A New Approach to Teaching Biomechanics Through Active, Adaptive, and Experiential Learning

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Demand of biomedical engineers continues to rise to meet the needs of healthcare industry. Current training of bioengineers follows the traditional and dominant model of theory-focused curricula. However, the unmet needs of the healthcare industry warrant newer skill sets in these engineers. Translational training strategies such as solving real world problems through active, adaptive, and experiential learning hold promise. In this paper, we report our findings of adding a real-world 4-week problem-based learning unit into a biomechanics capstone course for engineering students. Surveys assessed student perceptions of the activity and learning experience. While students, across three cohorts, felt challenged to solve a real-world problem identified during the simulation lab visit, they felt more confident in utilizing knowledge learned in the biomechanics course and self-directed research. Instructor evaluations indicated that the active and experiential learning approach fostered their technical knowledge and life-long learning skills while exposing them to the components of adaptive learning and innovation.

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1 Introduction

The rapid growth in health care cost is dramatically changing the landscape for bioengineering in the U.S. Bureau of Labor Statistics estimates future employment for biomedical engineers to grow by 27% over the next 8 years, as compared to 9% on average for all engineers [1]. Thus, the demand for engineering students with expertise in biomedical fields is rapidly growing. Accordingly, there is a crucial need to provide appropriate training for the emerging workforce that will be responsible for translating new devices and technologies from the bench to the bedside. Transforming math, science, and engineering knowledge into real-world solutions to improve healthcare and the development of biomedical technologies requires that biomedical engineering students gain experiences integrating technology with real-world conditions beyond the classroom/lab. However, the dominant theory-based instructional model logically represents a potential barrier to improved biomedical engineering education since it lacks the key components of practical adaptability and innovation. Furthermore, the theory, design, and active learning process require further integration and enhancement especially in the field of biomedical engineering for which the knowledge base and regulatory climate are changing rapidly. Two critical components that need to be addressed in biomedical engineering education include: innovation and adaptability. While traditional instructional methods are effective at developing the knowledge dimension, very rarely does it prepare them for real world scenarios that encompass ill-defined problems, ethics, biological complexities, and solutions that are heavily driven by user's needs.

It is also noteworthy that majority of the design projects place emphasis on teaching the engineering solution strategy for a specific problem statement that are professor-driven or industry sponsored. Rarely is an emphasis placed on problem identification. Eliminating the problem observation and identification step limits the student design experience and their preparedness for real-world problems. In 2005, only 15% of capstone design project

ideas nationally were student generated [2]. The lack of problem identification poses additional problems in the field of biomedical engineering education since the collaboration between bioengineers and medical professionals plays a key role on 21st century solutions to complex, interdisciplinary problems in health care. In typical engineering curriculum, biomedical engineers become good at solving given problems in routine ways; lack of courses that integrate need identification in addition to encouraging exploration of innovative solutions, while identifying customer needs often limits skills in break-through ideas and innovation. Additionally, while the traditional lecture-based teaching approach offers the engineering competency, there still exist significant challenges in teaching biomedical engineering students how to adapt their expertise in a new context, which is often the case in biomedical engineering field that offer novel challenges outside the technical domain [3].

Inquiry methods are frequently effective at developing the innovative dimension and adaptive learning experience. Inquiry learning methods including problem- and project-based learning, authentic inquiry, challenge-based learning, and discovery learning [4] have shown to successfully engage students in developing solutions to real-world problems while increasing student motivation and awareness of the connections between their in class experiences and their future work. These techniques have also been reported to result in positive learning attitudes resulting in significant increases in knowledge [5–12]. Based on these findings, this study aims to further investigate the efficacy of combinational teaching approaches using lectured-based and project-based learning in a senior-level biomechanics course. Based on the previous studies we hypothesize that project-based learning approach through clinical immersion will result in positive student engagement and better understanding of complex problems in a real-world setting. We also hypothesize that adaptive learning will offer: (1) enhanced opportunities for innovation through the identification of problems and (2) deeper understanding of the clinical problems will lead to the development of safe and useful devices and technology while utilizing their technical knowledge acquired in the classroom setting. Overall, the clinical exposure will not only increase critical thinking in the design process of a solution, but also offers a life-long learning skill.

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Fig. 1 Project-based learning approach to integrate clinical immersion (adaptability) and problem identification and solution phase (innovation) to meet the course objectives and outcomes

2 Methods

2.1 Course Details. Active and adaptive learning using project-based learning approach was used in a senior level 14 weeks biomechanics course offered during Fall 2014, Fall 2015, and Fall 2016. This was an interdisciplinary course with a total of 12, 15, and 20 students in the three cohorts with majors from mechanical and biomedical engineering departments. Teaching biomechanics by itself is challenging because the field integrates two difficult bodies of knowledge: the complexity of human anatomy and physiology with the mechanics of the body and the external forces it encounters while being stationary or during motion. Furthermore, teaching the class to a team of multidisciplinary students warrants teaching techniques that enhances student learning in the classroom. To accomplish the goals of this course, students were provided with PowerPoint lectures, guest lectures, and visits to kinematics and kinetics labs during the two-times/week 75-min class periods. Topics covered in the course included: Introduction to biomechanics, biomechanical models, kinematics, kinetics, bio-instrumentation, tissue biomechanics of bone, muscle and soft tissue, and medical devices—hip, knee, and spine, injury biomechanics and sports biomechanics. A wide range of topics covered in one semester course often poses several challenges, including the assessment of what was taught and what student

learned in the class [11]. To overcome this challenge, we utilized a project-based learning approach (Fig. 1), where integration in the nursing simulation clinic warranted adaptability of the acquired knowledge and identifying an unmet need and solution aimed to promote innovation learning.

2.2 Project-Based Learning Approach Through Clinical Immersion. The process started with exposing the students to clinical settings in week 10 of the course, where they had an opportunity to explore the clinical setting and make observations (two class-meetings). In week 11, students were taken to the Center for Simulation and Computerized Testing located in the School of Nursing within the University. They met with the Director of the center and were exposed to the working of the existing simulation mannequins including the SimMan, Noelle (a birthing simulator), two baby Hal simulators, a pediatric simulator, and two iStan simulators that were used for teaching nursing students (Fig. 2).

2.3 Components of Innovation and Adaptability. In week 12, students were expected to have a thorough understanding of the facility, and teams of 2–3 students were assigned to identify an unmet need (innovation component) in the mannequin used in the clinic by nursing students and instructors. Students had opportunity to meet with the Director if they had any additional questions. In week 13, students were required to pitch their unmet need proposals to the entire class. From a total of six to ten pitches, each semester, the course instructor and each student team scored all pitches and selected top four to five proposals. Unselected student teams were reassigned to a selected project based on the scores they assigned to the selected projects. In week 14, students in teams of two to four proposed an engineering solution (adaptability component) for this unmet need utilizing knowledge obtained in the course. Key components of the final presentation included: background, clinical importance, solution, design details, clinical application, failure points, and conclusion. Selected examples of a few student preproposals/pitches, final projects, and solution strategies are shown in Table 1. Each student was also required to submit a technical report detailing the proposed solution.

2.4 Course Surveys. With the Institutional Review Board approval from Widener University, voluntary anonymous student surveys regarding student's perception about the clinical immersion and project-based learning approach were collected at the end of the course each year. All questions asked students to answer on a five-point Likert scale (with five being "strongly agree"). Students overall perception on difficulty level of the final project was also assessed using the same scale.

2.5 Student Learning Outcomes and Assessments. Course instructor assessed the engineering techniques and principles utilized in the proposed solution, while two external reviewers including the Director of the simulation center and an MBA professor used the Rubric shown in Table 2 to assess student oral

Fig. 2 Clinical immersion at Center for Simulation and Computerized Testing for problem identification

presentations in all 3 yr. Additionally, students also provided a peer evaluation for this team-based project approach per year using the rubric provided in Table 3.

2.6 Statistical Analysis. After tabulating surveys and outcomes/assessments data, one-way analysis of variances for each question were conducted (Microsoft Excel, Microsoft, Redmond, WA), with “cohort” as a factor.

3 Results

The data were combined across three cohorts because there were no significant differences in the student survey data, reviewer’s scores, and peer evaluations between the 3 yr.

3.1 Student Survey Data. Over 92%, 88%, and 95% of the students responded to the student survey from Fall 2014, Fall 2015, and Fall 2016 offering of the biomechanics course. Students’ survey data were collected to assess the following: clinical immersion experience, outcome of innovation and adaptability,

traditional versus project-based learning approach, assessment of difficulty, life-long learning outcome, other developed skills outcome, and overall course and instructor assessment (Fig. 3).

3.1.1 Clinical Immersion Experience. Over 94% of the students enjoyed the SimMan lab visit and found it to be a rich learning experience. Furthermore, 82% students indicated that the visit served as a tool to help understand the application of biomechanics knowledge and 100% agreed that the clinical immersion and project-based learning approach should be continued in future offerings of the course.

3.1.2 Innovation and Adaptability. Over 83% of the students not only found the final project to be exciting and intellectually challenging through the translational component but also felt confident in both identifying and solving real-world problems. Furthermore, 83% of the students could relate the topic discussed in the class to the goals of finding solution for the identified unmet need in the SimMan. Over 100% of the students felt comfortable in the innovation and adaptability components of learning including problem identification and solution.

Table 1 Example of project-based learning projects for the biomechanics course

Pitched proposals	Final proposals	Proposal design
Electromechanical lever to lift up the manikin upper body A new obese SimMan	Electromechanical lever to lift upper body in obese patients
SimMan: incorporating EMG responses SimMan improvement proposal: motorized joints	Motorized leg and arm joints with muscles
Improved neck movement in pediatric SimMan Improvements in pediatric SimMan	Introducing shaken baby syndrome Sim-Man
Improved biofidelic Jaw in SimMan	Designing a biofidelic jaw
Improving circulation system in SimMan Improved IV system in SimMan	Improving IV training and circulation system in SimMan

Table 2 Grading rubric for the final project used by external reviewers and course instructor

Oral presentation		Beginning	Developing	Competent	Accomplished	Exemplary
1.	Statement of project objectives and scope	O	O	O	O	O
2.	Identification of existing modern engg developments	O	O	O	O	O
3.	Problem solution	O	O	O	O	O
4.	Engineering justification	O	O	O	O	O
5.	Identification of project constraints	O	O	O	O	O
6.	Evaluation of alternative approaches	O	O	O	O	O
7.	Attainment of objectives	O	O	O	O	O
8.	Identification of possible issues with the proposed design	O	O	O	O	O
8.	Organization of presentation	O	O	O	O	O
9.	Manner of delivery	O	O	O	O	O
10.	Appropriateness for nonengineering audience	O	O	O	O	O
11.	Answers to questions	O	O	O	O	O
12.	Effectiveness of visual aids	O	O	O	O	O

Beginning—Not meeting expectations for an entry-level engineer.

Developing—Occasionally meeting expectations for an entry-level engineer.

Competent—Meeting expectations for an entry-level engineer.

Accomplished—Meeting and occasionally exceeding expectations for an entry-level engineer.

Exemplary—Generally, exceeding expectations for an entry-level engineer.

3.1.3 Traditional Versus Project-Based Learning. When compared to traditional teaching approaches, 94% students reported that the project-based learning approach was useful in their learning, and 83% agreed that project-based learning utilized more critical thinking than traditional courses. Furthermore, 94% student also reported that seeking solutions for self-identified problems was more effective learning tool than instructor defined projects.

3.1.4 Life Long Learning. Over 88% of students reported that they learned to apply biomechanics knowledge in the real-world and 83% agreed that such a skill-set was a lifelong learning skill. Furthermore, 83% students also agreed that the knowledge gained through this course was important and valuable to train future engineers.

3.1.5 Other Developed Skills. The course included a student proposal pitch presentation, a final project presentation, and a technical report. When asked if students enjoyed and valued listening to other student's ideas, 94% of students reported listening to other students as an important part of learning. Engineering education often limits student's presentation to engineering audience, which rarely is the case in real-world especially in the field of biomedical engineering. This course required students to present their identified problems and solution to external nonengineering reviewers, and student's survey (83%) reported that to be a valuable communication skill.

3.1.6 Difficulty Assessment. Over 50% of the students found that the final project assignment to be neither easy nor difficulty.

Furthermore, 33% of them found it somewhat difficulty, and 16% found it easy.

3.1.7 Overall Course and Instructor Assessment. One of the challenges with using project-based learning as a teaching tool is that the active and experiential learning environment places students as the learner, and a balance between self-discovery and directed instruction becomes critical to yield any beneficial outcomes. Eighty three percent students not only enjoyed the course but also reported to be enthusiastic about what they learned. The students also reported that the course outcomes were met (85% students), while they understood the subject better (92% students) and its engineering application (87% students).

3.2 Student Learning Outcomes and Assessments Through Reviewers and Instructor Scores. Two external reviewer's scores are shown in Fig. 4. All students met the required target of >80% score for the parameters assessed using Rubric shown in Table 2.

Using the rubric provided in Table 2, individual students were scored on a five-point likert scale by the two external reviewers and the course instructor. As shown in Fig. 5, students scored 4.25 ± 0.6 for problem statement (Q1) and 4.75 ± 0.18 for the proposed solution (Q3), while identifying the existing modern engineering development (score of 4.5 ± 0.35 , Q2). Their scores were 4.7 ± 0.3 for their ability to present it to a nonengineering audience with clarity (Q10). Other categories such as offering engineering justifications, understanding the constraints and offering alternative solutions achieved a score of 4.6 and above (Q4-6).

Table 3 Rubric used for peer evaluation: an ability to function on multidisciplinary teams

Attends the team meetings and contributes in the discussions	Does not contribute or avoids assigned work	Only partially completes assignments	Completes assigned tasks, but does not take on additional work	Completes assigned tasks and volunteers for extra	Completes all assigned tasks and additional ones on her/his own initiative
Takes responsibility and fulfills duties of team member as assigned	Does not complete duties on schedule, or work is of poor quality	Usually completes tasks on time, but work contains many errors	Usually completes tasks on time or informs team if she/he cannot complete, work is acceptable	Completes tasks on time and submits good-quality work	Completes tasks on time or ahead of schedule, and submits high-quality work
Has a positive attitude during the discussions and disagreements	Usually does most of the talking, or pays no attention in team meetings	Allows others to speak, but is focused on her/his own ideas	Listens to other's viewpoints and forms opinion	Listens to other's viewpoints, validates, or discount personal opinion	Listens to other's viewpoints, encourages speakers to develop their ideas regardless of personal opinion

Students scored 4.8 and above for attaining the project objective and proposing possible issues with the problems (Q7, Q8). Other questions that assessed student's oral presentation skills, ability to address questions, and use effective visual tools yielded an average score of 4.6 and above (Q9, Q11, Q12). Overall, the average

student scores were above the target values of 4.0 for each question used for assessment of student learning. When assessed on their technical report, 85% of the students were able to meet the required acceptance score of 7.5 and above out of 10 (Fig. 5) among each cohort.

Fig. 3 Student Survey data from the three cohorts of the biomechanics course that utilized project-based learning approach

Fig. 4 External reviewer and course instructor's average scores for all students from the three cohorts. A target value of above 80 for at least 75% of the students enrolled in each cohort was set as success rate.

3.3 Peer Evaluations. An important component in team-based learning is that every student be equally involved in the learning process. While external reviewers and course instructors grading was performed for individual student, the team-based project heavily relied on group effort of the students in the team. Peer evaluations (using rubric provided in Table 3) were used to assess the contribution of students in the team as reported by their own team members. Hundred percent of the students performed peer evaluations. Almost every student was reported to be highly involved in the final project problem identification and solution process, was available for meetings, and made contributions to the project for up to 85% or more (Fig. 6).

4 Discussion

Engineering education aims to build engineers who can solve problems in their discipline. Especially, the rapidly developing biomedical engineering industry requires engineers who can expand their knowledge and skills over time [13]. Among all engineering disciplines, this is accomplished through the introduction of designing and problem solving skills as early as during the first year Intro to engineering course. The curriculum then builds upon familiarizing the students with technical content, while teaching engineering solution approach involving concept generation, selection, prototyping, and validation. In majority of problem identified, significant emphasis is placed on teaching the engineering solution strategy for a specific problem statement that was introduced to the students. These statements are often well-defined with known wants/needs and constraints. Rarely is an emphasis placed on problem identification, which can often be ill-defined and in a nontechnical domain or out of context. While lacking the problem identification phase not only places limitations on innovation learning, it also limits engineer's ability to adapt to the new settings where the problem

exists. Current demands of biomedical engineering field require entrepreneurial skill sets in the workforce along with technical aptitude warranting students training in adaptive reasoning and innovation. Bioengineers should be able to transfer the required observation when confronted in a nonroutine setting and apply the required knowledge to develop a solution.

While traditional lecture-based approach offer technical competencies, studies have reported that these approaches also makes it difficult for students to apply their knowledge out of context, and their long-term retention is often poor [13,14]. Further, students have difficulty in relating the knowledge to problems in the "real world" including the workplace or graduate school [14]. An alternative could be utilizing inquiry methods, however, predominant utilization of these methods in courses have also reported some drawbacks such as students not learning important concepts and fundamental principles for the subject. Students also lack the ability of knowing how to apply these principles and structuring their solution approach to these open-ended problems [8,15] resulting in less students' knowledge gains than in traditional educational settings [4,8,15]. Thus, a strong balance between two techniques may be needed to overcome the drawbacks while filling the gaps in preparedness of biomedical engineers in the workforce.

In this study, we utilized the traditional lecture-based approach that followed the order of taxonomy of knowledge presented in a textbook or other resources specified for the course. Additionally, we utilized project-based learning approach that exposed students to an active and adaptive environment replicating real-world scenario, where they learn to make observation and identification of an unmet biomedical engineering problems, followed by proposing engineering solutions. Prince and Felder provide support for the effectiveness of active learning strategies [4,16,17]. Our study was also based on a model for the development of adaptive expertise adapted from Schwartz et al. [18]. Using these approaches we not only accomplished innovation and adaptability learning but also enhanced student's critical thinking and communication skills, while exposing them to the components of creativity, global awareness, self-directed research, and life-long learning skills. These are some of the most important skill sets needed in the new generation of biomedical engineers.

The problem-based approach through clinical immersion used in this course presented students with challenges of innovation and adaptability. Finding unmet need in a clinical setting outside the technical domain required students to go beyond their current capabilities and adapt to developing a solution for a novel problem that embeds technical issues with which they are unfamiliar. Using the governing principles, solution methods, and constitutive equations that students learned in the class could, when applied adaptively, helped them develop a viable approach to the self-identified problem thereby completing the cycle of innovation.

While technical competencies can be assessed through midterm and exams, innovation and adaptive learning require rubrics for the assessment of student learning. We developed these rubrics to

Fig. 5 Course instructor's scores based on the technical report submitted by each student from the three cohorts. A target value of above 7.5 for at least 75% of students enrolled in each cohort was set as success rate.

Fig. 6 Peer evaluation scores of each student from the three cohorts obtained from team members perception of student contribution to the project

assess if students could create well-defined problem statements and address the problems from a global perspective, while understanding the primary issues of importance and then moving toward developing specific equations or other solution methods [16,19,20]. Novices are often known to skip the step of developing a deep understanding of the problem, and attempt to quickly apply equations or solution methods that match the problem on surface features [16,21]. We found that by exposing students to a nursing simulation clinic, they learned to expand the problem space and consider multiple possibilities before settling on a solution path [14,22]. Overall, students' survey data also indicate that the method of teaching promoted knowledge growth, enthusiasm, and positive attitude to learning while showing significant added value in promoting students' innovation skills. Reviewer score also indicated that the combined approach help achieve the student learning outcomes.

This paper presents quantitative results of an experiment studying the effects of combined teaching approaches using traditional as well as active and adaptive experiential-based learning that aims to develop knowledge, innovation, and adaptability in biomedical engineering students. Several teaching techniques have been reported while teaching biomechanics course. Use of computer-assisted instruction in introductory biomechanics has shown to have no significant effect, even though the student attitudes about computer-assisted instruction were positive [23]. Research using the biomechanics course inventory (BCI) has identified course and instructor characteristics to account for much smaller variance (2–5%) in learning [24] than student characteristics and behaviors (14–40%) do [25,26]. Another important factor that plays a key role in student learning of biomechanical concepts is student's perception of career relevance and their interest in the subject. Implementing student-initiated projects in the course increases student motivation due to ownership and high level of interest that sets them for a desire to succeed. Furthermore, since the senior design capstone course/s often limits the identification phase, having students learn about it in other courses in the curriculum helps expand their knowledge of the design process.

There are a few limitations in this reported study including lack of control group or baseline data of students who received lecture-based biomechanics course with no clinical immersion components. Potential differences in the students among the three cohorts and improvement made in courses from first to third offering of the course could also affect the study outcome. Instructions across the three cohort classes and potential positive bias induced by implied benefit of problem-based learning unit could have also affected the student responses.

In summary, findings from this study indicate that the combined traditional and project-based learning may be an effective strategy to help undergraduate engineering students develop innovation and adaptive skills that will serve them well in future professional endeavors. This hypothesis should be confirmed by future studies with baseline data and control groups using traditional biomedical engineering instruction in similar courses. These studies will also confirm that the student survey questions did not result in a biased response toward a positive perception of the current project.

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