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Transforming Biomedical Engineering Education Through Instructional Design*

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In 2016, our biomedical engineering (BME) department created a new model of instructional change in which undergraduate BME curriculum is closely tied to the evolution of the field of BME, and in which faculty, staff, and students work together to define and implement current content and best practices in teaching. Through an Iterative Instructional Design Sequence, the department has implemented seven BME-in-Practice modules over two years. A total of 36 faculty, post docs, doctoral candidates, master's students, and fourth year students participated in creating one-credit BME-in-Practice Modules exploring Tissue Engineering, Medical Device Development, Drug Development, Regulations, and Neural Engineering. A subset of these post docs, graduate students and undergraduates (23) also participated in teaching teams of two-three per Module and were responsible for teaching one of the BME-in-Practice Modules. Modules were designed to be highly experiential where the majority of work could be completed in the classroom. A total of 50 unique undergraduates elected to enroll in the seven Modules, 73.33% of which were women. Data collected over the first two years indicate that Module students perceived significant learning outcomes and the Module teaching teams were successful in creating student centered environments. Results suggest that this mechanism enables effective, rapid adaptation of BME curriculum to meet the changing needs of BME students, while increasing student-centered engagement in the engineering classroom. Findings also suggest that this approach is an example of an intentional curricular change that is particularly impactful for women engineering students.

Keywords: biomedical engineering, instructional change, instructional design

1. Introduction

Formal biomedical engineering (BME) education and training began in the 1960s with the formation and subsequent growth of doctoral programs intended to create professionals who were well versed in both life sciences and a specialization of engineering [1, 2]. Soon after, the creation of undergraduate BME programs followed. When undergraduate BME degree programs were first created, they largely served as a pathway to graduate or medical school, thus not commonly viewed as a terminal degree [2, 3]. More recently, however, career paths and interests of BME students have broadened beyond graduate education opportunities [4]. Yet undergraduate BME curriculum has not kept pace with the changing landscape of BME in practice and thus leaves many believing that they are unprepared for work in industry after their undergraduate education [1, 5]. Many undergraduate BME students express that they know very little about the possibilities of their BME degree and lack experience in any specialization of BME adequate enough to make informed decisions about their future career plans [5]. Furthermore, BME graduates perceive themselves to be outcompeted for jobs in the medical device industry by other engineering disciplines including mechanical and electrical engineers [5]. Therefore, there is a need to change biomedical engineering education to better prepare students to be competitive in their future careers, especially for those who do not pursue graduate degrees.

Concurrently, there is a global call for engineering education to be transformed and include more hands-on, experiential learning [6]. Studies show that students learn better when they are actively engaged in their own learning via inquiry-based learning, active learning, and other student-centered learning approaches [1, 7–10]. Research shows that not only are such practices effective, they are particularly well suited for BME education given the interdisciplinary critical thinking required for the field [2, 11]. However, the majority of undergraduate STEM education remains dominated by teacher-centered, didactic practices [7]. If a transformation in education is to occur, instructors must be given opportunities to explore innovative teaching practices. Unfortunately, future instructors are not formally trained to teach [12, 13]. As graduate students are the pipeline for higher education instructors, instructional change should start with graduate students if we are to change the future of education [14]. Without support, instructors and graduate students have a tendency to teach the way in which they themselves were taught [15–18], neglecting newer, student-centered teaching practices. Thus, we designed an iterative instructional design sequence that both trains graduate students and faculty in student-centered pedagogy and cre-

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ates 1-credit BME experiential learning modules, BME-in-Practice Modules, to increase industry relevant student centered curriculum into BME education for first and second year BME undergraduates.

The purpose of this paper is to examine the impact of the first two iterations of the BME Iterative Instructional Design Sequence. Specifically, we explore student perceptions of learning outcomes and graduate student instruction in the BME-in-Practice Modules by asking the following research questions: (1) How do students enrolled in the BME-in-Practice modules perceive their learning outcomes? And, (2) How do students enrolled in the BME-in-Practice modules perceive the student-centeredness of instruction?

2. Background

In 2017, the BME Department designed and launched the Iterative Instructional Design Sequence to address calls to revolutionize BME instruction. This two semester sequence engages faculty, post docs, graduate students, and upper level undergraduates in learning about instructional design [19–22] and student-centered learning [23] in an Instructional Incubator course and the subsequent implementation of BME-in-Practice Modules. In the fall semester, incubator participants work in teams to design industry-relevant BME-in-Practice Modules and then serve as teaching apprentices for their "BME-in-Practice" Modules the following semester. The Instructional Incubator course is offered annually, and teaching teams have the opportunity to either iterate on and improve previous Modules or create new Modules. Modules that are no longer relevant are phased out. This iterative design approach allows for curriculum to be consistently improved upon and adapted to the changing and growing field of BME. This approach to curricular design is especially helpful for BME undergraduate students for a number of reasons. Specialized Modules focusing on specific areas in the biomedical engineering industry provide students with exposure to industry skills they often say they lack [5] and help students identify and prepare for potential internship opportunities. The inclusion of graduate students as the primary instructors for these courses also facilitates beneficial peer-to-peer learning and helps undergraduate students make connections within the BME department. Finally, inclusion of post docs and faculty immerses current instructors in curricular design from the perspective of student-centered learning.

2.1 Instructional Incubator (Fall)

The Instructional Incubator experiential course was first offered in the fall of 2017. Incubator participants interview and shadow stakeholders, including professional biomedical engineers, researchers, and recruiters who hire BME students, to become familiar with the current state of BME practice and understand the needs of BME stakeholders. Incubator teams then learn about student learning theory [22, 24–26] and curriculum design best practices [22, 27] while conceptualizing and designing 1-credit "BME-in-Practice" Modules to address gaps in the undergraduate curriculum as they relate to growing post graduate needs in industry and other BME career opportunities (i.e. nonprofits, government agencies, etc.). Incubator teams are required to design the curriculum from a student centered perspective [28]. This sequence meets the career development needs of current graduate students as instructors and non-academics [29] by exposing graduate students to non-academic post graduate alternatives and training future academics in pedagogy and teaching. The Incubator also lays a foundation for long-term institutionalization of professional career development within the academic program.

2.2 BME-in-Practice Modules (Winter)

In total, nine Modules have been developed, six in fall 2017 and three in fall 2018. The six Modules developed in fall 2017 included Computational Modeling, Neural Engineering, Tissue Engineering, and three Modules focused on Medical Device Development. In fall 2018, Incubator teams iterated upon two previous Modules (Tissue Engineering and Medical Device Development) and a third new Module was created (Regulations). Each Module is four weeks long and is intended to be an elective introductory course requiring no previous experience.

Seven of the nine Modules were offered in the winter terms, three in winter 2018 and four in winter 2019 (Table 1). Two of the Medical Device Development Modules developed in W18 were not offered due to the unavailability of the teaching teams. While the Computational Modeling Module was developed in fall 2017, the Module was not taught until W19 due to scheduling conflicts. The Compu-

Table 1. BME-In-Practice Modules offered for student enrollment

Winter 2018 (W18)	Winter 2019 (W19)
Neural Engineering	Computational Modeling
Medical Device Development	Medical Device Development 2.0
Tissue Engineering	Tissue Engineering 2.0
	Regulations

tational Modeling teaching team was the same team that developed the course in fall 2017. Appendix A provides brief description of each Module offered.

3. Methods

A pre-/post survey approach was used to examine student perceptions of learning outcomes and student-centered learning. Research in this study was approved by the University of Michigan Institutional Review Board in exempt protocol HUM00120328. Quantitative and qualitative data were collected simultaneously with two different surveys; one survey focused on learning outcomes and one survey focused on teaching team evaluation. The response rate was 96.75% (n = 62) and 93.75% (n = 60) for the learning outcome survey and teaching team evaluation survey. For this study, only the quantitative data was analyzed. Inferential statistics were applied to test the statistical significance of students' perceived learning gains from pre- to post-survey. Descriptive statistics were also calculated for each Module.

3.1 Participants

Across both academic years, a total of 50 unique students participated in at least one of the BME-in-Practice Modules (Table 2). Occasionally, students enrolled in more than one Module within the same academic year, bringing the total number of students enrolled to 64. Seven students took two Modules, two students took three Modules, and one student took four Modules. Of the ten total students who enrolled in more than one Module, three were men and seven were women. The 2018 winter semester had a total of 20 students, with 11 students in Medical Device Development, 5 students in Neural Engineering and 9 students in Tissue Engineering. Enrollment increased in the 2019 winter semester for a total of 30 students: 11 in Medical Device Development, 4 in Computational Modeling, 15 in Tissue Engineering and 9 in Regulations.

The majority of students enrolled in the BME-in-Practice Modules were in the second year (54%) or first year (22%) of their undergraduate program (Table 2). Upperclassman undergraduates (third year or above) and graduate students also enrolled in several of the modules, although these students were far more numerous in 2019 compared to 2018. Women constituted 76% of the module students and men constituted 24%. This is a notably high proportion of women compared to the 46% in winter 2018 and 50% in winter 2019 in the BME department [31]. Women comprise 27% of undergraduates in the college of engineering as a whole [30].

3.2 Data Collection

3.2.1 Learning Outcome Surveys

The primary focus of the learning outcome surveys was to evaluate student perceptions of learning outcomes specific to each Module. Pre and post learning outcome surveys were specific to each module (Appendix B). All surveys were administered online and contained a combination of open-ended questions and Likert-scale questions.

Likert-scale questions probed students' experience, confidence, or familiarity with skills, terms, and concepts related to Module content. All of the Modules used a 5-point Likert-scale, with the exception of Regulations, which used a 4-point Likert-scale. Qualitative questions either directly tested the

Table 2. Demographics of students enrolled in the BME-in-Practice Modules

	Students enrolled winter 2018		**Students enrolled winter 2019**		**Students enrolled total**	
Demographic	**Count**	**Frequency**	**Count**	**Frequency**	**Count**	**Frequency**
Gender						
Men	4	20%	8	27%	12	24%
Women	16	80%	22	73%	38	76%
Education level						
1st year undergrad	5	25%	6	20%	11	22%
2nd year undergrad	14	70%	13	43%	27	54%
3rd year undergrad or above*	1	5%	9	30%	10	20%
Graduate student	0	0%	2	7%	2	4%
Enrolled students						
Unique students	20		30		50	
Total enrolled	25		39		64	

* Undergraduate students beyond their second year were grouped together due to lack of proper data to distinguish them.

Table 3. Teaching team evaluation questions sorted by HPL factor

Knowledge and community-centeredness	Learner-centeredness	Assessment-centeredness
• Fostered a collaborative learning environment. • Encouraged me to work interactively with my team. • Emphasized learning new skills. • Shared skills I can apply in the future. • Encouraged the students to learn from each other in the class. • Encouraged a nonthreatening environment where students could ask questions of comment about academic content. • Asked questions to make me think. • Acknowledged the diverse learning styles of students in the class. • Applied knowledge to everyday situations. • Shared his/her own practical experience. • Explained how to solve specific problems. • Helped me understand key course concepts. • Related the content of the course to a big picture. • Acknowledged my misunderstanding of a concept.	• Helped my team when we needed assistance. • Addressed my individual needs or concerns. • Provided responses that guided me in problem solving. • Motivated me to continue learning. • Translated theoretical knowledge into practical skills. • Facilitated my communications with professors or other course staff. • Provided verbal feedback about my progress. • Acknowledged that learning engineering concepts can be challenging at times.	• Provided written critiques about my progress. • Acknowledged when I was improving in the class. • Addressed my concerns about my grades in this course. • Provided written critiques to my team about our progress on course deliverables. • Acknowledged my misunderstanding of a concept.

students' knowledge of Module content (e.g., "Please list the steps of the design process", "True or False? All drugs in the form of medications or supplements require FDA approval") or asked the students for their perspective or opinion on the Module topics (e.g., "What is tissue engineering to you?", "Which topic [covered in the course] do you think was the most valuable?").

3.2.2 Course and Teaching Team Evaluation

The teaching team evaluation surveys consisted of open-ended and Likert-scale questions for formative assessment and teaching team feedback. Pre-survey questions probed student expectations of the Modules. Post-surveys probed both student opinions of their experience with respect to pre-Module expectations and student opinions of their teaching team. Pre-surveys were administered to students within the first week of the four-week Module and post-surveys were administered to students during the last week of the Module. All surveys were administered online.

Survey questions with respect to the teaching team differed between winter 2018 and 2019. For winter 2018, teaching team evaluation questions were adopted from the University of Michigan Course Evaluation Question Catalog (Table 4, below). Winter 2019 teaching team evaluation questions were adopted from Zhu et al.'s (2013) Graduate Teaching Assistant (GTA) Survey [32]. The Zhu et al. GTA Survey is a validated survey, informed by the How People Learn (HPL) framework, that can be used to provide pedagogical feedback to GTAs [32], [33]. Three distinct factors are assessed, knowledge- and community-centeredness, learner-centeredness, and assessment-centeredness [32]. All questions led with the prompt "During the module sessions, the graduate student teaching team", followed by the action or behavior of interest as written in Table 3. All questions assessing knowledge- and community-centeredness and learner-centeredness were included in the survey. For brevity, and since assessment-centeredness was not a focus of the Instructional Incubator, five of the eight total questions for assessment-centeredness were used. One question was used to assess both knowledge-centeredness and assessment-centeredness as indicated in the validation of the survey ("Acknowledged my misunderstanding of a concept").

3.3 Data Analysis

All student responses were anonymous or deidentified. Pre- and post-data were matched when possible. Pre-post survey responses that could not be matched or were less than 80% complete were not analyzed for this study. Qualitative data was specific to each module and not generalizable for the purposes of this study, and thus is not addressed in this paper. Finally, due to the low number of participants (n = 4) and inability to match pre- and post-responses, learning outcome data from the Computational Modeling module was excluded from this analysis.

3.3.1 Learning Outcomes

Pre- and post-responses to Likert-scale questions were analyzed separately for each Module using Excel. The mean and standard deviations of all Likert-scale responses were computed for pre- and post-surveys. The distribution of Likert-scale responses within each Module is assumed to be normal. This assumption becomes progressively less important as the number of survey respondents increases. Two-tailed paired and unpaired t-tests were run on the pre- and post-data for each Module.

Further analysis was performed to explore learning outcomes by dividing the Likert-scale questions into two categories, skills and concepts (Appendices B and C). Skill questions were defined as those that assess the student's ability to perform a task or use a tool, while concept questions assess the student's familiarity with a term, understanding of complex concept or subject, or ability to think critically or problem solve with regard to a certain topic. The pre- and post-means and standard deviations were calculated separately for skills questions and concept questions. Two-tailed paired t-tests were run separately for skill and concept pre- and post-data for each Module.

The difference in learning outcome responses (post-pre) were also analyzed with respect to gender and student level across all modules. The average pre and post responses were also calculated for men, women, and student education level (first year, second year, and upper level undergrad/graduate student). A two-tailed t-test, assuming unequal variances, was used to analyze difference in gender, while an ANOVA and additional two-tailed t-tests were performed to explore differences between student levels.

3.3.2 Teaching Team Evaluation

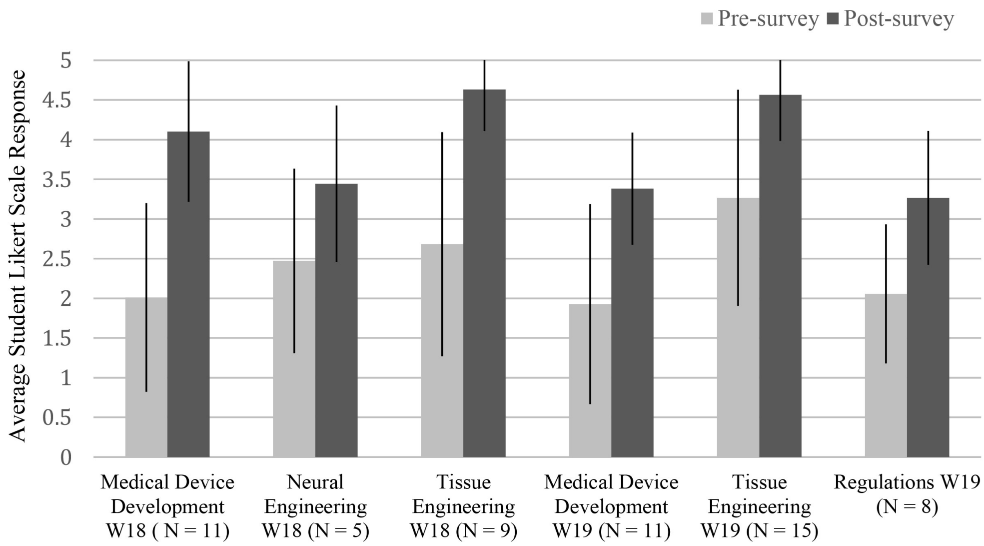
Likert-scale teaching team evaluation data was analyzed separately for each year. Mean response and standard deviation for all responses was calculated for both winter 2018 and winter 2019. For winter 2018, the distribution of student responses to each question were calculated and for winter 2019, the average and standard deviation for each HPL factor was calculated.

4. Results

4.1 Pre- to Post-Student Growth

The average Likert-scale response for the Module-specific surveys increased for each Module to varying extents (Fig. 1). Using paired t-test results with a cutoff of $p < 0.1$, all six Modules analyzed yielded significant results. Neural Engineering had the lowest change in mean from pre to post (0.972) and Medical Device Development W18 and Tissue Engineering W18 had the highest changes in mean (2.091 and 1.949).

Analysis of the difference in learning outcomes



Pre mean	2.011	2.471	2.682	1.927	3.267	2.056
Pre S.D.	1.189	1.164	1.412	1.260	1.362	0.876
Post mean	4.102	3.443	4.631	3.382	4.563	3.266
Post S.D	0.885	0.987	0.524	0.707	0.580	0.843
Change	2.091	0.972	1.949	1.455	1.296	1.210
p-value	0.000	0.000	0.000	0.000	0.000	0.000

Fig. 1. Results of average student responses for pre- and post-surveys for module-specific content knowledge.

Table 4. Learning outcome analysis results by gender and student level

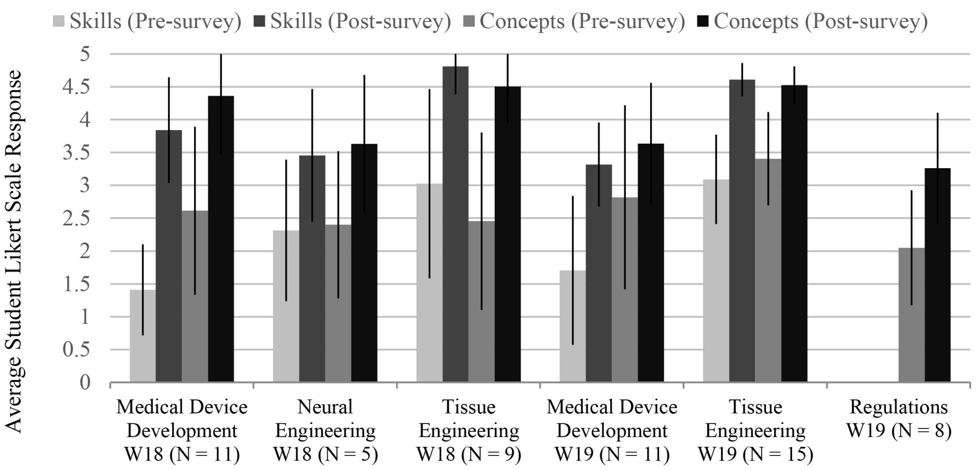
	Gender		**Education level**		
	Men	**Women**	**First-year**	**Second-year**	**Upper-level**
Average mean change	1.34	1.63	1.64	1.70	1.25
Averaged pre mean	2.86	2.62	2.47	2.66	2.94
Average post mean	4.19	4.27	4.11	4.35	4.19
t-test p-value	0.01		*Between first-year and second-year* 0.67 *Between lower-level and upper-level* 0.00		
ANOVA p-value	N/A		0.001		

(post – pre) across all modules, between men and women, were statistically significant ($p < 0.1$). Women showed a larger average increase in their perceptions of learning (Table 4). The average pre-response for women (2.62) was lower than that of men (2.86) (Table 4), whereas women showed higher average post-responses (4.27) than men (4.19). When reviewing differences across student level, the ANOVA reported a significant difference between the average difference in learning outcomes for first-year, second-year and upper-level students ($p < 0.1$). Upper-level students includes undergraduates in their third-year or beyond and graduate students. Further analysis of education level data demonstrated that there was no statistical difference between the lower-level groups (first- and second-year) learning outcomes ($p > 0.1$). However, lower-level students showed larger learning gains than the upper-level students ($p < 0.01$).

4.2 Assessment of Growth in "Skills" and "Concepts"

Comparing growth in skills and concepts separately provides more insight into areas of student growth and stagnation (Fig. 2). All Modules had significant student-reported growth from pre to post ($p < 0.1$). It should be noted that most Module surveys did not ask the same number of questions assessing skills and concepts (Appendices B and C). Neural Engineering, Tissue Engineering (both semesters), and Regulations assessed more for concepts while Medical Device Development either asked an even number of questions (W18) or assessed more for skills (W19).

Tissue Engineering W18 saw greater change in concepts than in skills, while Medical Device Development W18 and W19 had a greater change in skills. Neural Engineering and Tissue Engineering W19



Skills Change	2.432	1.143	1.785	1.614	1.329	N/A
Concepts Change	1.75	1.127	2.050	0.818	1.256	1.215
Skills p-value	0.000	0.000	0.000	0.000	0.000	N/A
Concepts p-value	0.000	0.001	0.000	0.015	0.000	0.000

Fig. 2. Results of average student responses for pre- and post-surveys divided by question type.

Table 5. Distribution of student responses for the 2018 winter semester teaching team evaluation questions

	Always	Most of the time	About half the time	Sometimes
The teaching team explained material clearly	47.83%	47.83%	4.34%	0%
The teaching team appeared to have a thorough knowledge of the subject	78.26%	17.39%	4.35%	0%
The teaching team seemed well prepared for class meetings	95.65%	4.35%	0%	0%
The teaching team made the course interesting	73.91%	17.39%	4.35%	4.35%
The teaching team was enthusiastic about the subject matter	90.91%	9.09%	0%	0%
The teaching team was open to contributions from all class members	100%	0%	0%	0%
The teaching team handled questions well	82.61%	17.39%	0%	0%
	Strongly agree	**Somewhat agree**	**Neither agree nor disagree**	**Somewhat disagree**
I was very satisfied with the educational experience the teaching team provided	86.96%	8.70%	4.34%	0%
The teaching team made good use of examples and illustrations	73.91%	17.39%	8.70%	0%
The teaching team treated students with respect	100%	0%	0%	0%
The teaching team used class time well	60.87%	39.13%	0%	0%

had very similar changes in mean response for skills and concepts.

4.3 Evaluation of Teaching Teams

The winter 2018 research surveys consisted of 11 questions that directly addressed the teaching teams and had a total of 23 respondents. Student responses by question are shown in Table 5.

The mean of all responses was 4.701 and the standard deviation of all responses was 0.632. The winter 2018 results indicate that the teaching teams were particularly effective with creating a respectful and welcoming classroom environment since "The teaching team was open to contributions from all class members" and "The teaching team treated students with respect" each had the highest possible response from all students. Students indicated room for improvement in the use of class time, explaining material clearly, and making the course interesting.

The teaching team evaluation portion of the winter 2019 surveys consisted of 26 questions and had a total of 36 respondents. The mean of all responses was 4.662 and the standard deviation of all responses was 0.715. When separated by their "How-People-Learn" (HPL) factor, questions that addressed learner-centeredness had the highest mean response rate with an average of 4.774 (Table 6). Knowledge and community-centeredness followed closely with an average of 4.725 and assessment-centeredness averaged the lowest, with a mean of 4.306.

5. Discussion

This paper presents a novel approach to curricular change by leveraging multigenerational teams, undergraduates, graduate students, post docs and faculty. Results indicate that Module students perceive significant gains in skills and concepts in these short Modules led by graduate students. Results are particularly promising for the impact of this curricular approach to engaging women in engineering. Additionally, teaching team evaluations demonstrate that teams were successful in cultivating a student-centered classroom.

5.1 Student Growth

In this study, we explored the impact of six BME-in-Practice Modules on student learning. Our results indicated that students perceived significant learning gains in all six of the Modules we analyzed. Of the 50 unique students that electively enrolled in the Modules, 73.3% were women. Further analysis of results with respect to gender indicated that women showed greater increase in learning gains than their men enrolled in the Modules. Analysis with respect

Table 6. Results of 2019 winter semester instructor evaluations using by HPL factor

	Knowledge and community-centeredness	Learner-centeredness	Assessment centeredness
Mean	4.725	4.774	4.306
Standard Deviation	0.616	0.529	1.047
Number of questions	14	8	5

to student education level, indicated that lower-level students showed larger learning gains than the upper-level students.

For this study, student learning was collected through self-reported perceptions of learning gains. While the value of individual self-report data is controversial, research suggests that the aggregation of student self-report data is a valid and reliable for measuring differences in learning between groups [34]. All of the BME-in-Practice courses were designed from a learner perspective, leveraging evidence-based practice that have been shown to increase student learning [36, 37]. Consistent with the literature, study results showed significant learning gains for all Module students.

Mounting calls for increasing the diversity in science [38–40] have stimulated significant research in the understanding the causes of the gender gap in engineering [41, 42]. The resultant research has identified numerous factors that have the potential to influence gender disparities in engineering, including self-efficacy [43] and faculty and peer relationships [44, 45]. As a result, researchers have called for new approaches to engineering program development to support women engineers [46]. The high percentage of female enrollment suggest that the BME-in-Practice Modules is one such approach. While it is noted that biomedical engineering is commonly recognized as an engineering discipline that attracts higher percentages of women [46, 47], the 73.3% elective enrollment in the BME-in-Practice Modules is considerably higher than reported numbers of women pursuing BME degrees (30–40%) [46, 47] and the approximately 50% of women currently enrolled in this study's own institution.

In 2016, Ro and Knight [45] explored how college experiences influence different learning outcomes for men and women in engineering programs. In their quantitative study, Ro and Knight surveyed 4,901 students in 120 engineering programs and found that women self-reported greater design skills when curriculum emphasized professional skills and there was a greater frequency of student-center teaching. Results from this study are consistent with Ro and Knight's findings and broadens opportunity for non-design skills. Women Module students reported greater learning gains than men enrolled in the Modules. This suggests that the creation and implementation of the BME-in-Practice modules may be a start to helping women develop learning outcomes more effectively.

The observed difference in student learning with respect to education level offers an interesting area of exploration. Lower-level students showed larger learning gains than the upper-level students. While both lower- and upper-level students' report similar post-mean scores, lower-level students start with lower pre-mean scores. A first order assessment of this finding, suggests that upper-level students may have already been exposed to the skills and concepts in the curriculum. Although a worthy area of future research could look at the relationship between student reported learning gains with respect to epistemology research [48, 49], as epistemological beliefs can play a significant role in understanding educational strategies for teaching and learning [50]. Research on epistemological beliefs, beliefs about the nature of knowledge and learning [51], have shown that student epistemological beliefs are influenced by domain [52], schooling [48] and educational level [48].

5.2 Student Centered Approach

The last 20 years, higher education has experienced a significant push to transform the way in which we teach students in higher education [53]. These efforts have attempted to move instruction from lecture based content delivery to the promotion of student discovery and knowledge construction [28] based on research findings on how people learn [54]. Numerous studies have demonstrated that these student-centered pedagogical approaches have numerous benefits, including improving learning outcomes, attracting diverse students, and increasing retention. Unfortunately, while the research clearly demonstrates the value of a student-centered approach to teaching, adoption of these approaches is significantly slow.

The literature reports several reasons for slow adoption, including priorities, instructor beliefs, and personal experience. In science, technology, engineering, and mathematics (STEM) courses, the most commonly used method of teaching is lecture-based [55], where students passively take-in information while the instructor speaks [28]. Most of today's academics were educated in this style when they were going through their undergraduate or graduate coursework [56]. Faculty therefore, often retain this status quo in teaching in addition to citing lack of training and time as barriers for implementing new teaching practices [56]. Other researchers believe slow adoption could also be a result of instructor beliefs about teaching [57] and limited formal training available to new faculty on evolving strategies for implementing student-centered learning [58], [59]. Often though, graduate students and upper-level undergraduate students are the facilitators of the active learning components of a course such as a hands-on activity or laboratory experiment [60].

In this study, we attempt to address the barriers to adoption by immersing graduate students, post docs, and faculty in a class experience, the Incubator, that is taught with student-centered pedagogies, such as think-pair-share, problem-based learning, collaborative learning, cooperative learning, peer instruction [36]. Incubator participants form teams to create BME-in-Practice Modules. Throughout this project-based course, the teams also discuss education literature and practice. Course evaluation results from both years demonstrate that Module students perceived the teaching teams in a positive light. Teaching evaluation data collected in winter 2018 were consistent with traditional higher education teaching evaluations. For the second year, questions specifically evaluated teaching teams in the context of the "How People Learn Framework[32]." Our results demonstrated that the teaching teams were able to translate their experiences and what they learned about student centered pedagogies into the classroom. These findings suggest that the Instructional Iterative Design Sequence may be an effective way to train prospective new faculty (graduate students and post docs) and current faculty in student-centered pedagogies.

5.3 Limitations and Future Research

There are a few limitations in the current study. One is the lack of uniformity across learning outcome surveys in the number of questions and types of questions. It should also be noted that the Regulations learning outcome survey was based on a 4-point Likert scale while the rest of the modules were based on a 5-point Likert scale, making the ability to compare growth between them less accurate. Another limitation of the study is the lack of qualitative data to unpack the quantitative data. While qualitative data was collected in the surveys, the questions were not focused specifically on learning outcomes, thus less relevant to this study.

Future work could consider the effectiveness of the Module courses in increasing self-efficacy for specific skills and concepts versus general skills and concepts by assessing for the same general skills and concepts across all Modules. Observations of differences in learning outcomes versus student level also suggest that exploration of student epistemologies are also a worthy area of exploration. We also plan to analyze the influence of the Modules on enrolled students' professional development, career goals, and educational goals. A future study could also synthesize Module student evaluations of teaching teams with surveys and reflections from the teaching teams to more closely examine how they translated what they learned about active learning and pedagogy to the classroom. Finally, administering all surveys together so each student's teaching team evaluation could be linked with self-efficacy responses would allow for an evaluation of the potential links between how students perceive the effectiveness of their teaching team and their learning outcomes.

6. Conclusion

We have described an iterative instructional design sequence with a focus on "BME-in-Practice" Modules designed to enhance undergraduate BME education. Pre-post results from Module student surveys demonstrate a potential for Incubator participant led BME-in-Practice Modules to foster student growth in current BME professional practice skills and knowledge. The findings also provide evidence for the Instructional Incubator as a method for training future educators in student centered teaching practices and course design, particularly for women.

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Appendix A: Course descriptions for the 2018 and 2019 semesters

Course Title (Module)	Course Description	Teaching apprentices
Introduction to Medical Product Design, Prototyping and Testing (Medical Device Development W18)	Students learn the design process via an open-ended design project with design constraints. Students learn how to apply computer-aided design, 3D printing, finite-element analysis, and physical testing to solve biomedical problems. For this iteration of the course, students must design and print a barrier for an egg to protect it from a toy truck collision.	Three Masters students
Introduction to Neural Engineering (Neural Engineering W18)	Students learn the research and ethics of neural engineering, its clinical applications, and current field-wide problems. Students are guided through the implementation of models of neural recording and stimulation, as well as how to process and interpret relevant data sets using engineering software (MATLAB and COMSOL).	Three PhD candidates
Building a Tumor: An Introduction into Tissue Engineering (Tissue Engineering W18)	Students explore the various components of a cellular microenvironment and how these components work together to influence cell morphology and phenotype. Students design and engineer various hydrogels to be used as cellular scaffolds and study how cancer cells proliferate and migrate within them. They develop laboratory skills in cell culture, cellular encapsulation in 3D hydrogels, and imaging 3D hydrogels.	Two Masters students, one PhD candidate, and two postdocs
Roadmap to Drug Development (Computational Modeling W19)	Students are introduced to developing models that will help biomedical engineers make more informed decisions when developing drugs. Students combine their knowledge of cell signaling and MATLAB skills to model a cell-signaling pathway and draw conclusions about effective ways to target the pathway using drugs.	Three PhD candidates
Introduction to Medical Product Design (Medical Device Design W19)	Students learn to use computer aided design (CAD), 3D printing, physical testing and finite element analysis (FEA) to refine, prototype, and evaluate a design. Students explore how to use the results of these physical and computational evaluations to inform the next iteration in the product development cycle. For this iteration of the course, students must design and print bone plates.	One senior undergraduate student, one Masters student, and one postdoc
Engineering the Cellular Microenvironment: An Introduction into Tissue Engineering (Tissue Engineering W19).	Students are exposed to the various components of a cellular microenvironment and how these components work together to influence cell morphology and phenotype. Students apply these concepts by encapsulating cells in hydrogel scaffolds with varying properties to control their microenvironment and manipulate cell performance. Students gain hands-on laboratory experience with cell culture, 3D cell encapsulation, imaging techniques, and quantitative assays	Three PhD candidates
Wrangling with Regulations: Introduction to Regulatory Science (Regulations W19)	Students are introduced to the evolving regulations and compliance requirements in the healthcare industry. Students learn to classify medical products and understand the differences in their FDA approval pathways. Students also gain knowledge of various pre-approval requirements and post market surveillance requirements for different medical devices.	Two Masters students and one PhD candidate.

Appendix B: BME-in-Practice Module Learning Outcomes Questions (Skills)

Module	Skill
Medical Device Development (2017–2018)	**On a scale from 1 to 5, how confident are you with. . .** • Computer-Aided Design software • Applying finite-element analyses (FEA) • Generate a 3D-print file • Print the STP file
Neural Engineering (2017–2018)	**Please rate your familiarity with the following:** • Programming • Modeling • MATLAB • COMSOL
Tissue Engineering (2017–2018)	**How strong of a grasp do you feel you have on the following skills:** • Sterile technique • Good Lab Practice (GLP) • Maintaining a lab notebook • Passaging cells • Counting cells with a hemocytometer • Encapsulating cells in hydrogel • Focusing a microscope • Pipetting
Medical Device Development (2018–2019)	**What is your level of experience with:** • Computer-Aided Design software* • Applying finite-element analyses (FEA)* • 3D Printing • Physical testing of materials
Tissue Engineering (2018–2019)	**Please rate your confidence in your ability to perform the following lab related activities:** • Sterile technique • Good Lab Practice (GLP) • Maintaining a lab notebook • Passaging cells • Counting cells with a hemocytometer • Encapsulating cells in hydrogel • Focusing a microscope • Pipetting
Regulations (2018–2019)	N/A

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Appendix C: BME-in-Practice Module Learning Outcomes Questions (Concepts)

Module	Concept
Medical Device Development (2017–2018)	**On a scale from 1 to 5, how confident are you with . . .** • Applying ideation techniques to generate solutions • Applying downselecting techniques to downselect solutions • Using simple conservation of energy equations to model physical scenarios • Describe a test to evaluate if the physical prototype meets the design specifications
Neural Engineering (2017–2018)	**Please rate your familiarity with the following:** • Math (calculus) • Biology • Neuroscience • Signal processing • Reading research articles • Ethics
Tissue Engineering (2017–2018)	**How strong of a grasp do you feel you have on the following concepts:** • Reading and interpreting scientific literature • Regenerative medicine • Tumor engineering • Immortalized cell lines • HeLa cells • The Extracellular Matrix (ECM) • Protein structure (amino acids, domains, motifs) • 3D cell culture • Hydrogels* • Fibronectin • Interpenetrating Polymer Networks (IPNs) • Cell Migration • Mechanotransduction • Hallmarks of cancer • The scientific method

Module	Concept
Medical Device Development (2018–2019)	**What is your level of experience with:** • Stress and strain
Tissue Engineering (2018–2019)	**Please rate your familiarity with these terms:** • Reading scientific literature • Interpreting scientific literature • Tissue Engineering • Cell spreading • Regenerative medicine • Immortalized cell lines • The Extracellular Matrix (ECM) • 3D cell culture • Hydrogels • The scientific method
Regulations (2018/2019)	**Please rate your familiarity with the following:** • FDA • GMP, GCP, GLP • Design controls • OSHA • Biomedical device classification • Schedules/Classifications of Drugs/Biologics • Quality management systems • Risk analysis • Human factors engineering • 510k or PMA Pathways

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