A Survey of Biomedical Design Projects to Inform Skill Development in a New Undergraduate Biomedical Engineering Curriculum

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Abstract

Hands-on design projects are widely used in engineering curricula to improve hardware/software skills, develop design mindsets, and tie real-world problems to engineering curricula with an eye toward increased student engagement and retention. In Fall 2018, Kansas State University (KSU) accepted its first cadre of incoming freshmen into a new Biomedical Engineering (BME) degree program. In an effort to increase the effectiveness of the program's design courses, which will be offered annually to students of various ages beginning in Fall 2020, the authors performed a search of recent engineering education literature related to the inclusion of design projects in undergraduate BME curricula, focusing on (a) projects that could be reasonably incorporated into courses that support undergraduate students with little-to-no design experience, (b) efforts that map to the emphasis areas for this new BME program, (c) student-learning assessment techniques that have proved useful in these hands-on contexts, and (d) projects that would make interesting recruiting examples for high school students considering such a program. The overall goal of this work is to allow lessons learned from these earlier efforts to inform projects offered as part of this new BME curriculum. This paper presents (1) an overview of this new curriculum, (2) the skillsets that this new BME program intentionally addresses and the courses that will support that skillset development, (3) BME project-based efforts described in the literature that relate thematically to the emphasis areas in this curriculum, (4) assessment methods that have appeared useful when applied to such projects, and (5) suitable categories of starter projects for this new curriculum, including those that can be prototyped prior to the Fall 2020/2021 onset of the initial junior/senior-level design sequences.

I. Introduction

A. Motivation and Goal

A new Kansas State University (KSU) undergraduate Biomedical Engineering (BME) degree program was approved by the Kansas Board of Regents in June 2016 [1]–[3], and the first incoming cadre of freshman joined this program in Fall 2018. This program, partially spurred by demand from prospective students and their families, (a) strengthens the preexisting biomedical teaching/research synergy in the KSU College of Engineering, (b) attracts new students who might not otherwise have enrolled at KSU and/or in an engineering curriculum, (c) increases tuition revenue, and (d) helps to provide a pipeline of engineering talent for the growing Midwest U.S. biomedical industry. Consistent with similar, well-established BME programs nationwide, this program incorporates substantive hands-on design, as this learning format is known to (1) improve student engagement and retention [4]–[8] and (2) develop an engineering mindset and the hardware/software skillsets essential for success in industry [9], [10]. This intentional skillset development is especially important in BME curricula, as these skills help to remedy the breadth versus depth challenge faced by all BME programs [11]. That is, the need to address a broad collection of curricular topics bears the risk that specific topics and their requisite skillsets will not be covered in much depth unless they are explicitly singled out for emphasis. In other words, skill development in some areas may not well occur unless those skills are intentionally built into the curricular foundation, and these skills make students useful to employers and therefore hirable.

Some of the design elements embedded in the first instantiation of this undergraduate curriculum begin in Fall 2020/2021, at which point the first cohort of KSU BME students will engage in their two-semester junior/senior design experiences. To help prepare for these experiences, the authors thought it sensible to perform an early search of recent (~2008 and newer) engineering education literature focused on design projects supported by undergraduate BME curricula. The goal is to use lessons learned from earlier hands-on design efforts to guide the BME curriculum committee in their choice of projects and educational venues that map to the learning outcomes and skillsets emphasized in this BME curriculum. Such projects should be suited for undergraduate students with little-to-no design experience and preferably be appropriate thematic matches to the emphasis areas in the degree program. Further, project elements should align well with effective student-learning assessment methods. Ideally, these projects should also be interesting by nature to potential incoming students so that the projects can serve as program recruiting mechanisms.

B. Paper Contents

This paper takes a two-pronged approach to address undergraduate design in the context of this new biomedical engineering curriculum. First, Section II addresses the courses that comprise this curriculum and identifies the specific courses targeted for the development of specific skills. Second, Sections III and IV lay out the literature review approach/results and offer thoughts based on the results of that survey, where the restated goal is to allow published lessons learned from earlier undergraduate BME design efforts to inform projects offered as part of this new KSU BME curriculum. An appendix presents a tabular listing of these academic papers and some of their descriptors.

II. Overview of the New Kansas State University Biomedical Engineering Curriculum

The Kansas State University (KSU) Biomedical Engineering (BME) curriculum (128 credit hours) incorporates core courses (102 credit hours – see Figure 1) coupled with technical electives (26 credit hours – see Figure 2), where the latter comprise an area of emphasis [1]–[3]. Every student in the program takes the core courses, but technical electives vary depending on a student's chosen emphasis area and career path. For example, the BME core courses, when coupled with the required technical electives for an emphasis area (see the next section) and 9 credit hours of properly chosen discretionary technical electives (e.g., CHM 550 & 532 – Organic Chemistry II plus a lab (5 hours); BIOL 455 – General Microbiology with a lab (4 hours)), flesh out the courses required for entrance into nearby medical schools. Up to 13 hours of additional courses are suggested as preparatory courses for the Medical College Admission Test (MCAT) [12].

The following sections briefly describe these core courses, the emphasis areas, and the skills addressed in specific classes. Overarching program outcomes and areas of knowledge development can be found in the original curriculum proposal submitted to the Kansas Board of Regents [1].

A. Curriculum Description

Core Courses and Credits. The four curricular cores amount to 102 credit hours. Core courses address subject matter that the affiliated KSU faculty consider essential to a BME curriculum, regardless of a student's area of emphasis. High-level descriptions of these cores follow:

1. **Math & Science Core (52 credit hours)** – This core consists of math, physics, statistics, and chemistry courses typical of an ABET-accredited engineering program [13], [14]. Additional courses in organic chemistry, biology, and human anatomy/physiology have been added to strengthen the backgrounds of these students in preparation for their upcoming BME courses and their subsequent career paths.
2. **Biomedical Engineering Core (36 credit hours)** – These core courses, consistent with model programs across the U.S., address a range of subjects relevant to biomedical engineering (refer to [1] for a representative topic listing). It is impossible to offer one generic curriculum that prepares students for all biomedical engineering topical areas at a suitable level of depth. As a partial solution, the BME core curriculum incorporates courses that address cross-cutting subject matter intended to strengthen each student's knowledge base with regard to a number of topical areas:
   - **Biomedical engineering** (BME 001, 200) – Application areas, research, and career opportunities in biomedical engineering.
   - **Biomaterials** (BME 430) – Interactions between materials and biological systems, techniques to assess biomaterial characteristics, and the role of biomaterial selection in the design of medical devices.
   - **Biomechanics** (BME 451) – The mechanics of biological tissues and systems at the macroscopic scale. This course addresses the structure and mechanics of biological tissue based on the principles of statics and dynamics.
   - **Biomedical signals and instrumentation** (ECE 512, ECE 540, and ECE 772/3) – Signals that describe physiological processes, instrumentation to acquire those signals from human and animal subjects, and means to process those data.
   - **Clinical systems** (BME 575) – Biomedical "systems of systems" in health care scenarios, including hospitals, home care settings, and ambulatory environments. Material focuses on "clinical engineering" subjects, emphasizing institutional implementation, training, ethics, design standards, and interoperability.
   - **Medical imaging** (BME 674 and ECE 772/3) – Medical imaging modalities as an extension of biomedical instrumentation. Methods for image data acquisition, processing, and display form the core for these courses, which also address industry standards for image storage and transmission.

   The Biomedical Engineering Core supports **two two-semester design sequences**, intended to produce graduates who can think through complex design challenges. Design courses in the junior year are more scripted, whereas design courses in the senior year are more open-ended. A sophomore-level design course, where each student engages in a design effort mapped to each emphasis area, is being considered consistent with the model adopted by the University of Wisconsin-Madison [15], [16].
3. **Communication Core (8 credit hours)** – This core involves oral/written communication courses taken by all students in the KSU College of Engineering.
4. **Humanities & Social Sciences Core (6 credit hours)** – This core represents a 6-hour block of humanities and social sciences credit typical for departments within the KSU College of Engineering.

Math & Science Core		Credits	Semester
MATH 220	Analytical Geometry and Calculus I	4	FSSu
MATH 221	Analytical Geometry and Calculus II	4	FSSu
MATH 222	Analytical Geometry and Calculus III	4	FSSu
MATH 240	Elementary Differential Equations	4	FSSu
PHYS 213	Engineering Physics I	5	FS
PHYS 214	Engineering Physics II	5	FS
STAT 510	Introductory Probability and Statistics I	3	FS
CHM 210	Chemistry I	4	FSSu
CHM 230	Chemistry II	4	FSSu
CHM 531	Organic Chemistry I	3	FS
BIOL 198	Principles of Biology	4	FSSu
BIOL 341[◊]	Human Body I	4	FS
BIOL 342[◊]	Human Body II	4	FS
	Sub-Total Credit Hours	**52**	

[◊]Or KIN 360 – Anatomy & Physiology (8 credits, FS) instead of BIOL 341 & 342

Biomedical Engineering Core		Credits	Semester
BME 001	New Student Assembly	0	F
BME 200	Introduction to Biomedical Engineering	3	F
BME 430	Biomaterials	3	F
BME 451	Biomechanical Engineering	3	S
BME 490/491	Undergraduate BME Design Experience I/II	3	FS
BME 575	Clinical Systems Engineering	3	S
BME 590/591	Senior Design Experience I/II	5	FS
BME 674	Medical Imaging	3	S
CIS 200	Programming Fundamentals	4	FS
ECE 512	Linear Systems	3	FS
ECE 540	Applied Scientific Computing for Engineers	3	FS
ECE 772/3	Theory & Techniques of Bioinstrumentation Lecture/Lab	3	F
	Sub-Total Credit Hours	**36**	

Communication Core		Credits	Semester
ENGL 100	Expository Writing 1	3	FS
ENGL 415	Written Communication for Engineers	3	FSSu
COMM 105	Public Speaking 1A	2	FSSu
	Sub-Total Credit Hours	**8**	

Humanities & Social Sciences Core		Credits	Semester
KIN 110[◊◊]	Introduction to Public Health	3	FS
	H&SS Elective	3	
	Sub-Total Credit Hours	**6**	

[◊◊]Or ECON 110 - Principles of Macroeconomics (3, FSSu)

Figure 1. Required BME core courses (102 credit hours). Semesters: Fall, Spring, and Summer.

Emphasis Areas. The KSU BME curriculum currently supports two emphasis areas: "Biomedical Sensors and Devices" and "Biomedical Computation" – see Figure 2. Each area of emphasis defines a set of required technical electives that every student must take plus a set of discretionary technical electives that depend on student career goals, e.g., in the case of a pre-medicine student, as noted earlier. Additional emphasis areas are being considered, e.g., "Tissue Engineering" and "Biomechanics," consistent with the literature search table in the appendix.

Area of Emphasis: Biomedical Sensors & Devices		**Credits**	**Semester**
ECE 210	Introduction to Electrical Engineering	3	FS
ECE 241	Introduction to Computer Engineering	3	FS
ECE 431	Microcontrollers	3	FS
ECE 410	Circuit Theory I	3	FS
ECE 511	Circuit Theory II	3	FS
ECE 647	Digital Filtering	3	F
	Additional Technical Electives	8	
	Sub-Total Credit Hours	**26**	

Area of Emphasis: Biomedical Computation		**Credits**	**Semester**
ECE 241	Introduction to Computer Engineering	3	FS
CIS 300	Data and Program Structures	3	FS
ECE 431	Microcontrollers	3	FS
ECE 519	Electric Circuits and Controls	4	FSSu
CIS 501	Software Architecture and Design	3	FS
ECE 670[◊◊◊]	Engineering Applications of Machine Intelligence	3	S
	Additional Technical Electives	7	
	Sub-Total Credit Hours	**26**	

[◊◊◊]Or ECE 771 - Control Theory Applied to Bioengineering (3 credits, S)
[◊◊◊]Or CIS 730 - Principles of Artificial Intelligence (3 credits, S)
[◊◊◊]Or CIS 732 - Machine Learning and Pattern Recognition (3 credits, F)

Figure 2. Emphasis areas (26 credit hours each).

Target Skills. High-level skills to be possessed by each graduate of the KSU BME program include the ability to

- apply calculus-based mathematics when analyzing and designing physical systems,
- statistically describe medical data and hardware/software system performance,
- quantify and report tissue movement,
- operate biomedical instruments and medical imaging systems,
- analyze biomedical data in the space, time, and frequency domains,
- develop software to control devices and to process biomedical data,

- pursue a component- or system-level biomedical design based on an understanding of customer requirements and resource availability,
- lay out a medical "system of systems" comprised of commercially available hardware and software that utilize industry interoperability standards, and
- demonstrate professional skills centered around an understanding of personality profiles and an ability to communicate effectively in oral and written form.

More specific skillsets relate to the following areas, where supporting courses are noted in parentheses (core courses carry a normal font, whereas emphasis-area courses are in italics):

- **written/oral communication** (ENGL 100, COMM 105, ENGL 415, BME 200, BME 490/491, BME 590/591, ECE 772/773),
- **hardware** (*ECE 210*, *ECE 241*, *ECE 431*, BME 490/491, BME 590/591, ECE 772/773),
- **software – C/C++/MATLAB/other** (CIS 200, *ECE 241*, *CIS 300*, *ECE 431*, BME 451, *CIS 501*, BME 490/491, BME 590/591, *ECE 647*, *ECE 670*, BME 674, ECE 512, ECE 540, ECE 772/773),
- **benchtop/portable/virtual instrumentation** (PHYS 213/214, *ECE 210*, *ECE 241*, *ECE 410*, BME 451, BME 490/491, BME 590/591, ECE 772/773),
- **time- and frequency-domain signal processing** (BME 451, BME 490/491, BME 590/591, ECE 512, ECE 540, *ECE 647*, ECE 772/773),
- **image processing** (BME 674),
- **statistical analyses** (STAT 510, BME 451, BME 490/491, BME 590/591, BME 674, ECE 540),
- **feature extraction/classification** (BME 674, ECE 512, *ECE 647*, *ECE 670*, ECE 772/773),
- **printed circuit board population** (ECE 772/773),
- **3D modeling/printing** (BME 490/491, BME 590/591, ECE 772/773),
- **laboratory skills** (CHM 210/230, BIOL 198, *ECE 210*, *ECE 241*, BME 430, BME 451, BME 490/491, BME 590/591, ECE 772/773), and
- **wet lab skills and sterile techniques** (BIOL 198, BIOL 341/342, BME 430, BME 451, BME 490/491, BME 590/591).

Hands-on design plays a role in many of these courses, including courses labeled as 'lecture' or 'recitation' because they have an accompanying laboratory, hardware, and/or software component. Note that BME 490/491 (junior-level design) and BME 590/590 (senior-level design) address various skills by nature, so these design sequences provide a suitable match for the types of hands-on BME courses addressed in this literature search (see the next section). The emphasis on software skills is intentional and arguably atypical in comparison with other BME curricula. First, this investment in programming abilities helps to address breadth versus depth issues faced by many BME curricula, where finding jobs for BME graduates can be a challenge because the graduates do not have a large-enough skill base in any one area to be attractive to employers. Second, the ability to create and use software is essential in the current healthcare enterprise, where electronic medical records are now standard, and an increasing number of medical devices interact with smartphones.

III. Literature Review

As noted in the *Abstract* and in *Section I.A*, a search of recent engineering education literature was performed to identify hands-on design efforts previously supported by undergraduate Biomedical Engineering (BME) curricula. The goal is to allow lessons learned from prior design efforts to inform upcoming design experiences offered as part of the new KSU BME degree program [1]–[3], a program whose courses and target skillsets were laid out in *Section II*. Because these projects will be interspersed throughout nearly the entirety of the undergraduate BME curriculum, projects of interest for this literature search should be well suited for undergraduate students with minimal design experience and should provide a sensible thematic match for the emphasis areas in the degree program. Further, project experiences should map well to time-tested, student-learning assessment methods, and these projects should display the potential to serve as effective recruiting mechanisms for prospective BME students.

The resources employed for this search included Google [17], Google Scholar [18], IEEE Xplore [19], ASEE PEER [20], bound issues of the Journal of Engineering Education [21], the ASEE Computers in Education Journal [22], and Transactions on Techniques in STEM Education (ASEE Midwest conference papers), plus various bound proceedings for the annual conferences of the American Society for Engineering Education [23] and the IEEE Engineering in Medicine and Biology Society [24]. Search keywords included variants on the following terms: undergraduate, biomedical, design, project, hands-on, laboratory, device, build, sophomore, retention, and medical instrumentation. The initial search range was constrained to papers newer than 2007 to limit the number of overall papers and to increase the likelihood that these design efforts would employ modern engineering education tools.

IV. Results and Discussion

The annotated bibliography resulting from these efforts archived the following information for each source: author(s), year, title, level (e.g., high school, freshman, sophomore, …), rating (a 1-to-5-star rating depending on its perceived value), technical design area, emphasis area (i.e., the closest KSU BME emphasis area), description (short synopsis of the work), student skills (skills fostered by the design experience), assessment method(s) (approach(es) used to quantify student learning), funding (grant or source that supported the work, if available), notes (commentary related to the item), and the host institution. Citation information was simultaneously tracked using the online Zotero reference manager software [25].

A subset of the annotated bibliography that resulted from these efforts is attached in tabular form as *Appendix A* to the end of this document (after the *References* section). A few themes are of note in this appendix. First, as enumerated in Table 1 below, most of the projects relate to the "Sensors and Devices" emphasis area: 77 out of the 90 cited papers in *Appendix A* relate to at least one project involving sensors and/or device design. The "Computation" emphasis area came in second, represented by 21 out of 90 papers. The "Tissue Engineering" and "Biomechanics" emphasis areas garnered 19 and 7 papers, respectively. Given that most projects which involve biomechanics, computation, or tissue engineering also involve some form of a sensor or device, it is not surprising that a large number of projects fall within the "sensors and devices" area. Additionally, biomedical instrumentation has been an area of study for so long (e.g., when compared to a relatively new area such as tissue engineering) that a greater relative weight in terms of the number of educational sensors and devices efforts is not surprising.

Target students range in age from high school students (e.g., who attended summer courses/camps) up to seniors in college engaged in capstone design efforts. A large number of papers cited in the literature review were geared toward sophomore-to-senior-level students, whereas fewer were aimed at freshmen and high school students. This result may have been influenced by the fact that many freshmen and high school courses attempt to address multiple topics at a limited depth rather than focus on a single emphasis area, as a means to give the students an overview of the field.

Assessment approaches identified in the publications vary but generally reside in one or more of the following five categories (see the rightmost column in the summary table in *Appendix A*):

1. direct student feedback in the form of end-of-project surveys, pre/post surveys, and other student self-assessments (including interviews with students, and student focus groups),
2. quantitative assessments based on project/laboratory notebooks, write-ups, papers, reports and/or assignments (including pre/post laboratory exercises and questions), often guided by a formal rubric,
3. student presentations and/or demonstrations, including peer/instructor evaluations, some based on over-the-shoulder observations,
4. quizzes/exams, and
5. time reports and general activity/participation.

The relative frequencies of selected assessment types are tallied in Table 1, where the predominant assessment mechanism relates to student feedback in the form of surveys, interviews, and focus groups. Note that there is not a one-to-one correspondence between these overall assessment counts and the corresponding publications. Some efforts map to multiple types of assessment, and others involve none. In publications where education assessment methods are unidentified, a learning assessment (a) may have been performed but not noted or (b) may not have been performed because it was considered irrelevant, e.g., in a situation where the only goal was to summarize the technical aspects of a design experience or to produce a concept demonstration as a prototypical effort. Finally, no particular correlation is observable between different assessment categories and certain types of subject matter, institutions, or educational venues.

Table 1. Paper counts related to the emphasis areas, the target student ages, and the assessment methods employed.

Emphasis Area	Paper Count
Sensors and Devices	77
Computation	21
Tissue Engineering	19
Biomechanics	7

Target Age	Paper Count
High School	5
Freshmen	20
Sophomore	30
Junior	29
Senior	32
Unspecified	22

Assessment Method	Paper Count
Direct Student Feedback	
Surveys	25
Pre/Post Surveys	24
Other Self Assessments	25
Quantitative Assessments	
Notebooks, Reports, Write-Ups, or Papers	24
Assignments or Pre/Post Lab Questions/Exercises	6
Presentations, Demonstrations, or Evaluations	18
Quizzes or Exams	16
Activity or Participation	2
None Listed	31

One of the primary goals of the authors is to use these survey results to identify suitable project themes for Fall 2020 implementation and beyond, with the goal to realize some of these projects early so that the prototypes can be used in Summer 2020 to recruit new freshmen into the program. One can reasonably assume that a topic area occurs more frequently in the appendix because it garners more relative interest on behalf of faculty and students involved in the various efforts. Given that assumption, the following thematic areas appear promising:

- cardiac signal acquisition, processing, and parameter extraction,
- hand/foot prostheses,
- projects that integrate 3D printing,
- physiological process simulation,
- medical imaging, and
- tissue growth and bioreactor design.

With regard to the junior design sequence (BME 490/491), one of the goals of this course sequence is to help students develop technical skills that they can use later in their senior design team projects. An overview and tutorial for each of several software platforms (e.g., Excel, LabVIEW, MATLAB, and COMSOL) will be covered. In addition to completing tutorials, students will step through scripted exercises to help them become familiar with various facets and capabilities of these software packages that make these tools so useful when solving engineering problems. As an example, a cardiac signal acquisition module (one of the thematic areas noted above) could task each student with collecting their electrocardiogram using a bioamplifier and a National Instruments data acquisition unit controlled by a LabVIEW virtual instrument. A related module covering MATLAB could have a student create and analyze functions to modify and extract information from their collected ECGs.

Finally, in addition to the subject areas addressed in the literature, experience dictates that students are also interested in design projects related to the following application scenarios:

- assistive technology for those with cognitive and physical disabilities,
- tools for other vulnerable populations, including infants and aging individuals,
- wearable devices and telemedicine,
- technologies for tissue replacement/enhancement,
- games that incorporate biosignal acquisition and feedback,
- designs for animals, especially companion animals,
- medical technology for under-resourced and developing environments,
- health care resources for first responders, disaster response, and battlefield medicine, and
- wellness capabilities for reduced-gravity environments.

These types of application scenarios can provide context for hands-on design projects and drive student interest by providing clarity in terms of societal benefits that can be achieved via the realization of such designs.

V. Conclusions

Hands-on design projects have been broadly employed in biomedical engineering programs to increase student engagement, learning, and retention. This paper addressed the layout of a new undergraduate Biomedical Engineering (BME) degree program at Kansas State University. This curriculum is designed to develop student skills within hands-on learning contexts – skills that will make these graduates hireable. To that end, the paper additionally addressed the results of a literature search related to undergraduate design projects in biomedical engineering curricula, where the goal was to find published results from earlier efforts that could inform hands-on design projects to be employed in courses supported by this new BME degree program. A subset of the resulting papers (~100 journal articles and conference papers) are summarized in tabular form as an appendix at the end of this document. These papers relate to projects intended for high school students up to seniors in college, and the projects address a number of subject areas germane to the emphasis areas supported by this new BME program.

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Appendix A – Literature Survey Results

For the "Course Level," F = Freshman, So = Sophomore, J = Junior, and S = Senior.
For the "Emphasis Area," B = Biomechanics, C = Computation, SD = Sensors & Devices, and T = Tissue Engineering.

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
Billiar [26]	2017	Canine hip forces: The ups and downs of project-based learning of static equilibrium	Worcester Polytechnic Institute	So	Acetabular Cup for Canine Hip	B	Formative Assignment; Report with Rubric; Self-Assessment; Quizzes
Meyer [27]	2016	Sensing Angular Kinematics by Embedding an Open-source Electronics Design Project into a Required Biomechanics Course	Lawrence Technological University	J/S	Angular Velocity Measurement Sensor	B, C	Report; Presentation; Pre/Post Surveys
Goldberg [28]	2016	The 'Invisible Handshake' Project as a Practical, Hands-on Experience in a Biomedical Electronics Class	University of North Carolina	So/J	Various	B, C, SD	Pre/Post Surveys; Final Project
Nasir [29]	2014	Introducing High School Students to Biomedical Engineering through Summer Camps	Lawrence Technological University	HS	Various	B, C, SD, T	Pre/Post Surveys; Student Feedback
Zapanta [30]	2009	An Integrated Undergraduate Biomedical Engineering Laboratory Course	Carnegie Mellon University	So	Various	B, C, T	Lab Notebook with Rubric; Survey
Rousche [31]	2006	A Bioengineering Summer Day Camp For High School Science Students And Teachers	University of Illinois-Chicago	HS	Various	B, SD, T	Pre/Post Surveys
Cezeaux [32]	2011	Implementation of a Biomedical Engineering Summer Program for High School Students	Western New England College	HS	Various	B, SD, T	Pre/Post Surveys
Kuo [33]	2014	Designing a reconfigurable biopotential amplifiers for medical instrumentation course	National Taiwan University of Science and Technology	S	Biopotential Amplifier	C	Survey
DesJardins [34]	2012	Emphasizing Core Calculus Concepts Using Biomedical Applications to Engage, Mentor, and Retain STEM Students	Clemson University	F/So	Orthopaedics	C	Pre/Post Surveys; Exams; Exit Interviews
Sun [35]	2014	A novel design method of anthropomorphic prosthetic hands for reproducing human hand grasping	Huazhong University of Science and Technology	Unsp.	Prosthetic Hand	C, SD	None Listed
Goldberg [36]	2010	Integrating Hands On Design Experiences Into The Curriculum	University of North Carolina	So/J/S	Bioreactor vessel	C, SD	Reports; Student Feedback
Mellodge [37]	2009	Digital Health: A Sophomore Level Interdisciplinary Engineering Design Project Course	University of Hartford	So	Digital Health Monitoring System	C, SD	Presentations; Report; Peer/Instructor Evaluations; Survey

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
Tranquillo [38]	2007	A Project Driven Approach To Biomedical Signals And Systems	Bucknell University	J	Signals and Systems	C, SD	Lab Notebook; Survey
Harrison [39]	2011	Wireless Neural/EMG Telemetry Systems for Small Freely Moving Animals	University of Utah	Unsp	Neural/EMG Telemetry System	C, SD	None Listed
Haase [40]	2018	Modeling and Design: a Hands-on Introduction to Biomedical Engineering	Johns Hopkins University	F	Various	C, SD	Survey; Student Feedback
Yao [41]	2005	Stimulating Student Learning with a Novel "In-House" Pulse Oximeter Design	Kansas State University	J/S	Pulse Oximeter	C, SD	None Listed
Baura [42]	2019	Building a Functional Cardiograph Over Four Semesters: Part 2 – Programming a Microcontroller	Loyola University Chicago	F to S	Cardiograph	C, SD	Pre/Post Surveys
Baura [43]	2018	Work in Progress: Building a Functional Cardiograph Over Four Semesters	Loyola University Chicago	F to S	Cardiograph	C, SD	Pre/Post Surveys
Bhatti [44]	2010	The Coding Of Sound By A Cochlear Prosthesis: An Introductory Signal Processing Lab	Georgia Institute of Technology	So/J/S	Cochlear Implant Signal Processor	C, SD	Pre-Labs; Lab Reports; Survey
Qian [45]	2016	Brain-Region-Specific Organoids Using Mini bioreactors for Modeling ZIKV Exposure	Johns Hopkins University	Unsp	Bioreactor	C, SD, T	None Listed
Farrell [46]	2014	Organ-izing the Engineering Curriculum with Biomedically Related Learning Modules	Rowan University	F/So/J/S	Artificial Organs	C, SD, T	Quizzes; Survey; Evaluation
King [47]	2002	Freshman Biomedical Engineering Design Projects: What Can Be Done?	Vanderbilt University	F	Various	C, SD, T	None Listed
Bazil [48]	2006	Bioinstrumentation Instruction Through Hybrid Wet/Circuit Laboratory Activities	Purdue University	J	Various	C, T	Survey; Pre/Post-Lab Exercises
Bedenbaugh [49]	2010	A Team Based Nerve Cuff Simulation Project In A Third Year Foundations Of Biomedical Engineering Course	East Carolina University	J	Nerve Cuff Simulation	C, T	Time Reports; Self Assessments;, Factual Questions
Kyle [50]	2016	Bioinstrumentation: A Project-Based Engineering Course	Columbia University	J/S	Cardiac Pacemaker	SD	Labs; Midterms; Pre/Post/Online Surveys
Atasoy [51]	2018	Biomechanical Design of an Anthropomorphic Prosthetic Hand	Boğaziçi University	Unsp.	Prosthetic Hand	SD	None Listed
Jones [52]	2018	Development of an Undergraduate Control Engineering Design Project: PID Control of Blood Glucose Levels in Type 1 Diabetes Mellitus Subjects	Zhejiang University	J	Glucose Monitor	SD	None Listed

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
Supakitamonphan [53]	2015	Electric prosthetic hand activated using two-channel surface electromyography	Rangsit University	Unsp.	Prosthetic Hand	SD	None Listed
Opuszynski [54]	2009	Experiential learning in an undergraduate biomeasurement course: Heart-rate meter	University of Rhode Island	F/So/J/S	Heart-Rate Meter	SD	None Listed
Tamayo [55]	2010	Microcontroller based pulse oximeter for undergraduate capstone design	University of Rhode Island	S	Pulse Oximeter	SD	None Listed
Breau [56]	2005	The Neuron Emulator: an undergraduate Biomedical Engineering design project	University of Rhode Island	F/So/J/S	Neuron Emulator	SD	Personal Assessment
Long [57]	2014	A design project based approach to teaching undergraduate instrumentation	University of Auckland	F/So/J/S	Sleep Apnea Device	SD	Final Exam; Design Reports
Constant [58]	2015	Pulseband: A hands-on tutorial on how to design a smart wristband to monitor heart-rate	University of Rhode Island	Unsp.	PulseBand	SD	None Listed
Bohorquez [59]	2019	Board 1: Introduction to Design Thinking and Human Centered Design in the Biomedical Engineering Freshman Year	University of Miami	F	Various	SD	Survey
Lai [39]	2019	Board 7: Work in Progress: Approaches to Introduce Biomedical Engineering Design to a Class with Diverse STEM Backgrounds	Carnegie Mellon University	HS	Various	SD	Survey
Silver-Thorn [61]	2002	A rehabilitation engineering course for biomedical engineers	Marquette University	S	Prosthetics/Orthotics	SD	Quizzes; Exam; Paper; Survey
Zeng [62]	2009	Exploration on Undergraduate Curriculum Reform of Hospital-Oriented Biomedical Engineering Major	Wenzhou Medical College	F/So/J/S	Hospital Devices	SD	None Listed
Nagurney [63]	2007	The evolution of a bioinstrumentation course	University of Hartford	S	ECG, Pacemaker	SD	Assignments; Labs; Final Exam; Student Interviews
Yu [64]	2009	Towards integrative learning in biomedical engineering: A project course on electrocardiogram monitor design	The University of Hong Kong	So	ECG	SD	Surveys; Participation; Demonstrations; Final Exam; Report
Chan [65]	2011	Integrative learning through the design of an electrocardiogram acquisition system	Carleton University	J/S	ECG	SD	Demonstrations; Reports
Aldridge [66]	2017	Autonomous robot design and build: novel hands-on experience for undergraduate students	Grand Valley State University	So	Robot	SD	None Listed
Fletcher [67]	2014	Design and clinical feasibility of personal wearable monitor for measurement of activity and environmental exposure	Massachusetts Institute of Technology	Unsp.	Wearable Monitor	SD	None Listed

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
Jeong [68]	2017	NFC-enabled, tattoo-like stretchable biosensor manufactured by “cut-and-paste” method	University of Texas at Austin	Unsp.	Tattoo-like Biosensor	SD	None Listed
Xiong [69]	2016	Design and Implementation of an Anthropomorphic Hand for Replicating Human Grasping Functions	Huazhong University of Science and Technology	Unsp.	Prosthetic Hand	SD	None Listed
Castles [70]	2016	Flipping the Microprocessors Classroom: A Comparative Assessment	East Carolina University	Unsp.	Microprocessor	SD	Final Exam; Survey
Hill [71]	2016	A Multidisciplinary Undergraduate Nanotechnology Education Program with Integrated Laboratory Experience and Outreach Activities	Mississippi State University	F	Nanotechnolog y	SD	None Listed
Farrell [72]	2016	An Adaptable and Transferrable Project Based on a Heart-lung Machine Design Challenge	Rowan University	HS/F/So /J/S	Heart-Lung Machine	SD	Survey; Design Report
Yildiz [73]	2016	Design and Development of a Non-Contact Thermography Device for Equine Research	Sam Houston State University	Unsp.	Thermography Device	SD	None Listed
Ruddy [74]	2016	Work in Progress: The Consumer Breathalyzer as a Model Design Project in Introductory Instrumentation	University of Auckland	So	Breathalyzer	SD	Lab Notebooks; Group Reports; Final Report; Presentation
Choi [75]	2016	Work in Progress: The Incorporation of Hands-On, Team-Based Design Challenges in a Large Enrollment Introductory Biomedical Engineering Course	University of California - Davis	F	Various	SD	Survey
Joo [76]	2016	Work in Progress: Hands-On Practice of Implant Surgery Using Artificial Bone in Design Course	Robert Morris University	S	Medical Device	SD	Survey
Schmedlen [77]	2016	The Medical Device Sandbox: A Creative Learning Experience for BME Students and Medical Learners	University of Michigan	F/So/J/S	Various	SD	Survey; Focus Groups; Pre-Test
Gibson [78]	2002	Capstone Design Projects: Helping the Disabled	Rose-Hulman Institute of Technology	S	Various	SD	None Listed
Bernitt [79]	2016	A Low-Cost Bio-Imaging and Incubation System	University of Bremen	Unsp.	Bio-Imaging and Incubation System	SD	None Listed
Grier [80]	2018	A low-cost do-it-yourself microscope kit for hands-on science education	N/A	Unsp.	Microscope Imaging	SD	Unstructured feedback; surveys
Jani [81]	2017	Design of a Low-power, Low-cost ECG & EMG Sensor for Wearable Biometric and	Dhirubhai Ambani Institute of Information	Unsp.	ECG and EMG Sensor	SD	None Listed

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
		Medical Application	and Communication Technology				
Pimentel [82]	2014	A $5 Smart Blood Pressure System	University of Oxford	Unsp.	Blood Pressure System	SD	None Listed
Casey [83]	2014	A cost-efficient spring-powered dermatome to treat skin trauma	Massachusetts Institute of Technology	Unsp.	Dermatome	SD	None Listed
Cruden [84]	2018	Frugal Skin Graft Expansion Device	Santa Clara University	Unsp.	Skin Graft Expansion Device	SD	None Listed
Wolf [85]	2009	On Setting-Up a Portable Low-Cost Real-Time Control System for Research and Teaching with Application to Bioprocess pH Control	University of Heidelberg	Unsp.	Real-Time Control System	SD	None Listed
Fuller [86]	2004	Portable, Low-Cost Medical Ultrasound Device Prototype	University of Virginia	Unsp.	Ultrasound Device	SD	None Listed
Kim [87]	2013	Smartphone-based Portable Ultrasound Imaging System: A Primary Result	Sogang University	Unsp.	Ultrasound Imaging System	SD	None Listed
Pan [88]	2004	Mechatronic experiments course design: a myoelectric controlled partial-hand prosthesis project	Kuang-Wu Institute of Technology	S	Prosthetic Hand	SD	Observations; Student Interviews; Survey
Warren [89]	2016	Design projects motivated and informed by the needs of severely disabled autistic children	Kansas State University	S	Various	SD	None Listed
Gale [90]	2019	Work in Progress: Multidisciplinary, Vertically Integrated Course on 3-D Printed Biomedical Devices	New York University	F/So/J/S	3D Printed Orthotics	SD	Lab Notebook; Survey; Student Feedback
Carlson [91]	2019	An Improved Cellphone-based Wearable Electrocardiograph Project for a Biomedical Instrumentation Course Sequence	Kansas State University	S	Cellphone-Based Wearable ECG	SD	Pre/Post Surveys
Carlsen [92]	2018	Project-based Learning: Engaging Biomedical Engineering Sophomores Through a Collaborative Vein-finder Device Project with Nursing	Robert Morris University	So	Vein Finder Device	SD	Rubric; Peer Evaluation; Surveys; Exams; Assignments
Rust [93]	2013	Engaging Undergraduate Biomedical Engineering Students in Lab on a Chip Research through a Course-Based Project	Western New England University	J/S	Microfluidic Device	SD	Pre/Post Surveys; Surveys
Warren [94]	2016	Student Proposals for Design Projects to Aid	Kansas State University	S	Various	SD	Rubrics

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
		Children with Severe Disabilities					
Warren [95]	2018	Board 79 : A Wearable Electrocardiograph as a Means to Combine Measurement and Makerspace Concepts in a Biomedical Instrumentation Course Sequence	Kansas State University	S	Wearable ECG	SD	Rubric, Surveys, Open-Ended Questions
Allen [96]	2018	Patient Centered Design in Undergraduate Biomedical Engineering	University of Virginia	J/S	Patient-Centered Design	SD	Student Feedback; Objectives Met; Completeness
Cezeaux [97]	2007	Design For The Disabled As An Interdisciplinary Laboratory Project	Western New England College	S	Tape cutting Device	SD	Final Report; Device Design; Peer Evaluation
Nagel [98]	2012	On a Client-Centered, Sophomore Design Course Sequence	James Madison University	So	Pedaled Vehicle	SD	Project, Course, and Performance Evaluations
Caplan [99]	2017	Curiosity and Connections (Entrepreneurial Mindset) in BME Sophomore Design	Arizona State University	So	Glucose Monitor	SD	None Listed
Caplan [100]	2017	Sophomore Design Course on Virtual Prototyping	Arizona State University	So	Glucuse Monitor Device	SD	Pre/Post Surveys; Rubrics
Reid [101]	2011	An Innovative Interdisciplinary Student Project: Engineering and Nursing	Ohio Northern University	F	Fetal Heartbeat Simulator	SD	Whether Redesigns Worked; Student Testimonials
Bucks [102]	2015	Engineering Your Community: Experiences of Students in a Service-Learning Engineering Design Course	University of Cincinnati	F/So/J/S	Various	SD	Course Evaluations; Student Reflections
Lai-Yuen [103]	2009	Integrating Real World Medical Device Projects Into Manufacturing Education	University of South Florida	So/J	Various	SD	Project Evaluation Forms
Cavanagh [104]	2017	Diseases, Devices, and Patients: Exposing BME Students to the Patient Experience	Bucknell University	J/S	Various	SD	Course/Instructor Evaluations; Instructor Observations; Student Reflections
Lasher [105]	2010	Design and characterization of a modified T-flask bioreactor for continuous monitoring of engineered tissue stiffness	University of Utah	Unsp.	Bioreactors	SD, T	None Listed
Rajan [106]	2018	A Portable Live-Cell Imaging System With an Invert-Upright-Convertible Architecture and a Mini-Bioreactor for Long-Term Simultaneous Cell Imaging, Chemical Sensing, and Electrophysiological Recording	Tampere University of Technology	Unsp.	Bioreactor, Live Cell Imaging System	SD, T	None Listed

First Author	Year	Title	Affiliated Institution	Course Level	Technical Area	Emphasis Area	Assessment Method(s)
Bhattarai [107]	2015	Enhancing Undergraduate Students' Learning and Research Experiences through Hands-on Experiments in Bio-nanoengineering	North Carolina A&T State University	So/J	Bio-nano Devices and Systems	SD, T	Content Assessment; Survey; Focus Groups
Nimunkar [108]	2014	Using Guided Design Instruction to Motivate BME Sophomore Students to Learn Multidisciplinary Engineering Skills	University of Wisconsin, Madison	So	Bioreactors	SD, T	Self/Peer Evaluations; Quizzes; Rubrics
Comolli [109]	2010	The Artificial Kidney: Investigating Current Dialysis Methods As A Freshman Design Project	Villanova University	F	Artificial Kidney Filter	SD, T	Pre/Post Surveys; Quizzes; Design Reports
Henkel [110]	2015	Teaching bioprocess engineering to undergraduates: Multidisciplinary hands-on training in a one-week practical course	University of Hohenheim	So	Bioreactors	T	Pre/Post Lab Questions; Exams
Vernengo [111]	2014	Undergraduate Laboratory Experiment TEACHING FUNDAMENTAL CONCEPTS OF RHEOLOGY In Context of Sickle Cell Anemia	Rowan University	F	Artificial Blood Construction and Analysis	T	Pre/Post Quizzes
Saterbak [112]	2002	Laboratory Courses Focused On Tissue Engineering Applications	Rice University	J/S	Tissue Engineering Experiments	T	Surveys; Student Interviews
Saterbak [113]	2001	Development Of A Novel Foundation Course For Biomedical Engineering Curriculum	Rice University	So	Organ Model	T	Mid/Post Surveys
Childers [114]	2019	A Gold Nanoparticle-based Lab Experiment Sequence to Enhance Learning in Biomedical Nanotechnology at the Undergraduate Level	University of Oklahoma	J	Gold Nanoparticles	T	Self/Instructor Evaluations; Final Exam