberosities (sit bones) and thighs [8], [9]. Recent research has explored active cushion designs that use soft actuation strategies to improve pressure distribution and user comfort [9]. These studies provide a meaningful real-world context for bioengineering students to understand healthcare applications of soft pneumatic systems.

The soft robotics course examined in this study is an undergraduate and graduate elective within a biomedical engineering curriculum designed to expose students to research-driven design, hands-on fabrication, and application-focused soft robotic systems. Prior offerings of this course have documented soft robot activities and the application of soft robots in medical simulation and task training [7], [10], [11]. The course discusses several biomedical applications of soft robotics. Within each application, students proceed through a design cycle (Figure 1). Students first learn a fundamental engineering concept, like energy storage or material stiffness. Next, we introduce a biomedical application where the property or concept is relevant to its function. Students then build a soft actuator and complete a short design task to use the relevant concept and hands-on build to address a clinical or biological need. While hands-on fabrication is central to soft robotics education, creating hands-on classroom or laboratory activities for all new and emerging technologies can be difficult due to increasing enrollment and resource constraints.

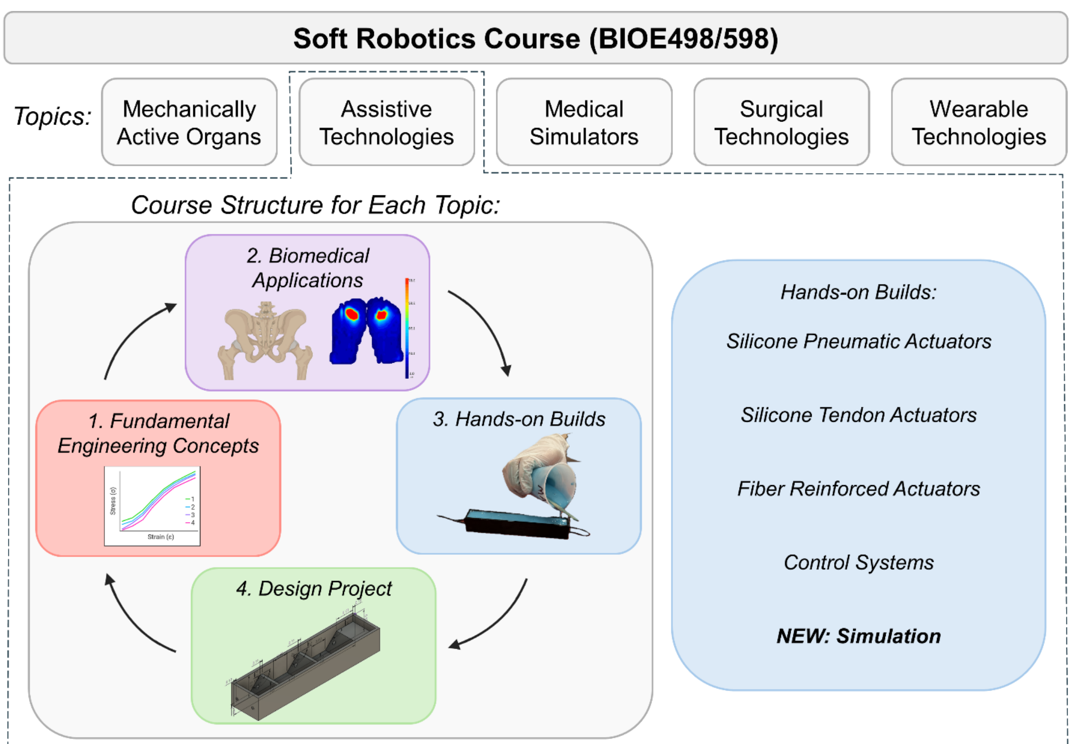

Figure 1. Structure of soft robotics elective course for bioengineers (BIOE498/598). The course covers a variety of topics that focus on applications of soft robots and guides students through a design cycle for each topic covered

Students often struggle to understand how 2D designs relate to 3D shapes, especially when problems involve multiple steps or transformations [12]. Visualization of 3D objects is an important skill for engineering students, but many students start with weak spatial abilities, often making early design and graphics tasks more difficult [13]. Spatial skills are closely connected to success in STEM, but they are not always emphasized in traditional education, which can create challenges for student learning and engagement [14]. We hypothesized that simulation could offer an open-source, low-cost way to make design accessible to more engineering students.

This paper introduces a new simulation tool that aims to help students understand how geometry affects soft robot actuator design. The tool allows students to quickly see how their 2D cushion designs inflate. Students can then make improvements without needing to fabricate every version, making iteration faster and more accessible. We evaluated the impact of simulation on student iteration behavior and perception of geometry-driven actuation in this pneumatic cushion example. This approach demonstrates that simplified simulation tools may create opportunities for students to better understand mechanics, improve their designs, and strengthen hands-on engineering learning.

Motivation for Using Simulation in Soft Robotics Elective

New methods of soft actuator fabrication allow designers to heat-seal layers of thermoplastic film to create custom inflatable structures [15]. This process is shown in Figure 2, where 2D designs are traced with a hot iron tool onto plastic layers, creating airtight seals and inflatable structures. While this fabrication technique is rapid on an industrial manufacturing timescale, current lab-scale techniques cannot support large classes of students fabricating simultaneously. To address our desire for students to experience cushion design without spending multiple weeks on the process, we have developed a simulation tool that inputs 2D drawings and visualizes 3D inflation at a constant pressure. This simulation tool, which we call Smart Ergonomic Air Technologies Simulation or SEAT-Sim, was developed by our research team to help quickly explore pneumatic cushion designs. The software is written in Python and uses a simplified model to estimate how cushion geometry and seams impact inflation height. Unlike traditional Finite Element Analysis (FEA) software, this tool generates inflation maps in seconds, comparable to minutes, allowing students to easily see how their designs will behave in use.

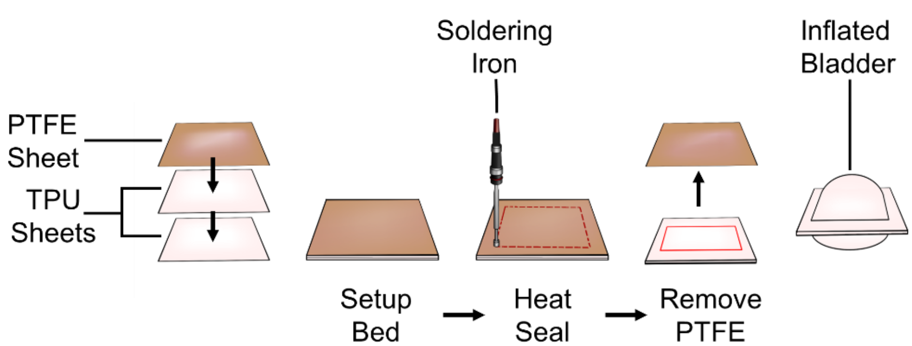

Figure 2. Physical fabrication of an air bladder unit

While originally developed for research purposes, our team recognized the potential to introduce students in the classroom to this application area (pressure injury-reducing cushions) and the fabrication method (2D heat sealing). Traditional modeling tools, such as FEA, are typically inaccessible within a design-based classroom setting for a single demonstration due to their complexity and steep learning curves. At our institution, FEA is not introduced in the required bioengineering major courses. FEA tools such as Abaqus, ANSYS, and COMSOL are widely used but require advanced training and significant setup. The simulation tool used in this class, provided to students in Google Colab, produces rapid results without complex setup or specialized software. This allows students to focus on understanding how geometry affects inflation, rather than learning complex simulation tools. SEAT-Sim addresses an educational gap by supporting predictive design and reducing barriers to engaging with simulation. SEAT-Sim enables many students to design together, simultaneously, and visualize their results in real time to broaden students' understanding of soft robot design in assistive technologies.

While hands-on fabrication is a central component of this course, relying solely on physical prototyping can be time-intensive and resource-limiting. Students frequently generate multiple design iterations before converging on a final design, reflecting limited intuition about how geometric and boundary constraints influence actuator behavior. Many students in this course have limited modeling or simulation experience. This challenge is amplified in a course of approximately 60 students (50 upper-level undergraduates and 10 graduate students in the semester in which it was tested). For many students, this was their first introduction to using simulation for design integration. This approach enables students to explore design changes independently and receive immediate visual feedback, supporting scalable and self-directed iteration. Using our tool, students can visualize the effects of design changes with no required fabrication.

Hands-on Activities that Precede the Simulation Project

The soft robotics course exposes students to several foundational actuation mechanisms that are widely used in both academic research and industrial applications [11]. These mechanisms are presented not as isolated devices, but as design strategies that can be adapted and combined to meet application-specific needs. Consistent with the course structure described in Figure 1, students are introduced to silicone pneumatic and tendon-driven, fiber reinforced soft actuators as modular design strategies [7]. Pneumatic and fluidic soft actuators form the core of the course content. These systems rely on internal pressurization of elastomeric or polymeric chambers to produce inflation [16]. By modifying chamber geometry, wall thickness, and seam placement, students learn how to generate bending, expansion, or localized inflation [16]. Prior work has demonstrated that pneumatic soft actuators are accessible and have a strong connection between design and physical behavior [17]. The actuator can be fabricated using accessible methods for teaching engineering design concepts, relying on low-cost materials and simple fabrication techniques that lower barriers to participation in soft robotics [18]. Guided activities on soft materials help students connect material properties to mechanical performance [19]. Soft robotics has been shown to increase engagement in a classroom setting and support hands-on design learning [20]. We anticipated that the simplified hands-on activities would lead to intuition in the simulation activity.

Development of Simulation Tool for Classroom Use

In many soft robotic devices, particularly pneumatic and inflatable actuators, overall mechanical behavior is governed less by detailed material properties and more by geometry, boundary constraints, and applied pressure [3]. For example, inflatable soft structures behave primarily as tension-dominated membranes, where inflation is driven by membrane tension and constrained by seams, chamber geometry, and fixed boundary conditions [2]. Thin polymer membranes, elastomers, and thermoplastic films are commonly used due to their flexibility, durability, and ease of fabrication. While fully nonlinear material models and large-inflation analyses are often required for high-fidelity prediction, simplified mechanical assumptions can capture relative inflation and provide useful insight into how geometric design parameters influence actuator behavior. These simplified mechanics are particularly valuable in an educational context, where the goal is to build intuition and support design exploration rather than achieve exact quantitative prediction. The goal is not to replace fabrication, but to give students an accessible way to explore designs, improve their ideas quickly, and support hands-on learning. We believe this will reduce barriers to engaging with the simulation in a purposeful way.

Simulation Workflow

SEAT-Sim and its workflow are designed with simplicity as a priority (Figure 3). Students begin by creating their designs using accessible drawing software (e.g., MS Paint, Google Draw). They then upload their 2D cushion designs into the simulator, which automatically converts the geometry into a computational grid and generates inflation height maps based on simplified membrane mechanics (Figure 3). The simulation estimates relative inflation height by modeling the cushion surface as a tension-dominated membrane constrained by seams and boundaries. This workflow requires no CAD modeling or coding and supports rapid iteration across multiple design variations. Because the tool is adapted for educational use, all computational steps are automated, allowing students with no prior simulation experience to generate and interpret results without additional training.

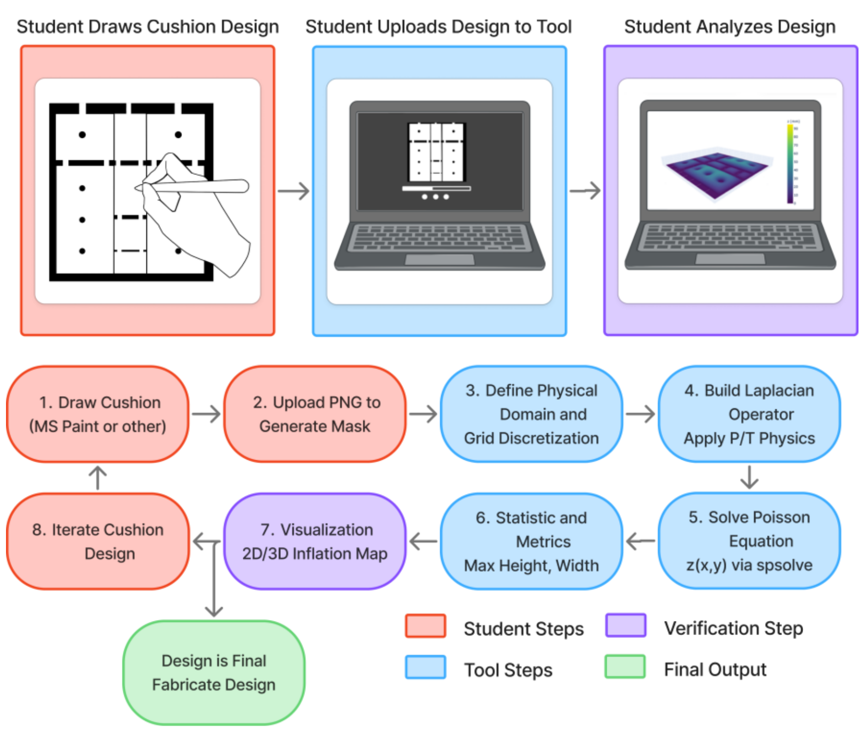

Figure 3. Simulation workflow overview. Students draw the cushion, define its dimensions, and upload a design, while all physics and computation steps are automated to enable rapid inflation-map generation (Images from biorender.com)

Course Implementation

The tool was introduced near the end of the semester after students completed foundational actuator builds. Students were given a short demonstration on simulation use and a research objective to design a cushion that offsets pressure around the ischial tuberosities (Figure 4). Students were asked to submit an initial cushion design (V1), run it through the simulation, reflect on the meaning of the results by discussing with a neighbor, and then revise the design (V2) based on predicted inflation patterns.

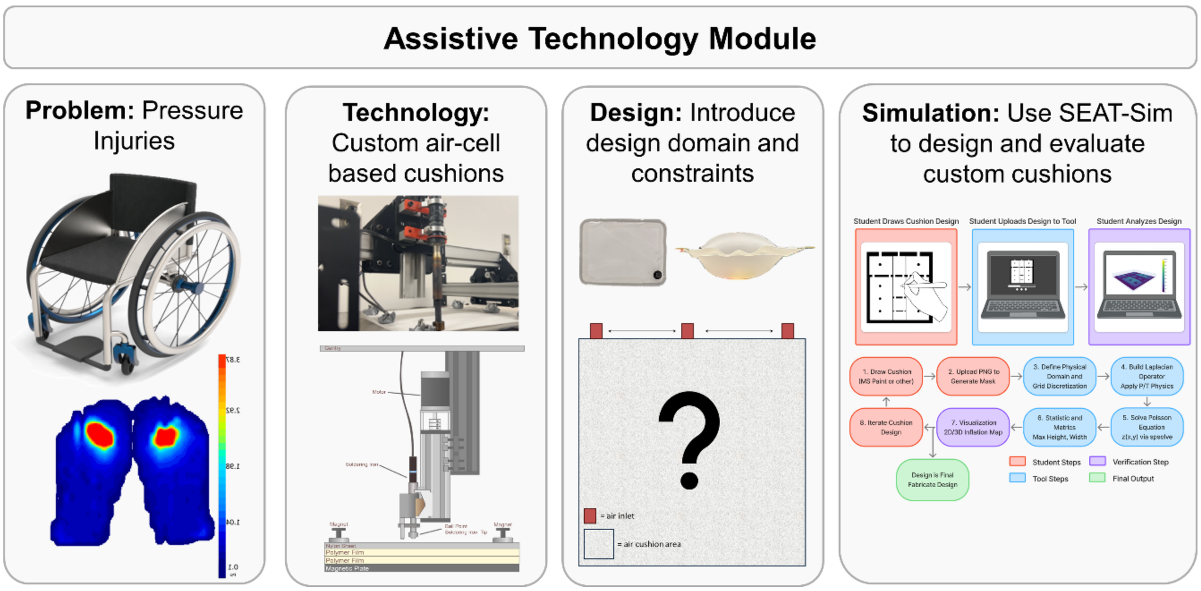

Figure 4. Structure of the Assistive Technology module in BIOE498/598 Soft Robotics

While only V1 and V2 were formally submitted for assessment, some students explored additional intermediate variations to evaluate how geometric changes such as seam placement, bladder size, and symmetry influenced inflation behavior. This rapid feedback loop enabled students to engage in iterative design exploration that would not have been feasible using fabrication alone due to time and resource constraints. Students submitted reflections describing their design modifications and completed a Likert-scale survey evaluating the usefulness of the simulation tool. The goal was to have a simulation-guided design process, instead of iteration from a limited fabrication process of trial-and-error physical prototyping.

Study Methods and Data Collection

Data sources included student design files for V1 and V2 cushions and their corresponding simulation outputs, post-assignment Likert-scale survey responses (N = 52), and written student reflections describing their design and what features they added and why. We also made informal observational comparisons between V1 and V2 designs to note common changes such as added seams, increased symmetry, and redistribution of inflatable regions. During the in-class assignment, students submitted V1, ran the simulation to visualize inflation behavior, and then V2 based on simulation feedback. Immediately following completion of the activity, students completed a short survey and submitted written reflections describing how the simulation influenced their design decisions and what modifications they made.

Survey responses were summarized using descriptive statistics (counts and percentages) for each Likert-scale item. Written reflections were analyzed using a thematic analysis approach. Responses were reviewed, recurring themes were identified, and a coding scheme was developed to categorize common design changes and stated mechanical rationale. These themes were then grouped and summarized to highlight patterns in student iteration behavior and design reasoning. Observational comparisons between V1 and V2 designs were used to provide additional context for interpreting student-reported learning and iteration.

Results and Discussion

We evaluated student iteration to determine if the simulation tool improved 2D to 3D visualization and understanding. Student iterations showed that learners consistently improved their designs by modifying geometry and observing the resulting changes in behavior. Many students enlarged inflatable regions after observing insufficient inflation in their initial designs and added any drawn seam constraints, such as buttons, to suppress overly inflated areas. Designs became more anatomically intentional, with increased support around the ischial tuberosities, side supports for postural stability, and redistribution of pressure toward the thigh regions.

Common geometric changes included increasing bladder area to enhance inflation, adding seams to locally constrain inflation, improving symmetry to promote uniform inflation, and modifying bladder placement to better offload pressure-sensitive anatomical regions such as the ischial tuberosities. These changes demonstrate that students used simulation feedback to make intentional design decisions rather than relying solely on intuition. Reflection responses further indicated that students were actively interpreting simulation results and applying reasoning, such as recognizing the relationship between bladder area and inflation height or understanding how local constraints influence inflation behavior.

One student (Student #13) participant shared the following in their first reflection:
“I have one bladder to support the ischial tuberosity, another to support around the base of the legs, and a final one to support the front of the legs.”

Then Student #13 shared the following in their second reflection:
"I changed some of the lines I added to control the shape so that the shape better conforms to the seated person."

Another student (Student #22) participant shared the following in their first reflection:
“I added borders along the back and sides for stability when seated. To reduce pressure on high pressure areas, I included circular inflators that will raise the sides of both sides of the bottom to reduce pressure in the center. I also included inflators on the sides of the thighs for comfort and to reduce pressure on the legs as well.”

Then Student #22 shared the following in their second reflection:
“From the simulation, I realized that the bladders were too thin and would be ineffective to relieve pressure. In this new design, I increased the width of the bladders and placed them closer together.”

Survey results of 52 submissions are shown in Figure 5, further supporting these findings, with nearly 90% of students agreeing that the simulation changed their perception of how 2D cushion geometries perform when inflated and helped them achieve a better V2 design (Figure 5). This high level of agreement suggests that the simulation effectively supported conceptual understanding and enabled students to make informed design decisions.

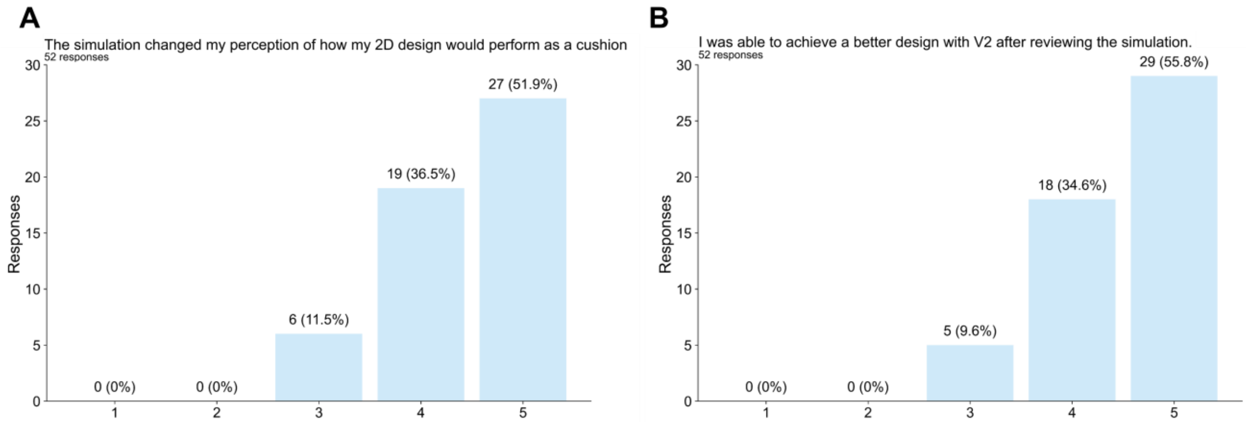

Figure 5: Results from student feedback survey. A: Students responded to the following prompt: "The simulation changed my perception of how my 2D design would perform as a cushion" B: "I was able to achieve a better design with V2 after reviewing the simulation" 1 = Strongly disagree, 5 = Strongly agree. N = 52 students responded to the survey

Students made simulation-informed geometric refinements to their initial intuition-based layouts (Figure 6). These results indicate that introducing a simplified simulation tool into a hands-on soft robotics course may improve student understanding of geometry-controlled actuation and support predictive design behavior. While some V1 and V2 designs appeared visually similar in overall layout, student reflections revealed substantial improvements in mechanical reasoning and intentional design modifications. Many students incorporated targeted geometric adjustments, such as enlarging pressure-relief regions or adding constraints to control inflation, demonstrating increased understanding of how geometry influences actuator behavior. Table 1 categorizes the students' written responses, with V3 referring to hypothetical planned revisions. These themes were consistently observed across student responses, indicating widespread engagement with simulation-guided design refinement and improved ability to interpret inflation behavior.

Table 1. Themes summarized from free response data collected after each simulation iteration.

Stage of Design Assignment	*Emergent theme*
After first simulation: Critiques or planned changes for V2	• Small chambers under the ischial tuberosities (Fig. 6A) • Overinflated side regions (Fig. 6B) • Flat central cushion (Fig. 6C) • Increased symmetry (Fig. 6D)

After second simulation: Critiques or planned changes for V3	• Enlarged rings/bladders (Fig. 6E) • Added more seams (Fig. 6F) • Added hollow & larger airbladder section (Fig. 6G) • Increased symmetry (Fig. 6H)
Mechanical Rationale: Justifying why changes were made	• Larger membrane area gives greater inflation • Local constraint reduces inflation • Pressure redistribution • Balanced geometry improves uniformity

Student cushion designs evolved from initial intuition-based layouts to simulation-informed geometric refinements, with computational inflation feedback helping students identify overinflated regions, asymmetries, and opportunities to redistribute pressure more effectively (Figure 6). Computational feedback guided students toward more mechanically intentional cushion layouts. These observations indicate that the simulation enabled students to interpret actuator behavior and apply geometry-based mechanical principles to refine their designs.

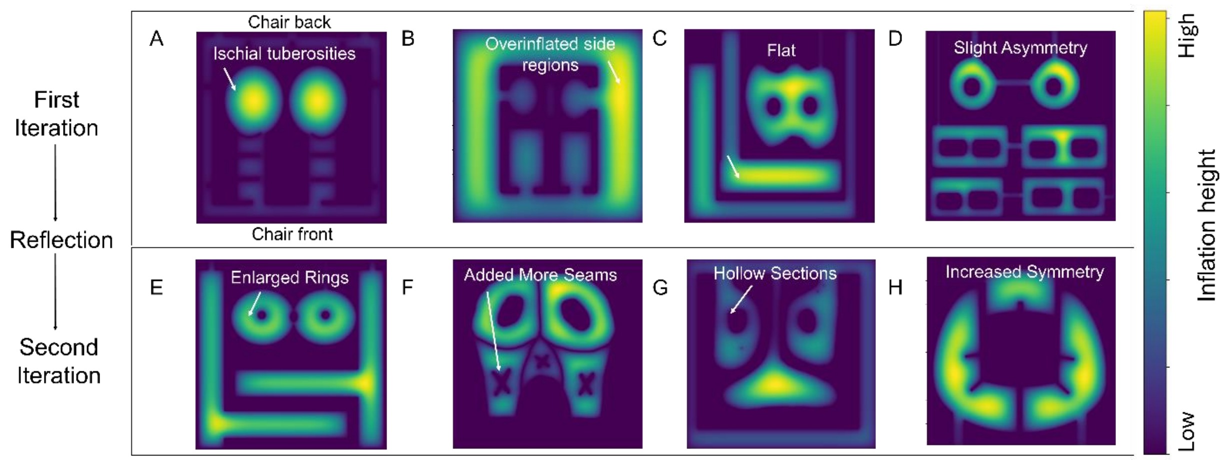

Figure 6: Examples of inflation plots of different student designs. Multiple designs include torus (donut) shapes after students learned about the importance of redistributing pressure away from the ischial tuberosities

Conclusion and Future Work

This work shows that adding a simple cushion simulation based on geometry to a soft robotics course may support student design training. SEAT-Sim provides students with an easy way to experience cushions made from airbladder designs and contribute their own iterative designs. Reflections and survey responses show that the tool moved design choices away from guess-and-check toward intentional changes guided by mechanics, especially in critical areas in the body like the ischial tuberosities, plus thigh supports. The model treats the bladder as a thin membrane and, while it does not capture small details, it provides clear design guidance that enables students to iterate with greater confidence and intent. These results highlight that computationally inexpensive, easy-to-use computer tools may help link lab work with forwardthinking design. Future iterations of this activity will expand opportunities for student iteration by encouraging multiple simulation cycles prior to final design submission, more time between iterations, and fabrication of a final design. Without the use of simulation, each iteration would require physical fabrication. Each fabricated design alone takes approximately 2–4 hours, depending on complexity.

Simple simulation tools can support design in a wide variety of courses and majors in engineering, where students must understand how part geometry influences physical behavior. Because the simulation tool runs quickly with simple drawings and requires no prior modeling experience, it can be integrated into classroom activities, design assignments, or rapid prototyping workflows without requiring specialized commercial simulation software or significant computational resources. The educational framework demonstrated in this work can also be adapted to other soft actuator systems, such as pneumatic networks, wearable soft devices, or inflatable biomedical structures. These findings support the use of accessible simulation tools as a valuable complement to fabrication-based learning in engineering education.

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