2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #50224

Designing and Testing a Prosthetic Disc: Elementary Students as Biomedical Engineers in an Afterschool Program (RTP, Out of school)

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Abstract: This study examined how 10 elementary students (ages 8–11) engaged in an engineering design activity focused on the role of biomedical engineers. Students constructed spine models, designed prosthetic discs, and tested various prosthetic materials through compression and bending tasks. Drawing on constructionism and distributed cognition, reflexive thematic analysis of video recordings and open-ended survey responses revealed four themes: (1) problem framing and reasoning about constraints, (2) testing and generating evidence through measurement and material exploration, (3) evidence-based decisions and iterative improvement, and (4) collaboration and feedback as part of engineering culture

Introduction

Over the last 30 years, we have been moving toward a world where technology is not only part of our daily lives but increasingly integrated within our bodies, shaping how we live and think. Biomedical engineering, a discipline that integrates principles of science and engineering, is leading us toward this future by developing technologies that unify human bodies and machines, such as pacemakers, AI-enhanced prosthetics, and wireless e-health systems that save lives [1]. This trajectory reflects the idea of extended cognition introduced by Clark and Chalmers [2], which suggests that technologies closely integrated with the body may function as part of the broader cognitive system. As Hutchins noted, "The future of medicine is not just in the machine that comes to your bedside, but in the technology that comes to your body" [3, p. 226]. This is even more true now than when Hutchins said it. Despite these advances, biomedical engineering concepts and practices remain largely absent from K-12 education.

To prepare young people for this future, the education system must redefine scientific competencies and support students in applying interdisciplinary knowledge and developing 21st-century skills [4]– [6]. In a technology-integrated world, 21st-century skills like critical thinking, creativity, and problem-solving are essential for students' success [7]. Science, technology, engineering, and math (STEM) education—especially engineering—enhances problem-solving, analytical thinking, and innovation, and offers real-world learning that supports the development of an engineering mindset [8], [9]. As STEM fields evolve rapidly, new jobs emerge, while older skills become obsolete, increasing demand for qualified workers—yet engineering continues to face shortages, as few students pursue STEM education to fill these roles [10].

Despite incorporation of engineering in the Next Generation Science Standards, and curricular efforts like *Engineering is Elementary* [11], research on engineering in elementary education remains limited, especially in biomedical engineering, which is rarely included in classroom activities or curricula. This limits early interest and career awareness [12],[16],[24]. While many K–12 students are passionate about health and the environment, most are unaware of the critical role of biomedical engineers, particularly in promoting health [14].

To address this gap, we introduced elementary students to biomedical engineering through a hands-on, health-related STEM activity. Although tested in an afterschool STEM club, the activity was designed for easy classroom use with accessible, everyday materials. It integrated concepts from multiple fields, particularly biology, biomedical engineering, materials science, and mathematics. From biology, students explored human anatomy. From biomedical engineering, they engaged in aspects of the engineering design and testing process. From materials science, they investigated properties such as stiffness and flexibility. Finally, from mathematics, they compared test results to draw data-driven conclusions. This learning environment was designed to familiarize students with key concepts in biomedical engineering and to support extended cognition through interaction with tools, materials, and people, reflecting the principles of distributed cognition, where cognitive processes are shared across individuals, artifacts, and the environment [3].

Our aim was to explore the following questions:

(1) How does a learning activity informed by distributed cognition support elementary students' sensemaking of biomedical engineering concepts and the development of an engineering mindset?

(2) In what ways do elementary students participate in engineering practices, and how does this participation influence their interest in biomedical engineering?

Theoretical framework

This study employed distributed cognition and constructionism, which informed both the learning design and the analysis. We draw on the framework of distributed cognition, which posits that thoughts and actions are distributed across humans and non-human artifacts, including tools, representations, and environments [3]. Biomedical engineering devices such as prostheses and implants can be understood through this lens, as they represent sites where functional responsibilities are shared between the body and technological artifacts. Clark and Chalmers similarly argued that cognition extends beyond the individual, as humans form coupled systems with tools and representations that become integral to thinking and action [2]. Within this view, embodied cognition is integral, as bodily actions and gestures, in coordination with tools and peers, constitute the cognitive system that supports sensemaking in activity [17]. Designing learning environments informed by these perspectives involves creating opportunities where cognition is extended to and distributed across tools, materials, and peers, reflecting the ways in which humans augment both bodily function and cognitive processes with artifacts.

Constructionism suggests that learning is most effective when students create tangible artifacts to represent understanding [18]. Constructionist learning environments encourage hands-on making, experimentation, prototyping, and refining ideas [19]. In this study, the activity was designed to help students learn biomedical engineering concepts through hands-on making, iterative design, and testing of tangible artifacts, rather than through passive reception of information or abstract instruction. These artifacts served as evidence of learning, revealing how students conceptualized the structure of the spine, the arrangement of vertebrae, the placement of the lumbar disc, and its flexibility.

To situate this activity within established expectations for elementary engineering, the learning design aligned with the NRC Framework's Engineering Design core idea for grades 3–5 [20]. This framework emphasizes engaging learners in defining a simple design problem that reflects a need or want, as well as identifying criteria for success and constraints related to materials and cost. It also encourages generating and comparing multiple possible solutions. Finally, it highlights planning and carrying out fair tests in which variables are controlled, and failure points are considered to identify aspects of a model or prototype that can be improved [20]. In this study, the design challenge was intentionally structured to support students' reasoning about how design solutions are shaped by available materials and resources. The activity encouraged students to refine alternative ideas and use testing results to make evidence-based decisions aligned with the identified criteria and constraints [20].

Method

The study aimed to help elementary students learn about biomedical engineering and gain a clearer sense of the work biomedical engineers do. An activity was developed by the first author, a second-year PhD student in learning sciences and educational psychology who has bachelor's and master's degrees in biomedical engineering. Drawing on her biomedical engineering background, she developed a hands-on activity to introduce biomedical engineering to elementary learners; this session served as the initial implementation of the activity. The workshop was facilitated by the PhD student alongside the second author, a university professor with expertise in learning sciences, a university makerspace facilitator, and a teacher-librarian. This 90-minute session was run as a part of an afterschool program that is part of ongoing research and teaching project run by the second author at a racially and socioeconomically diverse suburban elementary school in the Midwestern United States. Of the 90-minute session, 5 minutes were allocated to the pre-survey, 10 for an introduction and discussion of biomedical engineering, and instructions on how to complete the activity. 70 minutes were devoted to small-group work, with students forming self-selected groups by choosing their own teammates. Finally, 5 minutes were allocated to the post-survey. Of the 20 children who participated in the session, 10 consented to participate in the research (3 girls, 7 boys; ages 8–11; grades 3–5). Only data from these 10 students were included in the analyses reported in this paper.

The workshop began with a pre-survey containing both open- and closed-ended questions assessing students' prior knowledge of biomedical engineering, their career attitudes, and their familiarity with the spine, prosthetics, and material properties such as rigidity and flexibility. Example pre-survey items included: "What do you think biomedical engineers do?", "Can you give any examples of what biomedical engineers make?", "Do you know what a prosthesis is? Can you give an example?", and "Do all materials feel and behave the same when you touch or bend them? Can you give some examples?" The pre/post-survey also included a career-interest question asking whether students would like to be an engineer in the future (Yes/No/Maybe), followed by a brief explanation.

The PhD student led a brief instructional segment on biomedical engineering, including the role of biomedical engineers, basic spine anatomy, and disc damage, using a spine model as a visual aid (Figure 1).

Figure 1. Spine models with herniated disc, artificial lumbar disc components, and disc implants.

Each student was given two kits. Kit A, used to build the spine model, included Styrofoam discs (vertebrae), playdough (intervertebral discs), flexible balloon wire (spinal cord), and a balloon (the head) for artistic expression (Figure 2). A real lumbar disc prosthesis typically consists of a flexible core positioned between two endplates (superior and inferior), which anchor the implant between adjacent vertebrae. Kit B was designed to reflect this basic structure. It included two round cardboard pieces representing the superior and inferior endplates for prosthetic design. For the central core, students selected from materials with varying stiffness, ranging from very rigid to highly flexible: a wooden disc (hardest), a black 3D-printed disc (rigid; printed in polylactic acid [PLA]), a gray 3D-printed disc (more flexible; printed in thermoplastic polyurethane [TPU]), a blue foam disc (more flexible), and a marshmallow (most flexible).

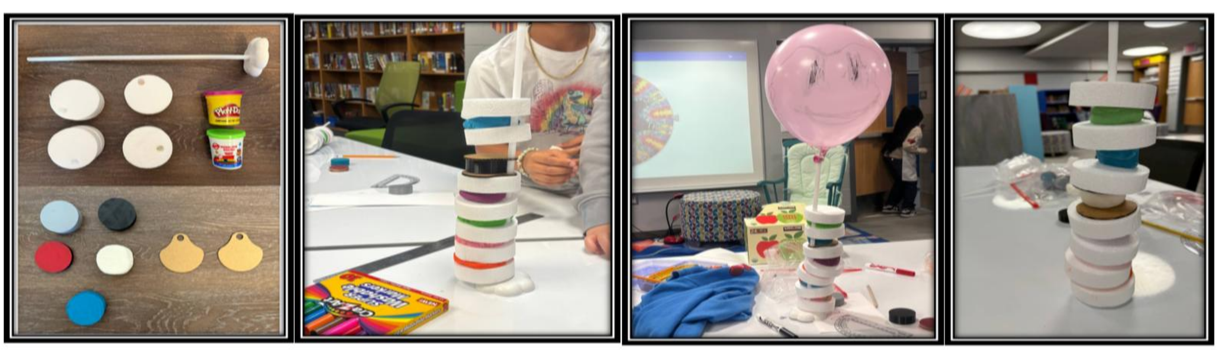

Figure 2. Materials provided to students for building spine models and examples of student-constructed spine prototypes created during the activity.

Students worked in groups of three to evaluate material performance using rulers and protractors. They measured height changes for compression and angular changes for bending to assess range of motion. Worksheets were used to record measurements and selected prosthetic materials. A table on the worksheet guided students to document measurements before and after each compression and bending test so they could compare material performance and select their final prosthetic design materials based on the data. The session ended with a post-survey and a whole-group reflection and discussion on students' designs. Data sources included video recordings, pre/post surveys, student worksheets, and final prototypes. Video data were collected using wearable cameras worn by researchers and consenting students, along with a stationary camera that captured whole-room interactions. This study followed a qualitative design, with video analysis serving as the primary data source; the pre/post surveys, worksheets, and prototypes provided complementary evidence [25]. We used these other data sources to triangulate our findings by cross-checking identified themes across multiple sources, including video observations, open-ended survey responses, and student artifacts [26].All video recordings were transcribed using Adobe Premiere.

The student first author conducted a reflexive thematic analysis of the video data [22], generating initial codes focused on students' talk, actions, gestures, and material manipulation. Themes were iteratively refined through memo-writing and a return to the data, then defined and named with representative examples. To ensure interpretive rigor, the second author then reviewed the coding and theme structure, and discrepancies were discussed to reach a shared interpretation. In addition to open-ended survey questions, the pre- and post-surveys also included Likert-scale type questions. Because only 10 students participated, survey results were used for descriptive patterns rather than statistical inference, serving as exploratory evidence that supports the validity of the qualitative themes.

The analysis produced four themes describing students' participation in the activity. We elaborate on each of these themes in the Findings section with representative examples from video data We also share descriptive data from the survey and worksheets to provide additional context for interpreting the video-based findings.

Findings

Our reflexive thematic analysis of video and open-ended survey data from the biomedical engineering activity yielded four themes in students' participation in engineering practices: (1) problem framing and reasoning about constraints, (2) testing and generating evidence through measurement and material exploration, (3) evidence-based decisions and iterative improvement, and (4) collaboration and feedback as part of engineering culture. In the sections that follow, we will elaborate on each with data examples from our analysis of video. We will then share descriptive data from the survey and worksheets to provide additional context for interpreting the video-based findings.

Problem framing and reasoning about constraints

Across survey responses and video data, students demonstrated early problem framing by identifying what needed to be fixed and attending to design constraints. In response to the question, "How would you help someone with a lumbar disc injury?", several students emphasized the importance of understanding the problem first, writing, "First, I must see what is wrong," and "I need to assess the severity of the damage before deciding on a solution." Others proposed solutions that reflected the function of a disc, such as "I would make materials that can move or bend," and "I would make components that help support the injured area." Video analysis also showed students reasoning about constraints as they constructed and adjusted their models. For example, one student instructed a peer, "So pull it as hard as you can, but without breaking it," while another cautioned, "We don't wanna make [a] mistake again." Students also evaluated size and fit of the prosthetics while constructing their models, asking, "You think that's big enough or a bit bigger?" and discussing how to maintain internal support (e.g., "You want to keep [a] little pressure right inside"). Together, these moments suggest that students were not only building an artifact but also iteratively testing and adjusting their designs in response to constraints, demonstrating engineering practices of optimization, troubleshooting, and evidence-based decision-making.

Testing and generating evidence through measurement and material exploration

Students gathered evidence by testing how their spine models and prosthetic materials responded to bending and compression, using embodied manipulation, simple tools, and peer coordination to make material properties visible. Early testing involved physical manipulation, including touching, pressing, and comparing textures and stiffness. One student pressed the marshmallow and observed, "It's really cool, it's squishy," while another pushed the 3D-printed disc and asked, "Why is it squishing?" Students also tried to identify unfamiliar materials, with one asking, "What is this? I'm not sure—maybe metal," and another advising, "Just don't focus on the texture of the marshmallow." One student bent their torso and told a peer, "Look, I am bendy." After completing the task, a student placed a balloon with a face on the spine and said, "Oh, it's me—with a purple face and my vertebrae!" By relating the model to their own body, students made the anatomical structures more meaningful and personally relevant. These moments show students treating material exploration as part of design evaluation rather than simply noticing differences, while also using embodied actions to make their understanding visible and relevant. As students continued testing, they began linking these observations to biomechanical function, with one explaining, "This is like when we squish the discs," using analogy to connect the testing experience to the role of an intervertebral disc.

Measurement and calculation also supported evidence generation during bending and compression tasks. At the end of the activity, one student summarized the bending test results, saying, "We tried bending in the end… doesn't bend very well," highlighting how trial outcomes shaped their evaluation of functional performance. The worksheet task similarly required students to record height and angle changes; overall, students answered 73.3% of the math items correctly, indicating that many groups were able to produce and interpret basic quantitative measures. Students also described practical difficulties during testing, including maintaining model stability and resisting the temptation to eat the marshmallow.

Evidence-based decisions and iterative improvement

Across surveys and video data, students used test evidence to compare options and justify decisions about which prosthetic materials worked best. In the post-survey, students explained their material choices using features such as firmness, flexibility, and movement. One student selected the black 3D-printed material for the disc prosthetic because "it's firm," while another chose the gray 3D-printed disc because "it stuck but it could still move." Many students chose the marshmallow because it was "flexible" and "bendy," and others selected foam for similar reasons. Video evidence further showed students grounding these decisions in testing outcomes rather than preference alone. For example, one student used numerical reasoning to interpret rigidity, stating, "Ninety-five minus ninety-five equals zero—very inflexible," suggesting an emerging understanding that lack of change under testing may not align with the flexibility expected of a disc. In another moment, a group's surprise at a small measurement change ("Only one?") suggested that students were comparing current evidence to earlier test outcomes and adjusting their expectations accordingly. Together, these decision points indicate that students engaged in evidence-based design reasoning by using observation, measurement, data and comparison to evaluate which options best met the functional goals and constraints of a prosthetic disc.

Collaboration and Feedback as Engineering Culture

Students' engineering reasoning was supported through collaboration and peer feedback during construction and testing. Collaboration and feedback functioned not as peripheral "soft skills," but as central features of an emerging engineering culture in which collective effort supports problem-solving and design improvement. For example, peers encouraged participation and reduced hesitation ("Why don't you start? It's not that hard, I can help you"), offered procedural feedback that shaped construction ("You don't do it that way—put Styrofoam first, then playdough"), and directed real-time adjustments during testing ("Tilt this that way").

Collaboration was especially central during evidence generation, as students stabilized tools and models to support accurate measurement. For instance, students coordinated recording results ("That's 110. Write it down") and requested assistance ("I need someone to hold this"), followed by a peer holding the model in place. Students also negotiated tool use and testing decisions through questioning and clarification (e.g., "Do we need to use the protractor for the height?" and "No, use the ruler"), showing how peer feedback shaped how they carried out measurement and testing. In summary, these interactions illustrate how elementary learners engaged in engineering as a coordinated social practice in which feedback and shared work directly supported testing, and comparison.

Descriptive Survey Findings

Finally, to complement these theme-based findings, we report descriptive results from the open-ended pre/post surveys and the worksheet to provide additional context on students' explanations and interest, as demonstrated through video data. From the 10 consented students, open-ended survey responses showed increases in students' understanding of what biomedical engineers do (from only 10 percent of students at pre-survey to 90 percent of students at post-survey), prosthetics (from 15 percent to 75 percent), and material behavior (from 20 percent to 90 percent). These gains were based on responses to questions such as, "What do biomedical engineers do?", "What is a prosthesis?", and "Do all materials feel or behave the same?" For example, in the pre-survey, most students responded with answers, such as "never heard the term biomedical engineering or IDK,". In contrast, post-survey, responses reflected clearer explanations of biomedical engineers as those who "make prosthesis for different parts of the body like arm," or "make biotech or replace body parts." In addition, six students expressed new interest in engineering as a future career, writing, "Yes I want to be an engineer, because I can build lots of stuff," "Yes, because I can make innovations," and "Yes, I want to be an engineer because I want to change the world."

In the post-survey, five students reported that they loved the activity, while the other five indicated that it was okay.

Discussion and conclusion

Our aim was to investigate how participation in a biomedical engineering design activity, grounded in distributed cognition and constructionism, supports elementary students' development of an engineering mindset, how students engage in engineering practices during the activity, and whether this experience influences their interest in engineering careers. To address this aim, we implemented a single 90-minute design workshop and collected data through pre- and post-surveys, student artifacts and worksheets, and video-recorded activity sessions, which were analyzed using reflexive thematic analysis. The results showed that students framed the design problem, considered constraints, and tested multiple solutions. They evaluated materials through bending and compression tests, using measurement to generate evidence. Throughout the activity, students collaborated to compare results and make evidence-based design decisions. These findings indicate that such hands-on activity supported students' understanding of biomedical engineering concepts, basic measurement and quantitative reasoning, and an engineering mindset through problem framing, testing, and evidence generation. The activity also helped students become more familiar with what biomedical engineers do by engaging them in collaborative engineering practices, supporting greater awareness of engineering work and increased interest in engineering careers. Our findings align with prior work suggesting that engineering activities can support collaboration, increase career awareness, and engage students in core components of the engineering design process [14], [21].

However, challenges with measurement accuracy suggest a need for additional scaffolding and more structured guidance, and future iterations may benefit from using non-edible materials. Overall, integrating engineering activities into elementary education can help students understand engineering work more concretely and may increase their interest in engineering.

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Appendix

Presurvey

1.Have you heard the term ‘biomedical engineering’? What do you think biomedical engineers do?

2. Can you guess or give any examples of what biomedical engineers make?

3.What is a spine?

4.Do you know what a prosthesis or fake body part is? Can you give an example?

5.Do all materials feel and behave the same when you touch or bend them? Can you give some examples?

6.When you grow up, do you think you would like to be an engineer? a. Yes b. No c. Maybe

Why or why not?

Post survey

1. What did you learn about biomedical engineers? What do they do? If you can, give an example.

2.Imagine you are an engineer, and you need to help someone who has hurt their spine. How would you help them?

3.Think about what materials you put between the cardboard for prosthesis, which one do you think worked the best? (Circle one.)

   a. Red Wood b. Marshmallow c. Black 3D-printed material d. Blue Foam e. Gray 3D printed

Why do you think it worked better?

4.How would you describe this activity?

5.What, if any, challenges did you face?

6.When you grow up, do you think you would like to be an engineer? (Circle one.)

a. Yes b. No c. Maybe

Why or why not?

7. How much did you like this activity?

a) I loved it! b) I liked it. c) It was okay. d) I didn’t like it much. e) I didn’t like it at all!

Figure1: Worksheet

After building your model, try using different materials. Place each material between pieces of cardboard, test how it works, and then record your results in the table

Material Name	**Example** 	**Marshmallow** 	**Gray 3D printed** 	**Black 3D printed** 	**Blue Foam** 	**Red Wood** 
Height before pushing	12 CM					
Height after pushing	10 CM					
Difference	12 CM - 10 CM 2 CM					