

Problem-Based Learning in Biomechanics: Advantages, Challenges, and Implementation Strategies

Alisa Morss Clyne¹

Mechanical Engineering and Mechanics,
Drexel University,
AEL 170C, 3141 Chestnut Street,
Philadelphia, PA 19104
e-mail: asm67@drexel.edu

Kristen L. Billiar

Biomedical Engineering,
Worcester Polytechnic Institute,
Worcester, MA 01609

Problem-based learning (PBL) has been shown to be effective in biomedical engineering education, particularly in motivating student learning, increasing knowledge retention, and developing problem solving, communication, and teamwork skills. However, PBL adoption remains limited by real challenges in effective implementation. In this paper, we review the literature on advantages and challenges of PBL and present our own experiences. We also provide practical guidelines for implementing PBL, including two examples of PBL modules from biomechanics courses at two different institutions. Overall, we conclude that the benefits for both professors and students support the use of PBL in biomedical engineering education. [DOI: 10.1115/1.4033671]

Introduction

Undergraduate biomedical engineering programs are rapidly expanding in both number and size. In fact, nearly 75% of the ABET-accredited biomedical engineering undergraduate programs in the U.S. earned their first accreditation within the last 15 years. Biomedical engineering curricula are continuously debated, evaluated, and restructured to determine the best method to provide students with the broad knowledge base and diverse skill set needed to solve complex problems at the interface between biology and engineering. The shortage of textbooks, homework problems, and laboratory modules makes it difficult to effectively teach biomedical engineering, and in particular, the associated subspecialties of biomechanics and mechanobiology, using off-the-shelf approaches. Furthermore, educators have recognized that the rapidly developing biomedical engineering industry requires engineers who can expand their knowledge and skills over time [1]. Biomedical engineering students need to build “adaptive expertise,” the ability to apply prior engineering knowledge to identify and solve new problems [2]. Over the past 20 years, these challenges have provided an opportunity for biomedical engineering education to lead efforts to teach engineering through active-learning approaches. In a recent survey, more than 80% of faculty who teach introductory biomechanics classes reported using active learning or interactive engagement techniques, as compared to only 48% of physics instructors [3].

PBL enables biomedical engineering faculty to integrate fundamental engineering concepts into the context of disease by engaging students in the process of creating innovative medical therapies and devices that fulfill a clinical need. PBL is based on the premise that knowledge is understood better and retained longer when presented in a real-world context [4]. In PBL, the problem is introduced first, and it then becomes the motivation for learning the subject material [5]. The process is inherently student-centered, with students learning how to determine what they need to know to solve the problem. The professor serves as a facilitator or guide to help students identify what they do and do not know, recognize their best manner and pace of learning, and critically evaluate knowledge sources. Through the PBL process, the student acquires knowledge on the subject matter and develops critical problem-solving skills [6]. While many active and

collaborative teaching strategies are more effective than traditional lecture formats in enhancing student knowledge and retention, studies suggest that PBL enhances students’ abilities to apply their knowledge both immediately and in the long term [7–9]. PBL also focuses student learning on problem solving and communication skills, which are among the most important skills in college graduates as defined by both academia and industry [10,11]. PBL may further develop students’ abilities to think like scientists and encourage participation in undergraduate research [12].

While the educational research literature shows that PBL and other active-learning techniques improve student performance, there remain significant challenges in implementing PBL in the classroom [13]. A 2010 report to the National Academies Board of Science Education highlighted the importance of implementing educational techniques with evidence of success (such as PBL). The report further suggested that efforts to encourage faculty members to adopt a new educational technique should provide both evidence of technique effectiveness and a description of how to implement the technique in adequate detail [14]. The purpose of this paper is therefore to briefly review the literature on PBL effectiveness, provide guidelines to implement PBL in biomedical engineering courses, describe PBL implementation in biomechanics courses at two universities (Drexel University and Worcester Polytechnic Institute (WPI)), and suggest strategies to overcome the challenges associated with PBL. Through this paper, we hope to increase the prevalence of PBL in biomedical engineering curricula.

Methods

In 1999, the National Science Foundation funded the VaNTH Engineering Research Center, a collaboration among Vanderbilt University, Northwestern University, the University of Texas, and the Harvard/MIT Division of Health Sciences and Technology, to develop biomedical engineering education resources [2]. VaNTH investigators used educational, psychological, and neuroscience research on learning [15] to define an effective biomedical engineering educational environment. To develop critical problem-solving skills, VaNTH adopted challenge-based instruction, a collaborative and technology-based derivative of PBL. The VaNTH investigators adopted the STAR.Legacy cycle (Fig. 1) as a proven instructional method to integrate conceptual knowledge and innovative thinking through an engineering approach [16].

¹Corresponding author.

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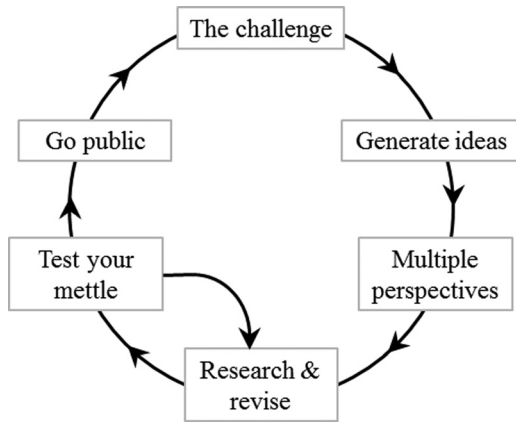


Fig. 1 The VaNTH STAR.Legacy cycle. The STAR.Legacy cycle begins with the challenge. Students generate ideas about how to solve the challenge based on their initial knowledge and then consider expert opinions on the challenge in the multiple perspectives phase. Students use these initial experiences to drive the research and revise phase. Students then test their mettle in an assessment, such as a quiz or problem set. If students discover they need to enhance their knowledge, they can return to the research and revise phase. Finally, the students go public to present their solution to the challenge.

The STAR.Legacy cycle begins by posing an initial challenge. Students then apply what they already know to generate initial ideas about how to solve the challenge as well as determine what additional knowledge they need to solve the challenge. In the “multiple perspectives” phase, students take into account ideas by other people familiar with these or similar challenges (e.g., industry professionals and end users). Students then use these initial experiences to develop questions to be answered during the research phase. Research is instructor-supported and can take the form of online or in-class lectures, discussions, and demonstrations among many others. Students then “test their mettle” by applying the new knowledge to an assessment technique, such as a quiz or problem set. This allows students to return to the research phase if needed to enhance their knowledge. Finally, the students “go public” by synthesizing their newly acquired knowledge to solve either the original or an analogous challenge (e.g., exam, presentation, and report).

The problem or challenge is the foundation of the STAR.Legacy Cycle or any PBL-based approach. Faculty should carefully research, assess, and revise problems prior to the start of the course. PBL problems can be created through an iterative five-step process:

Step 1: Consider Course Objectives and Context

Some of the most important work in creating PBL problems occurs even before the problems are written. As with planning any course, the course objectives and context should be considered before the course materials are created. Specifically, faculty should consider the course level and student maturity, since a problem for a freshman-level course should be less complex, require less existing knowledge, and incorporate guidance in finding reliable information as compared to a problem for a senior-level course. Faculty should also assess what knowledge the students already have, in terms of both lecture and laboratory based prerequisites and practical experience (e.g., co-ops or internships). Finally, faculty should consider the time frame in which the course will be taught (quarter or semester) and how much of the course will be converted to a PBL format. PBL-based instruction takes more time, since students must find, interpret, and then use knowledge. Therefore, a mix of traditional lecture-based teaching and PBL may be best for both faculty and students. A mixed format enables faculty to cover a greater breadth of required course

material and include classes and assessment techniques that are more familiar to both faculty and students.

Step 2: Identify Learning Objectives

The second step in creating a PBL problem is to define the learning objectives associated with that problem. Learning objectives are statements that describe what students should know or be able to do by the end of the problem module. Learning objectives can be both content- and process-oriented. A content-oriented learning objective is specific to the course subject and describes basic knowledge and understanding of specific concepts or techniques in the discipline. An example content-oriented biomechanics learning objective could be “draw a free-body diagram of forces acting on the knee.” Process-oriented learning objectives describe global skills, such as effective oral and written communication, working well with others, acquiring and evaluating information, and higher order critical thinking. An example process-oriented learning objective could be “critically review a scientific journal article.” Well-defined learning objectives guide problem development and ensure that the problem remains focused on the material that the students should master.

Step 3: Identify Real-World Context

The next step is to ground the problem in real-world context to enhance relevancy to the students. The problem context should be specific and easy to understand, while the problem solution should be ambiguous with no single right answer. Instead, the students must decide what they would do. Perhaps the quickest way to create an authentic problem is to take a current textbook problem and adapt it to fit a real-world situation. For example, a textbook problem analyzing flow through a stenosis could be adapted by introducing it within the framework of a celebrity who is considering when to get a stenosed aortic valve replaced and what type of valve to get. Real-world context can often be found in current events or in newspaper articles. For faculty actively engaged in research, real-world context can also be found in research papers or in the laboratory. For example, the authors previously based problems on endothelial cell response to flow and cyclic strain in diabetic conditions [17,18]. These types of problems can be simple to create and implement, since faculty already ground their research in clinical problems, and the techniques and sample data are readily available. The integration of research and education can furthermore make the PBL module more relevant and meaningful to both the professor and the students.

Step 4: Draft the Problem

Good PBL problems apply higher orders of Bloom’s taxonomy (Table 1) [19,20]. While a problem may start with requiring students to remember, understand, and apply knowledge, the problem should in the end require students to create something new or reach a consensus about a complex, open-ended situation. To write the problem itself, the professor should take on the additional role of being a storyteller. The problem should start with a hook to draw students in, and students should be able to relate to and care about the interesting characters in the problem. While the problem should contain enough context to motivate the students and make the problem seem solvable, the problem situation should remain somewhat ambiguous so that students uncover what information they do and do not have. While the professor may guide students to find critical information, part of the PBL process requires students to learn how to find the information that they need.

The problem can seem more interesting and manageable to students if it is written using a multistage approach. For example, a complex problem like designing a point-of-care cancer screening device might start with a stage to determine which cancer cell property to use for detection, continue with a stage to determine which point-of-care technology to select, and then conclude with a stage in which students design a new point-of-care device to detect cancer cells using their selected cell property. The professor can include prompting questions in the problem statement to help students discover what they already know and what they need to find out. The final problem outcome should include a written or

Table 1 Bloom's taxonomy as originally presented and as revised by Andersen et al.

Bloom et al.	Anderson et al.	Definition	Keywords	Example
Knowledge	Remembering	Recall previously learned facts, concepts, definitions	Define, describe, name, outline, state	List the valves in the heart
Comprehension	Understanding	Comprehend the meaning of and interpret a problem	Explain, translate, rewrite, summarize	State the problem in your own words
Application	Applying	Use a concept in a new situation	Compute, predict, demonstrate, solve	Calculate cardiac output
Analysis	Analyzing	Separate material into component parts to see interrelationships	Compare, contrast, diagram, break down, differentiate	Troubleshoot a faulty heart valve design
Synthesis	Creating ^a	Produce something new from component parts	Design, generate, plan, construct	Design a tissue-engineered valve
Evaluation	Evaluating ^a	Make judgements about value based on criteria	Appraise, conclude, critique, justify	Select the most effective valve

^aIndicates that evaluating comes before creating in the new version of Bloom's taxonomy, since evaluation is often a part of the creation process.

Table 2 PBL problem evaluation rubric from the Institute for Transforming Undergraduate Education at the University of Delaware

Criteria	Desirable (3)	Less desirable (2)	Not desirable (1)
Realism	Based on an actual or fictionalized real-world situation linking topic to learner	Contrived or contains unrealistic elements that decrease credibility	Unrealistic, lacking relevant context
Content	Addresses significant conceptual issues; directly related to major content goals	Encourages superficial rather than in-depth understanding concepts	Relevance of topic peripheral or not apparent
Engagement	Stimulates discussion and enquiry through its relevance and presentation	Generates limited or superficial discussion; provokes little curiosity	Lacks a "hook"; obscure or pedantic presentation
Complexity	Appropriately challenging; group effort and cooperation required; some ambiguity appropriate; integrates multiple concepts	Difficult but may encourage a "divide and conquer" approach. Concepts not well integrated	Solution accessible to most students working alone; focused on single concept
Resolution	Open to multiple resolutions or multiple pathways to solution, depending on the student assumptions and reasoned arguments	Resolution is more obvious but allows reasonable opportunity for judgment and discussion	One right answer is expected; limited opportunity for analysis and decision making
Structure	Progressive disclosure via multiple stages, builds on existing student knowledge	Staging does not flow well; transition could be improved	Too much or too little information provided at once; short cuts thinking/research
Questions	Limited in number, short, and open-ended; encourage deeper understanding	Most are directive; preempt student-generated learning issues	Lead to "yes-no" answers rather than thoughtful discussion
Research	Promotes substantive research using multiple resources	Research limited to textbook material	Limited necessity for research

oral communication requirement. However, these can move beyond the typical 8–10 pages report or PowerPoint presentation to include print advertisements, executive summaries, sales pitches, or even an infomercial. Finally, students should be encouraged to engage in formative assessment to monitor their own learning and their team's progress as well as summative assessment of their problem solution at the module conclusion.

Step 5: Evaluate the Problem

Finally, the professor should evaluate the problem or perhaps better have a teaching assistant or colleague to evaluate the problem. A sample evaluation rubric from the Institute for Transforming Undergraduate Education at the University of Delaware (Table 2) addresses how well the problem appeals to students, how the students will learn from the problem, how well the problem statement is structured, and what the student outcomes from the problem will be [21]. Problems can be evaluated and rewritten prior to the course; however, the most useful evaluation may come after the problem has been implemented in the course. Some professors may become discouraged when a particular

problem module does not work perfectly the first time. However, most successful problems are rewritten several times before the course starts and after the course ends, and even successful problems have challenges with each implementation in a new group of students.

Results

Example PBL Modules

Introductory Biomechanical Engineering Course (Drexel University, Junior-Level Students). A junior-level introductory biomechanical engineering course at the Drexel University was transformed into a PBL format. The goal was to educate biomechanical engineers such that they would gain increased ability to translate fundamental research into new technology. The official prerequisites for this course were freshman-level math, physics, chemistry, and biology. However, since most students were junior mechanical engineering majors, they had completed statics,

dynamics, mechanics of materials, fluid mechanics, and controls. The 10-week course had four modules, each motivated by a real-world problem which demonstrated how a mechanical engineering principle could be applied to biological systems. In the biomechanics module, students assessed the fluid and tissue mechanics of lung function in a cystic fibrosis patient. In the bio-manufacturing module, students created a bioreactor to tissue engineer a lung with a focus on recreating the mechanical environment. In the biomicrofluidics module, students developed a low-cost device to detect or monitor HIV/AIDS. And in the bio-inspired robotics module, students designed and modeled a prosthetic limb for running and jumping. The biomechanics module is provided below as an example.

Learning Objectives

- Describe respiratory system anatomy, physiology, and mechanics.
- Design, conduct, and interpret biomechanical engineering experiments.
- Analyze changes in the mechanical properties of proteins, cells, and tissues in health and disease.
- Evaluate current medical techniques and propose a new technique.

Real-World Context. A 10-yr-old patient (Sarah M.) suffered from cystic fibrosis and recently was given 1–3 months to live unless she received a lung transplant. Sarah was too young for an adult lung transplant, but no pediatric lungs were available. Her parents petitioned Health and Human Services Secretary Kathleen Sibelius to intervene, but she refused. However, a federal court judge granted a temporary order that allowed Sarah to join the adult organ transplant list, and she subsequently received a double lung transplant. Sarah's case resulted in a permanent change that enables children under the age of 12 to be considered for adult organ transplantation.

While lung transplants can save patients' lives, they are not without risks. Specifically, the patient trades the challenges of the original disease with the challenges of transplant disease due to medications used to prevent rejection. It is therefore critical to determine the time at which a cystic fibrosis patient needs a lung transplant. Kathleen Sibelius appoints you as the lead engineer to *determine how to measure lung function decline in patients with cystic fibrosis*. This test will be used to determine when to put a cystic fibrosis patient on the lung transplant list.

Problem Presentation. The challenge was presented in a multi-phase approach over the course of several class sessions, with assignments of increasing complexity due at each phase:

Phase 1: The professor provided students with a written hand-out describing the problem and key learning issues. For example, students were asked which fluid and solid mechanics principles they needed to use to analyze lung function as well as what lung anatomy and physiology concepts they needed to know to understand how cystic fibrosis damages the lungs. Students discussed what they knew about cystic fibrosis and lung physiology and described initial ideas for how to test lung function. Each student in the team was then tasked with researching a learning issue which would be presented to the rest of the team at a later session (STAR.Legacy Cycle: The challenge and Generate ideas).

Phase 2: A pulmonologist from the Drexel College of Medicine presented a minilecture on lung function, pulmonary function tests, and cystic fibrosis. Students then used these concepts to analyze pulmonary function tests from healthy and diseased patients (STAR.Legacy Cycle: Multiple perspectives).

Phase 3: Students presented what they had discovered about their learning issue to the rest of the team. They then took a group quiz to assess the depth of their knowledge. Finally, they developed several initial ideas of pulmonary function tests that could be used in cystic fibrosis patients (STAR.Legacy Cycle: Research and revise and Test your mettle).

Phase 4: Students participated in a lung laboratory. Porcine lungs were obtained from a local abattoir and treated to simulate human disease. One lung was maintained in phosphate-buffered saline to simulate healthy conditions; one lung was obstructed in the bronchus to simulate obstructive lung disease due to bronchial narrowing (e.g., cystic fibrosis); one lung was incubated in collagenase to simulate obstructive lung disease due to loss of alveolar structure (e.g., emphysema); one lung was incubated in formaldehyde to simulate restrictive lung disease due to tissue stiffening (e.g., pulmonary fibrosis). On the day of the lab, each lung was connected via a main bronchial tube to an air bladder with a pumping bulb and a pressure gage (Fig. 2). Students measured the pressure required to inflate the lung to a given volume. As the final deliverable, students prepared a one-page executive summary justifying the pulmonary function test they selected for cystic fibrosis patients as well as a short lab report (STAR.Legacy Cycle: Test your mettle and Go public).

Since the mechanical engineering students did not have experience in anatomy or physiology, the faculty provided online anatomy textbooks describing lung structure and online videos describing lung function. Students were provided with a lab guide to direct their inquiry since lab time was limited. With more time, students would have created their own process to determine which lung modeled each disease. Finally, several of the submitted executive summaries did not meet expectations. Formative feedback was provided, and all the student teams were given the opportunity to revise and resubmit.

Problem Evaluation. The problem was evaluated by examining student journals, deliverables, and pre/postcourse evaluation. Students felt that they learned best from the pulmonologist minilecture as well as from online videos describing lung function. Some students even went on to watch additional online videos about cystic fibrosis, and others related their learning about cystic fibrosis to how they as engineers could design devices to help patients with other disease (e.g., asthma). For student deliverables, four out of five student teams logically defended a pulmonary function test for cystic fibrosis. The students based their choice on lung physiology and their experience in the lung laboratory. For the lung laboratory, all five student teams successfully identified the simulated disease in each porcine lung. In the postcourse evaluations, students felt that the problem exposed them to practical implications of biomechanics, prepared them to function in an engineering work environment, and provided insight into a career as a biomechanical engineer. Future iterations of this problem would change the deliverable to one with more ambiguity, since most of the teams selected the same pulmonary function test. In addition, an example executive summary would be provided to guide students in how to write an effective short document.

Solid Biomechanics Laboratory (WPI, Junior-Level Students). Project-based laboratories are integrated throughout the biomedical engineering curriculum at the WPI. Here, we report on our efforts to develop a completely challenge-based tissue biomechanics laboratory course at the junior level and discuss the results of two offerings of the course. Although WPI does not allow official prerequisites for any course, the recommended background for this challenge-based solid biomechanics course was statics and mechanics of materials (stress analysis). The 7-week course had two biomechanics challenges, each posed by an orthopedic surgeon. The first challenge concerned the inconsistent clinical results for thermal capsulorrhaphy. The second challenge focused on the development of an osteoporotic bone model. The thermal capsulorrhaphy challenge is provided below as an example.

Learning Objectives

- Design and execute experiments to characterize the mechanical properties of biological tissues (specifically tendon and bone).
- Fit experimental data to a mathematical model.

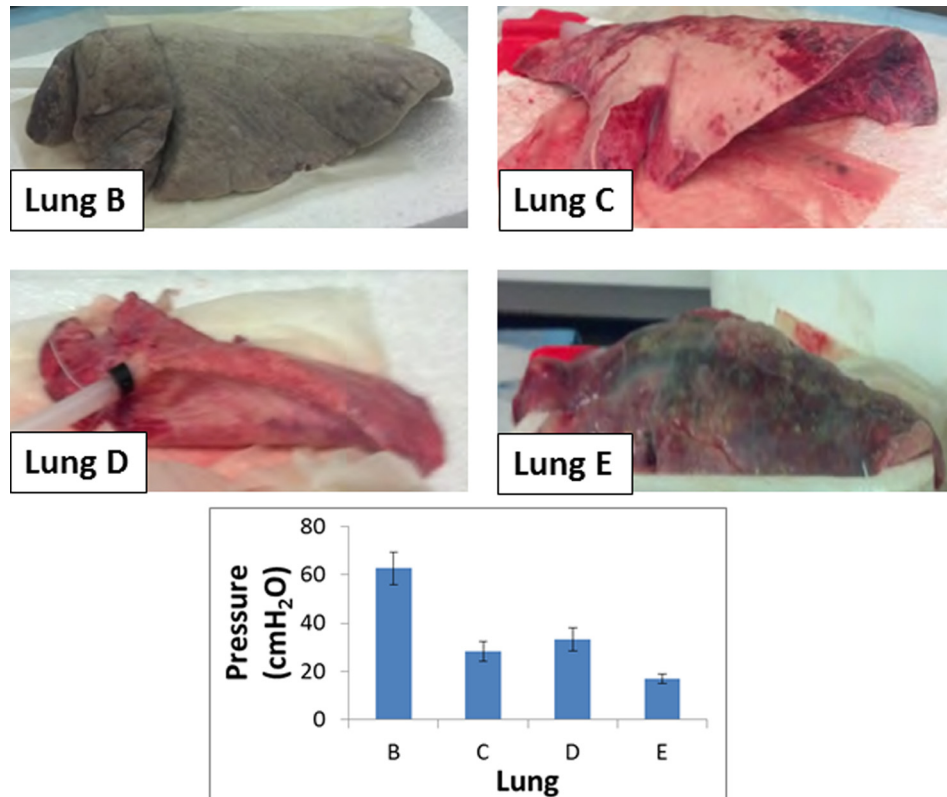


Fig. 2 Introductory biomechanical engineering course: Pig lung laboratory. Porcine lungs were treated to simulate human disease, where lung B was restricted (stiff, formaldehyde treatment), lung C was healthy (saline), lung D was obstructed (bronchial narrowing and obstruction), and lung E was obstructed (loss of alveolar structure, collagenase treatment). Students recorded the pressure required to inflate each lung to a given volume and used these data to determine which lung simulated which disease.

- Test hypotheses statistically.
- Identify a problem, communicate results and conclusions, and work effectively in teams.

Real-World Context. Heat-induced shrinkage of tendons has been used to treat joint instability; however, the long-term clinical results from this treatment have been inconsistent. Your challenge is to determine if heat treatment adversely affects the viscoelastic properties of tendons and comment on the clinical ramifications.

Problem Presentation. The students solved their challenge in a series of phases which paralleled the steps in the STAR.Legacy Cycle. In each phase, extensive feedback was provided by the instructor, mostly formative, but also summative, based on several individual and team-based assignments.

Phase 1: An orthopedic surgeon presented the challenge with background data, examples, and images from his/her clinical practice. The team then researched the problem in primary clinical and engineering literature and created a memo addressed to a job manager that summarized their approach to the challenge. The one-page memo included the problem statement, primary literature background, and proposed approach based on clear rationale (STAR.Legacy Cycle: The challenge and Generate ideas). Individual homework assessing soft tissue mechanics knowledge was also assigned.

Phase 2: Based on proposal feedback and preliminary tests on surrogate materials (e.g., leather or rope), the team submitted a detailed experimental design including an objective and rationale, materials and equipment, methods and assumptions, proposed analysis (mathematical and statistical), and example calculations with an order of magnitude estimation of results (STAR.Legacy Cycle: Multiple perspectives). Other teams provided peer

feedback regarding procedure completeness and clarity (i.e., Could they perform the test based on the written procedure?). Each individual student also completed a pilot test using a synthetic material and handed in the lab notebook write-up of the test data as a homework assignment.

Phase 3: The team then performed a sufficient number of replicate tests on the biological tissue model (e.g., pig tendon; controls and heat-treated) for statistical validity. A description of the entire project and these initial results were submitted as a one-page executive summary. If not successful in the first round of testing, the team provided a description of the shortcomings (e.g., slipping from grips, insufficient number of samples, and inadequate treatment) and detailed their new approach and modified test procedures with instructor feedback (STAR.Legacy Cycle: Research and revise and Test your mettle). Individual homework assessing ability to analyze instructor-generated test data in MATLAB was also assigned.

Phase 4: Additional tests and analyses were completed as necessary. Each team submitted their final results as an extended abstract including data, analysis, and conclusions (two-page IEEE format) and a 10-min poster presentation to their peers and departmental faculty (STAR.Legacy Cycle: Test your mettle and Go public).

Unlike the introductory course, in this completely problem-based laboratory course, no procedures were provided for the students. The student teams developed their own procedures based on primary literature, under the instructor's mentorship; for example, students were required to develop mechanical testing protocols, estimate material properties [22], and determine the thermal conductivity of various tissues [23]. To solve the challenges, students worked in teams of three to research the problem in medical and engineering literature and develop a hypothesis or model

Table 3 Example assessment guide for two-page summative abstract

Area	Expert level	Comments
Content and context: problem identification (1 pt)	Objectives, motivation, and relevance are clearly and persuasively established	
Content: approach (rationale) and methods (2 pts)	Translate challenge into problem that can be approached Background research into each area demonstrated Persuades reader to recognize the validity of a point of view Accurate and complete explanation of key concepts and theory Approach to problem based on literature and sound rationale Details of approach based on literature and sound rationale (do not need references this time)	
Content: data, analysis, and conclusions (3 pts)	Clear and concise description of analyzed data (parameter values) including statistics (mean, SD, CV%, p values, rms error, and R^2) Interpretation of the data (does it make sense in terms of general mechanical data and with respect to the literature) Comparison of data to the literature (are the values in the published range)	
Reader's needs/document flow (2 pts)	Abstract must be clear and concise and have quantitative values Organization effectively assists reader in understanding information Sufficient detail is to allow the reader to understand the content and make judgments about it Information presented clearly relates to the central report points The information is presented in a smooth-flowing and logical fashion	
Professional standards (2 pts)	Terms/jargon are properly defined when first used Sentences are complete, grammatical, and flow together easily Tone is objective with a full range of interpretation of results presented Others' opinions are referred to neutrally without attacking References in proper format (others' data should be cited!!)	
Questions	What would you ask the authors? Is there anything novel or outstanding that deserves mentioning? Are there any major problems you see that need addressing?	

system in theory. They then designed and completed experiments to test their hypotheses or validate their designs. Finally, they presented their findings to their peers both orally and in writing and compared their values to those in the literature. The majority of class time was used to discuss the assignments in various draft stages and to provide formative feedback. A few lectures were dedicated to theory (viscoelasticity, torsion, etc.). A peer writing tutor from the "Communication Across the Curriculum" program ran two in-class sessions to discuss well and poorly written model documents and provided feedback for the students on their proposals' style and organization.

Two further assignments were given to assess individual student progress and to assure that all the students understood how to use the equipment, run an experiment, and analyze and interpret data: (1) lab practicums in which each student set up and ran an experiment demonstrating knowledge of safety and testing techniques and (2) homework problems in which students were given mock data to analyze. Both were summative assessments of individual performance.

Problem Evaluation. Not surprisingly, the students were uncomfortable with the ambiguity associated with complex laboratory problems at first. As the term progressed, they became more confident in attacking the open-ended challenges, developing their own experimental designs, and communicating their ideas. The students thought that the homework assignments were helpful in clarifying how the theory could be used to analyze the experimental data. They did not, however, like the fast pace of the course and keeping track of drafts and assignment rewrites that were due almost every other day. Most of the teams worked well together, although mediation was needed in one case.

Although the course was "writing intensive" by the challenge-based nature of the course, the students appreciated learning how to write in a range of professional formats. As the students had limited experience with professional writing, a large amount of class time was used for providing models and formative feedback on various draft stages. In some cases, the students copied the

model document format too closely where it was not appropriate, and in the group assignments the level of written work generally represented the best writer in the group, thus obscuring assessment of individual progress.

The main reason for having two challenges was to assess how well students were able to progress in their ability to solve open-ended problems and to transfer their knowledge from one situation to another. Qualitatively, all the groups made substantial progress in the second challenge by proposing clearer experiments and more rational methods justification, as judged by formative assessments throughout the term. On the other hand, two full challenges proved to be too much work for a single 7-week term. It was not possible to complete the second challenge so only one or two samples were tested.

The grading was made as objective as possible by using a set of grading rubrics (based on Ref. [24]), which also served to clarify assignment requirements for the students. Assessment guides were also created (e.g., for the two-page abstract, see Table 3). The proposal grades improved significantly from 7.65 ± 1.50 for the first challenge to 8.63 ± 1.01 for the second challenge ($p < 0.02$, unpaired t -test). Furthermore, the experimental design scores increased from 7.71 ± 0.85 for the first challenge, to 9.01 ± 0.68 for the second challenge ($p < 0.001$, unpaired t -test). Unpaired tests were used since the team memberships were different for each challenge. Assignments with formative assessments could not be compared statistically.

Discussion

Problem-based instruction offers an effective means of facilitating learning by compelling students to solve authentic problems through a self-discovery process. In this paper, we present guidelines to creating effective PBL problems. We also provide two examples of PBL implementation in biomechanics courses to demonstrate how these PBL guidelines can be used in problem development, implementation, and evaluation.

Advantages of PBL. PBL develops some of the most important characteristics of college graduates, including the ability to define a problem, gather and evaluate information related to that problem, and develop solutions to address the problem; high-level communications, computational, technological, and informational abilities to gain and apply new knowledge; initiative, motivation, and persistence; the ability to work well with others, especially in a team setting; and the ability to use all of the above to address specific problems in complex, real-world settings [10]. PBL also emphasizes critical skills needed by biomechanical engineers in industry, specifically ABET a–k outcomes that are ranked most important by employers [11]. These include communicate effectively (g), engineering problem solving (e), apply math, science, and engineering (a), and teamwork (d). PBL also facilitates incorporation of active-learning techniques into the classroom, which have been shown to increase student performance, and helps students bring theory into practice and learn how to engage in life-long learning [13].

PBL has been demonstrated to have significant impacts on student learning and retention. In several reviews of PBL in medical education, students in PBL curricula found their programs to be more challenging, motivating, and enjoyable than conventional instruction. These reviews produced mixed results of student performance, showing that students in PBL curricula had less or equivalent factual knowledge with better or equivalent clinical performance [25–28]. A more recent meta-analysis that included studies beyond medical education showed mixed results in knowledge gained by students in PBL courses. However, students' ability to apply and retain knowledge was significantly enhanced [29]. When PBL outcomes were assessed relative to the knowledge structure level, with the understanding of concepts at the lowest level, understanding of principles linking concepts at the middle level, and linking of concepts and principles to application at the highest level, students in PBL courses performed better at the middle and highest knowledge structure levels [7].

In the VaNTH Center, an introductory biomechanics course was taught in both traditional and challenge-based instruction modes with as many variables as possible held constant between the two courses. Student performance was compared for specific knowledge-based final exam questions, and their perception of the course was assessed using surveys and questionnaires. Students in the challenge-based instruction class performed significantly better on the more difficult knowledge-based questions, whereas there was no significant difference on the less difficult knowledge-based questions. Course evaluations for a single instructor who taught both course formats showed that students enjoyed the challenge-based instruction class more and rated the instructor more highly when he taught in the challenge-based instruction mode [30].

PBL appears to be especially well suited for biomechanics and biomedical engineering laboratories in which quantitative measurements of complex and variable biological systems are required. In particular, the hands-on biomechanics laboratories provided an authentic context for students to attack their problems and an opportunity to observe how the physical world compares to the theoretical descriptions taught in the classroom. Biological test specimens and industry-standard test machines introduced students to the difficulty in sample preparation and gripping and the complexity of dealing with nonlinearity, nonhomogeneity, and variability inherent in biomechanical measurements. The variability of biological specimens naturally leads to the necessity of statistical treatment of the data for hypothesis testing (an additional ABET requirement).

In our PBL experience, students gained a real world, hands-on learning experience which helped them learn how to approach a problem and improved their ability to work in a team and communicate their goals, methods, data, and conclusions. Students in each of the described classes were able to successfully complete challenging biomechanics modules which required the highest levels of learning in Bloom's taxonomy (e.g., analysis, synthesis,

and evaluation). The students felt that the PBL approach exposed them to important knowledge, challenges, and methods associated with the rapidly changing field of biomechanics. Student evaluations consistently showed that the PBL-based courses were among the students' favorites in their undergraduate education. Faculty also enjoyed working with students to solve open-ended problems through the PBL course and appreciated adding the new technique to their teaching repertoire. A highlight for both students and faculty was the increased student–faculty interaction, which resulted in mentoring opportunities that might not have occurred in a traditional lecture-based course.

Challenges of PBL. PBL implementation is limited by challenges associated with the different teaching modalities. In PBL as in most active-learning techniques, the professor's job changes from delivering information (sage on the stage) to facilitating learning (guide on the side) [31]. This new role can be challenging for faculty who are accustomed to lecturing, since it requires a different set of skills. Faculty can address this challenge by gradually incorporating PBL into their classes to develop their skills and confidence. For example, a professor could begin by adding small group problem-solving sessions in the middle of lectures or could transform recitations into interactive PBL sessions while maintaining lectures during class time. The new role for the professor can also be challenging for students who are accustomed to having the professor provide the knowledge needed to solve the problems, which can result in poor teaching evaluations. The professor can address this challenge by reminding students of his/her changed role as well as assuring students that PBL is an effective learning technique. Department heads can also support faculty efforts to implement PBL by taking into account the new teaching method when evaluations are used in tenure and promotion decisions or in annual reviews. In our experience, we found that most students appreciate the PBL format as long as the professor is actively engaged during class and available for assistance outside of class.

PBL also can require more faculty time, especially in modifying an established course. Faculty spend additional time developing effective problems and helping students find necessary resources, although much *less time* is spent creating lecture materials. Since PBL problems should be created and evaluated prior to the start of the course, we recommend that faculty begin to develop problems several months in advance. In our experience, we find that the time is similar to that required to develop entirely new lectures. PBL assignments usually take more time to grade than homework problems or exams. Since the problems are designed to be ambiguous, grading fairly can be difficult but also more interesting and engaging. Rubrics and assessment guides are helpful tools to aid in grading open-ended assignments. In addition, in-class formative assessments can help students produce the expected quality of new types of deliverables (e.g., professional writing). For example, in-class peer review is a time-saving and effective process which provides formative feedback to students while also developing the students' skills in analyzing a document, identifying areas for improvement, and providing constructive suggestions [32]. Finally, the grading burden can be lessened by using online assessments wherever possible, for example, in assessing student preparedness for class through web-based content quizzes.

PBL-based courses usually take more time to cover technical material, and therefore, less content can be covered during the entire course. This can be challenging, especially in a course that is a prerequisite for a higher level course. Faculty can address this challenge by using a combination of PBL and lecture-based approaches. Concepts that require in-depth understanding may be best learned through PBL, whereas those that require only knowledge can be effectively learned in a lecture. Often there are inadequate resources to effectively implement PBL due to large classes, few teaching assistants, or teaching assistants who are not

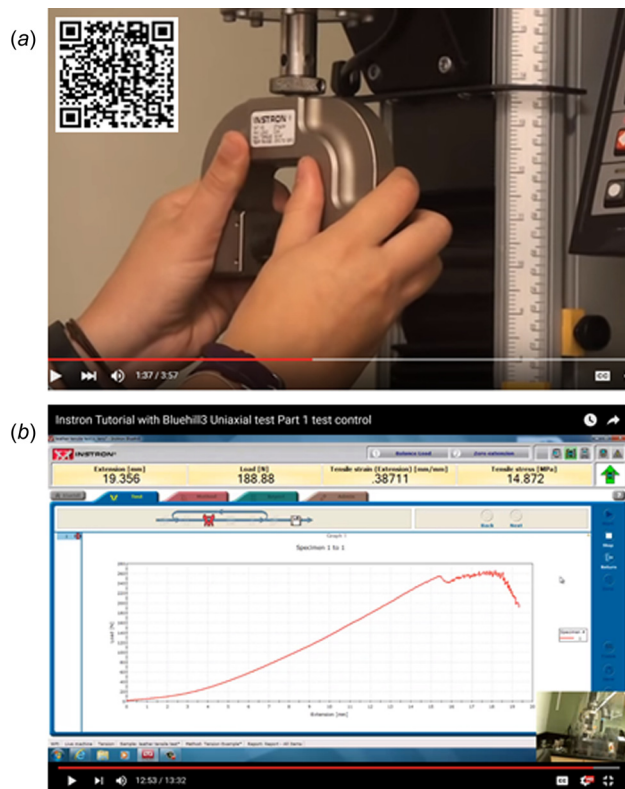


Fig. 3 Solid Biomechanics Laboratory: Online learning modules. (a) Video tutorials detailing how to use the equipment safely were provided via a YouTube channel. Inset: QR-code. These QR-codes that link to the videos were posted in the lab for quick smartphone access. (b) Video tutorials for using the software were also posted.

experienced in active-learning techniques. Colleges and departments can address these problems by designating specific courses or sections as problem-based, by providing graduate students with instruction in active-learning techniques (which also helps them when they seek academic positions), or by assigning the same teaching assistant to a class for multiple years.

Students also spend additional time determining what information they need, finding that information, and then completing the assignment. As shown previously [6], when students work in the laboratory in teams without the instructor present, they have to learn from their failures and re-engineer solutions for their setbacks. Yet, due to the time limitations within a single term, there may not be enough time to perform a full set of revised experiments. Both the Drexel and WPI courses were fast paced, with assignments due almost every other day. At WPI, learning to use the uniaxial test machine, writing the proposal, and completing the experimental design took a few weeks; thus, the bulk of the mechanical testing was completed in 1 week. The compressed timeframe made time scheduling on the single machine difficult. We suggest that instructors reduce the number of modules and increase time per module, or use a full semester or multiterm format where possible. Furthermore, teaching the students how to use the equipment well enough to perform the challenges required substantial resources. WPI previously developed web-based video tutorials to train the students to use complex (and potentially dangerous) industry-standard materials testing machines (Fig. 3; tutorials can be found on YouTube with search term “WPI Instron”) [33]. Since the instructor and teaching assistant were not required to train each student to use the equipment, students were able to work in lab without continuous oversight. Such tutorials, once they are created, can

decrease the time commitment required for both faculty and students.

Finally, both professors and students may have a fear of failure in PBL classes. Professors may fear that they will lose control of the class or have poor student evaluations. The potential for failure can have a significant impact on tenure and promotion and thereby make implementing PBL especially risky for junior faculty. We recommend that faculty implement PBL slowly to improve skills and confidence as well as discuss PBL implementation in a particular course with the department head before the course begins. Faculty can also provide students with formative feedback to assist them in successfully producing new types of deliverables. In addition, combining PBL assessments with traditional homework and exams will provide students with a variety of ways to demonstrate their understanding of the material. Faculty may also need to move beyond typical evaluations to assess student learning in a PBL course. Specifically, the impact of the course on student problem solving, cooperative learning, inquiry and independent thinking, as well as biomechanical engineering knowledge should be considered. This information can be gained through analysis of student products, structured pre/postcourse evaluations, student journals/logs/impression papers, and individual interviews or focus groups, if possible. For example, student journal entries can be rated from the lowest level of knowledge (telling) to the highest (transforming) to determine how students relate knowledge to new situations.

Universities can encourage faculty members to implement PBL by providing them with both support and incentives. Effective support measures include sponsoring workshops or peer-to-peer instruction in PBL and flipped classrooms, providing formative and summative assessment tools or external assessment expertise, increasing staff, teaching assistant, or grading assistance, and decreasing faculty workload (e.g., reduced service during the period prior to the PBL course). Effective incentives include increased teaching support, nominations for teaching awards, rewarding teaching innovation in tenure and promotion decisions as well as in annual reviews, and less reliance on student course evaluations, in particular, when a teaching technique is used for the first time. These efforts require leadership and commitment to high-quality undergraduate education by department chairs, deans, provosts, and even presidents.

Conclusions

In the authors' experience, the benefits of PBL far outweigh these challenges. PBL is an effective tool to integrate clinical and translational perspective into biomedical engineering courses. Faculty enjoy greater interaction and engagement with students and appreciate the variety in teaching and evaluation. Students are willing to commit the time and effort to learn material in a PBL course as long as the instructor is an active and helpful guide. Students enjoy the hands-on activities and feel that the PBL format better prepares them for an engineering career. Overall, while there are undoubtedly barriers for implementing PBL in biomechanics, the significant benefits for both students and professors justify increasing PBL implementation in biomedical engineering and biomechanics courses.

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