Biomedical Engineering: Staying hands-on in an online world

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Distributed biomedical engineering (BME) programs face persistent challenges in maintaining hands-on learning when coursework is delivered in hybrid or asynchronous formats. This paper describes the iterative redesign of a required Properties of Biomaterials course that is delivered across two geographically separated institutions. Declining student evaluations and qualitative feedback requesting experiential engagement prompted a response from the faculty. The course redesign was informed by scaffolding and self-efficacy frameworks in engineering education. To improve course morale and engagement, the instructor developed four low-risk, structured hybrid hands-on modules.

1. Toothpick and marshmallow crystal structures (edible activity)
2. 3-point bend testing (ASTM D790)
3. Tensile testing (ASTM D638)
4. Customized orthopedic finger splint design (final design project)

The modules leverage makerspace tools across both campuses for 3D printing finger splints and utilize equipment from the newly established Tissue Engineering and Cell Culture Laboratory (TECCL) and the Soft Matter Characterization laboratories. Mixed-methods assessment included student surveys, small group instructional diagnosis, exam performance, and project outcomes were used to evaluate the effectiveness of these interventions. Results indicate that scaffolded, standards-aligned hands-on modules were associated with improved student perceptions of understanding, confidence, and preparedness for professional engineering practice in a distributed hybrid BME program.

1. Introduction and Program Context

The Biomedical Engineering (BME) program at South Dakota Mines is delivered jointly across two state institutions located approximately six hours apart. Courses are often offered in hybrid formats, with students at one institution participating remotely while counterparts at the other institution engage in face-to-face instruction. Properties of Biomaterials is a required course serving students from multiple majors and has been delivered asynchronously online since 2020 to accommodate scheduling constraints and geographic separation [1]–[4].

While the asynchronous format provided flexibility, it also reduced opportunities for experiential learning traditionally associated with biomaterials education. Post-pandemic studies have documented similar challenges related to engagement, perceived learning, and student satisfaction in online engineering courses [1]–[3]. Following the COVID-19 pandemic, student evaluations reached a low point in Fall 2022, prompting a systematic re-evaluation of the course.

This work examines how scaffolded experiential learning redesign may support student preparedness and confidence within a distributed hybrid biomaterials course. It further contributes new evidence that scaffolded hybrid interventions may stabilize lower-tail student performance in distributed engineering environments, rather than simply increasing average outcomes.

2. Research Motivation

The course redesign was motivated by the need to integrate experiential learning within an asynchronous hybrid environment and was informed by scaffolding and self-efficacy frameworks in engineering education. Prior work in engineering education has shown that hands-on, scaffolded learning experiences are strongly associated with improved student confidence, persistence, and professional preparedness [5], [6].

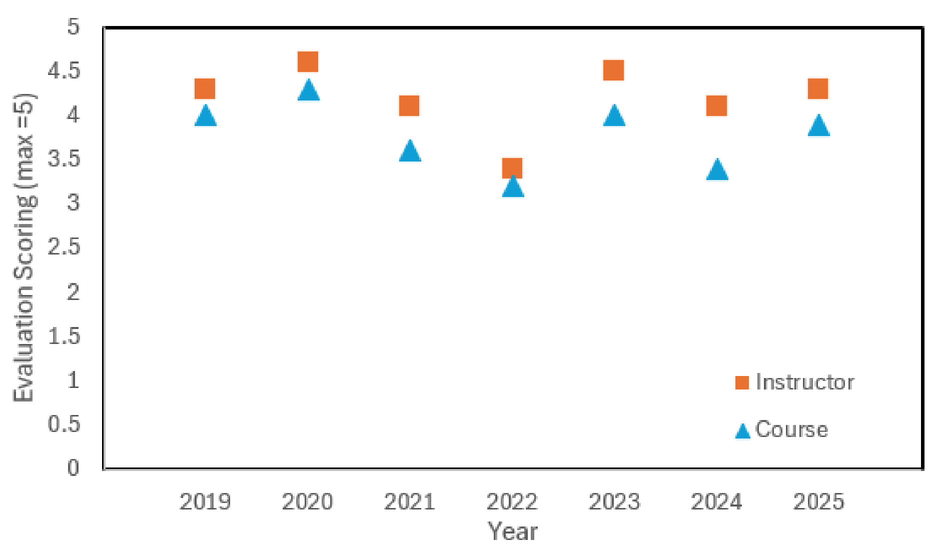

Fig. 1. Properties of Biomaterials course student evaluation scores spanning from 2019 to 2025.

The course saw an all-time low score in student evaluations during the fall of 2022, see Fig. 1. Responses were collected anonymously on a Likert scale with optional open-ended comments. Although pandemic-related disruption has been widely documented [4], [7–9], the decline offered an opportunity for systematic instructional redesign. The course re-evaluation was prompted by open-ended student survey questions. This survey approach was inspired by the success in an NSF IUSE grant [10] that was built on prior research that involves highly successful curricular and co-curricular programming integrating creative hands-on components into an undergraduate engineering degree program [9]-[11].

Taken together, the feedback suggested that the current asynchronous online format was not fully meeting the intended biomaterials learning objectives for the students. There was limited clarity regarding course content and how it connected to biomaterials applications. The course description states: "…provide students with an overview of the field of materials with specific emphasis on biological applications. The first part of the course will cover chemical and physical properties of metals, ceramics, polymers, and composites, including topics in corrosion, crystal structure, phase diagrams, and metallic microstructures.". The instructor needed to more clearly communicate course scope and emphasize key topics early in the semester.

The overall summary feedback from the survey was a request for in-person teaching. Programmatically this was not a possibility between the two institutions as a result of competing departmental and student needs. Maintaining an online asynchronous course during the pandemic supported research and apprenticeship opportunities at the medical school for students at the University of South Dakota while simultaneously finding an optimal time for in-person class time around faculty schedules and balancing required classes was not conducive to delivering in-person.

3. Research Question and Hypothesis

The course redesign was motivated by the need to integrate experiential learning within an asynchronous hybrid environment. Prior work in engineering education has shown that hands-on, scaffolded learning experiences are strongly associated with improved student confidence, persistence, and professional preparedness [7], [8]. Based on student feedback and institutional constraints, the following research question was developed:

Can structured, low-risk, hands-on hybrid modules improve learning in a distributed hybrid biomaterials course compared to asynchronous content delivery alone?

The corresponding hypothesis was:

Integration of ASTM-aligned experimental modules and makerspace-based design activities is expected to be associated with higher perceived preparedness for professional engineering practice relative to asynchronous instruction alone.

4. Course Redesign and Module Overview

Rather than implementing a full course overhaul, incremental changes were introduced between 2023 and 2025 to allow for targeted assessment while managing instructor workload. Four hybrid hands-on modules were developed:

1. Crystal Structure Modeling: An optional toothpick-and-marshmallow activity introduced early in the semester to promote three-dimensional visualization of crystal structures.

2. ASTM D790 Three-Point Bend Module: A CAD-based specimen design and data analysis activity aligned with standardized flexural testing.
3. ASTM D638 Tensile Testing Module: A more advanced CAD and data analysis module requiring students to design dogbone specimens and interpret stress–strain behavior.
4. Final Design Project: A makerspace-based orthopedic finger splint design requiring CAD modeling, 3D printing, iterative refinement, and a written technical report.

Module 1 was implemented during Weeks 2–3 as an optional activity requiring approximately 30–45 minutes. The ASTM D790 and D638 CAD modules were introduced sequentially between Weeks 5–10, with each module spanning approximately two weeks. The final design project was introduced at mid-semester and completed over the final six weeks of the course.

In-person students completed physical activities in laboratories and makerspaces, while remote students participated through recorded demonstrations, virtual lab tours, shared datasets, and remote CAD-based design activities. Both groups completed identical analytical and reporting components. Instructional materials, including CAD templates, assignment prompts, and example datasets, are available from the authors upon request.

Table 1 outlines the systematic changes over three years, the motivation for each change, and the metrics for success. The mandatory office hours will not be discussed in detail as critical mentoring [14],[15] is a vital component the instructor wanted to integrate. Additionally, the instructor reported a better personal connection to the students in the course.

Table 1: Systematic Changes to the Biomaterials Course.

Year	Change	Motivation	Metrics for Success
2023	Removed online discussion board and mandatory office hours.	Student feedback stating the discussion board did not add value.	Improved connection with students and improvement in Instructor Evaluation Scores.
2023	Added ASTM focused mini-CAD modules to build skill-mastery.	ABET feedback encouraging more ASTM integration.	Improved final design projects, increased student confidence, and reduced required student help meetings.
2023	Added a toothpick-and-marshmallow crystal structure lab.	Student feedback requesting hands-on modules.	Increased number of participants in this optional module and assessment of Exam I scores.
2024	Added ASTM tensile testing data analysis take-home to Exam II.	ASTM module importance reinforcement.	Reviewed the students' assignment and connected these results to their final design report.
2025	Added ASTM videos aligning with mini-CAD modules and optional lab tours.	TECCL*, new lab facility, and the equipment aligns with these CAD modules.	Increased student attendance in lab tours and increased research interest from BME students in the TECCL facility.
2025	Required students to 3D print their CAD module.	Connecting CAD results on computer to physical products.	Reviewed the students' assessment of their 3D Printed splints in their final report.
*TECCL is the Tissue Engineering and Cell Culture Lab			

5. Assessment Methods

Assessment employed a mixed-methods approach consistent with prior ASEE studies evaluating curricular innovation [11]–[13]. Anonymous student surveys collected quantitative and qualitative feedback on individual modules. Exam performance data were analyzed to explore associations between module participation and conceptual understanding. Final project scores and written reports were used to assess design competency, application of standards, and communication skills. While causal claims are not asserted, this quasi-longitudinal cohort comparison does not constitute an experimental design; however, multi-year trend consistency strengthens interpretive confidence. Cohort sizes were modest and student populations varied year-to-year.

IRB Statement: This study was reviewed by the Institutional Review Board of South Dakota State University and determined to be exempt from further review under Exemption Category 2 as outlined in 45 CFR 46, §104(d). The approved exemption protocol number is IRB-2106010-EXM.

6. Results

6.1 Crystal Structure Module

Survey responses (n = 16) indicated that 75% of students rated the marshmallow-based activity as useful or highly useful for developing intuition about crystal structures, consistent with prior research demonstrating the value of physical models in supporting visualization and conceptual understanding [10], [11]. Although participation was voluntary and not randomized, Exam 1 performance remained stable across cohorts (2023 M = 24.27, SD = 4.19; 2024 M = 24.68, SD = 3.77), with a negligible effect size (Cohen's d = 0.10). These findings suggest that the introduction of low-risk physical modeling supported conceptual development without altering early summative performance. Students were encouraged, when feasible, to complete the activity collaboratively, reinforcing peer discussion and shared spatial reasoning (see Fig. 2).

Fig. 2. BME students completing the marshmallow and toothpick module (cohort 2023).

6.2 Scaffolded CAD and ASTM Modules

Scaffolded CAD modules were introduced to reduce cognitive load and build student confidence prior to the final design project. Instructional scaffolding has been shown to improve learner self-efficacy by supporting mastery experiences and reducing cognitive overload [5], [6]. Survey results (n = 18) showed that 72% of respondents found the modular approach helpful in preparing for the final project. Average final CAD project scores increased from 89% (2022) to 94% (2023) following modular integration, representing a 5-point increase following scaffolded implementation.

Integration of ASTM D790 and D638 standards exposed students to professional testing protocols and reinforced connections between specimen geometry, material behavior, and performance. Recorded demonstrations added in 2025 further supported student understanding, particularly for remote learners.

6.3 Final Design Project and ABET Alignment

The culminating project required students to design, 3D print, and evaluate a custom orthopedic finger splint. Iterative design challenges highlighted discrepancies between digital models and physical fit, reinforcing engineering judgment and iteration. The final technical report required justification of material selection, processing parameters, and performance using relevant ASTM standards. These activities align with ABET outcomes related to engineering design (Outcome 2), communication (Outcome 3), experimentation and data analysis (Outcome 6), and professional practice and lifelong learning (Outcome 7) [16].

Final project performance remained high across cohorts (2022: M = 91.17%, SD = 8.36; 2024: M = 90.36%, SD = 7.07; 2025: M = 90.24%, SD = 9.64), with negligible effect sizes relative to the pre-sequential redesign baseline ($|d| \approx 0.10$). Importantly, while mean performance remained stable, distributional analysis revealed a substantial reduction in lower-tail outcomes. In 2022, 22.2% of students scored below 80%, compared to 10.7% in 2024 and 3.6% in 2025. This reduction in low-end performance suggests that scaffolded module integration may have supported struggling students without inflating overall grades. These findings align with scaffolding theory, which predicts floor stabilization through structured mastery experiences rather than mean amplification.

6.4 IDEA Learning Objectives and Course Perceptions

IDEA evaluation data (see Appendix B) were analyzed longitudinally to examine trends in student-reported progress on learning objectives following sequential module implementation. The 2022 cohort represented the lowest baseline (n = 15; 51.7% response rate), with moderate ratings across core objectives (e.g., Basic Understanding M = 3.3; Application of Course Material M = 3.2; Professional Skills M = 3.1).

Following scaffolded implementation of hands-on crystal structure modeling, ASTM-aligned data analysis modules, and CAD integration, high student-reported ratings were observed by 2025 (n = 16; 53.3% response rate). Ratings for “Gaining a basic understanding of the subject” increased to M = 4.0, representing a +0.7 shift on a 5-point scale. Similarly, “Learning to apply course material” increased from M = 3.2 (2022) to M = 3.86 (2025), and “Developing specific professional skills” increased from M = 3.1 to M = 3.71.

Importantly, these gains occurred while overall academic performance remained stable, suggesting that the redesign improved perceived conceptual mastery and application without inflating grades. The magnitude of change (approximately 0.6–0.7 on a 5-point scale) represents a meaningful practical improvement in student-reported learning, particularly in domains directly targeted by the scaffolded interventions.

Overall course ratings similarly rebounded from a 2022 low (Excellent Course = 3.2) to 3.9 by 2025, with converted IDEA scores shifting from "Much Lower" buckets toward institutional norms. Together, these results are consistent with the possibility that structured experiential scaffolding supported improved conceptual clarity and applied learning in a distributed hybrid environment.

7. Discussion

The findings suggest that structured scaffolding within distributed hybrid environments can stabilize academic performance while reducing lower-tail outcomes. Although mean project scores remained consistent across cohorts, the reduction in sub-80% outcomes indicates that the redesign may have strengthened performance floors without inflating grades. This pattern aligns with scaffolding theory, which predicts that structured mastery experiences disproportionately support learners at risk of underperformance. Because multiple changes were implemented sequentially, specific effects of any single intervention cannot be isolated. Instead, the results should be interpreted as evidence of the cumulative redesign strategy rather than any one module alone.

Student feedback emphasized reduced anxiety, improved visualization, and stronger connections between theory and practice. While professional preparedness was not directly measured through employer or internship outcomes, increased self-reported gains in application and professional skill development suggest enhanced readiness. These findings support scaffolding theory by demonstrating that incremental mastery experiences reduce cognitive load and increase perceived preparedness, as well as align with prior work demonstrating that hands-on, scaffolded learning experiences support self-efficacy and mastery in engineering education [5], [6].

Beyond student outcomes, the incremental redesign strategy also addressed instructor sustainability—an often underexamined factor in hybrid and asynchronous course delivery. Prior studies have documented elevated levels of stress and burnout among faculty teaching online and hybrid courses, particularly following the rapid instructional shifts associated with the COVID-19 pandemic [17]–[20]. By introducing modular, reusable hands-on activities rather than a full course overhaul, the redesign balanced pedagogical improvement with manageable faculty workload. This approach aligns with recommendations in the literature emphasizing sustainable instructional practices to mitigate burnout while maintaining instructional quality [18]–[20].

The use of scaffolded CAD and ASTM-aligned modules further reduced instructional friction by standardizing expectations and assessment criteria, which may alleviate cognitive and emotional demands on instructors in online environments [17], [19]. Recorded demonstrations and virtual lab tours also served as durable instructional assets, reducing the need for repeated synchronous explanations while supporting equal access for remote learners.

Additionally, the final design project incorporated informal mentoring elements through iterative feedback, design reviews, and guided reflection. Mentoring and developmental relationships have been shown to play a critical role in student persistence, professional identity formation, and confidence in engineering pathways [14], [15]. Embedding these mentoring practices within a required technical course allowed students to receive structured guidance without reliance on external mentoring programs, which may be less accessible in distributed or commuter-based institutions.

Collectively, the findings suggest that distributed hybrid engineering education does not need to sacrifice experiential rigor. When scaffolded appropriately, low-risk physical modeling, standards-aligned analysis, and iterative design can preserve disciplinary authenticity while supporting performance stabilization and instructor sustainability by reducing cognitive overload during early learning stages and enabling struggling students to achieve baseline competency before advancing to higher-complexity design tasks.

8. Design Principles

Based on iterative redesign and multi-year assessment, five design principles emerged for distributed hybrid engineering programs:

1. Scaffold before complexity. Early low-risk modeling activities (e.g., marshmallow crystal structures) reduce cognitive load and build visualization confidence prior to high-stakes assessment.

2. Align experiential learning with professional standards. Embedding ASTM-based modules strengthens authenticity and reinforces disciplinary identity.

3. Maintain analytical equivalence across modalities. While delivery mode may differ (in-person fabrication vs recorded demonstrations and shared datasets), assessment expectations should remain equivalent.

4. Protect performance floors. Sequential scaffolding should aim not only to raise means, but to reduce lower-tail outcomes.

5. Design for instructor sustainability. Sustainable hybrid innovation requires modularity and repeatability, reducing burnout while preserving rigor.

9. Conclusion

This work suggests that structured, standards-aligned hands-on modules can meaningfully support experiential learning in distributed hybrid biomedical engineering programs. The redesign's most notable contribution was performance floor stabilization rather than grade inflation. Student performance and feedback suggest improved preparedness for professional engineering practice. While not an experimental study, the multi-year evidence suggests that modest, scalable hands-on redesign strategies can improve the student experience in geographically distributed engineering programs. Future iterations will focus on earlier project milestones to allow additional time for design iteration and fabrication.

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Appendix A: Survey Instruments

Positive and Negative Constructive feedback from the survey are provided below.

> Student #1: "I really enjoyed this course and the teacher as well. The book was engaging and nice to read from. I liked that homework was assigned to each chapter as well as a hands-on crossword puzzle."
>
> Student #2: Decently paced throughout the semester…I liked how this course was set up and that it remained consistent throughout the semester
>
> Student #3: This class should not be online and asynchronous. This class not having any in person instruction or connection is absurd, and unacceptable. There is so much content and ability for this to be taught in person. I also lack the connection to biomaterials almost completely-this was just materials in general.
>
> Student #4: Horrible class...this is not a biomaterials course this is the same as MET 232 why should we take this course over 232? Overall one of the worst courses I have taken.

Another question posed to the students in student survey was "What do we need to know to continue to improve the experience of taking a class via distance?"

> Student #1: Asynchronous structure feels like "busywork"…Need to revamp everything.
>
> Student #2: I liked the way this online course was set up. It was easy to navigate and easily understood. I think it was more user friendly than the courses I have taken through University of South Dakota. I do not think discussion boards do anything or facilitate interaction between students. I think they usually just fly through and do not thoughtfully respond. I have never felt like I gained anything from an online class discussion board.
>
> Student #3: This class is designed okay for distance people, but the course should not be online.

Student #4: Please do not keep this an online class, this is a complete disservice to engineering students. This could've been a good class.

Student #5: This is a great, well-structured online class. I have no complaints about the course.

Appendix B: IDEA Learning Objective Gains (2022 vs. 2025)

Note: Results are descriptive comparisons across cohorts with modest sample sizes and varying response rates. They should be interpreted as directional trends rather than inferential statistical conclusions.

Learning Objective	**2022 Mean**	**2025 Mean**	**Absolute Gain**	**Scale Increase***
Gaining a basic understanding of the subject	3.3	4	**0.7**	14.00%
Learning to apply course material	3.2	3.86	**0.66**	13.20%
Developing specific professional skills	3.1	3.71	**0.61**	12.20%
Working effectively in teams	1.9	2.43	0.53	10.60%
*Percent of scale increase calculated relative to 5-point scale.				