Engineering Methods in Biomechanics: A Contextual Learning Strategy for Biomedical Engineering Pedagogy

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Abstract

Undergraduates studying biomedical engineering can easily become overwhelmed by the science within their coursework and miss much of the engineering. To address this concern, an undergraduate course in biomechanics was developed consisting of six contextual learning modules (CLMs). Each CLM emphasized a different fundamental engineering concept or theme that included the following: safety, usability/functionality, buildability, optimization, adaptability, and reliability. All the biomechanical principles taught in a given CLM were focused on how those principles could be used to evaluate the given engineering concept in a biomechanical system. The class met twice a week for 80 min. per class, and each CLM was taught in four to five classes. In addition to assigned readings from their textbook (Fundamentals of Biomechanics, 2nd Edition, Springer-Verlag, 1999), students were assigned to do the relevant skill-based problem sets in the chapters, which were also supplemented with additional problems sets as needed. Each CLM concluded with a class period devoted to applying the newly taught skills to design a novel solution to a broadly-based biomechanics problem. The students were assigned to a design team, consisting of three to five individuals, and each team selected a problem from a list supplied by the instructor. The design teams worked in class to develop general solutions, which were presented orally during the later part of the class and were also critiqued by their classmates. After class, the teams worked on their own to develop specific quantitative solutions that were written up and handed in to be graded. Thus, the students were enabled to immediately use skills in biomechanics to address broad-ranging engineering questions.

I. Background and Introduction

Throughout the 1960's, a shift in engineering curricula took place that focused engineering education towards more analytical techniques[1]. With dramatic developments taking place in the basic sciences, opportunities to introduce synthesis skills were displaced by the need to introduce new developments in mathematics, chemistry, materials, and of course, computer science. This represented a transition to the era of engineering science, an era which produced fine analytical engineers, but engineers who were required to learn most, if not all, of their design skills after securing their first engineering position. By the 1980s, the effect of this policy was evident in a report on the status of engineering education worldwide, which noted the students' remarkable lack of curiosity about the physical meaning of the subjects they were studying[2].

Unfortunately, this extensive emphasis on analysis rather than synthesis has contributed in a substantial manner to the decline of engineering as a career objective for many bright young students who in the past would have entered this field. Even if students undertake an undergraduate degree program, many (perhaps most in the field of Biomedical Engineering) are never employed as practicing engineers. As a result, our profession is currently undergoing a careful examination of the way we train engineers. While there has been a conscientious effort to reintroduce design back into the curriculum, a piecemeal approach to restructuring engineering education may not be adequate. It is necessary to thoroughly review the experience we are providing at the undergraduate level to determine whether we are providing our students with the knowledge and skills necessary to succeed in the field of engineering, whether this be in business, government, industry, or in the entrepreneurial environment.

Though perhaps not explicitly, each of multiple curriculum redesign efforts has included an attempt to incorporate within engineering educational programs opportunities for the students to develop the three major knowledge processes. These include, as they are now referred to by educational researchers, the cognitive, perceptive, and pragmatic processes. The shift in science and engineering education over the last half of this century has been toward the cognitive, i.e. the analytical, linear, and rational skills, which are critical to defining a problem, gathering information and diagnosis. While technical skills are an absolute necessity in engineering, organization leaders have noted that engineering graduates lack breadth of vision, flexibility and a business orientation. These skills are not associated with cognitive processes, but with perceptive (i.e. intuition, insight, and enthusiasm, leading to the ability to generate solutions and make decisions), and pragmatic (i.e. experiential/ observational modes of thought which facilitate planning, implementation and evaluation) processes.

In order to develop a curriculum that achieves the goal of producing a graduate engineer with vision and flexibility, we must re-think the distribution of material presented in our engineering programs. Specifically, the curriculum questions which are most commonly asked include[3] : Is there too much emphasis on tools and techniques? Is there a lack of emphasis on communication skills, social sciences and humanities? Is there enough emphasis on systems and complexity? And, have we gone too far in specialization? In addition, we must think about how we are delivering this material to the students. Are the students getting enough hands-on experience? Are they learning in isolation or are they learning to work in teams? And most importantly, are we instilling the sense of creativity and innovation that will motivate them through their undergraduate years and through their careers?

Perhaps in no area of engineering are these questions more salient than in Bioengineering. As in all the branches of engineering, we as faculty feel we must provide our students with the standard core (math, chemistry, thermodynamics, fluids, electrical theory, mechanics) of engineering. But in addition, there is a clear need to introduce the fundamentals of biology and physiologic systems. Furthermore, as our students are entering a relatively nascent field, we sense a particular need to ensure these students exit from their years of formal training with a reasonable competency in the design process. In the more established fields of engineering, many, if not most, of these students will enter small companies or start-up firms that have little engineering infrastructure to nurture these new hires while they develop their skills in the art of synthesis.

It may not be realistic to expect any faculty to accomplish these goals within the confines of a traditional "content based" engineering curriculum, although to date, most Bioengineering programs have attempted to do so. As a result, most Bioengineering undergraduate programs consist of a standard engineering core with several specialty electives offered. A minimal exposure to the biological sciences is provided as well as few opportunities to elect vital social science or humanities electives that are needed to provide students with an understanding of the societal context into which their future work will fit. Most importantly, there is even less time available in the curriculum to develop the critical synthesis skills than there is in any of the traditional engineering majors. This is not an optimum state of affairs if Bioengineers are to make the significant contributions expected of them in the field of health care[4], and just as importantly, the new and rapidly developing field of "sustainable engineering", which will rely heavily on biomimicry and therefore the expertise of bioengineers[5].

A thorough job of educating the Bioengineer can be accomplished in the usual four-year time frame of a Bachelor’s degree program, but the pedagogic approach may need to be fundamentally altered to place greater emphasis on both design, synthesis, and implementation (i.e., perceptive and pragmatic) skills. At Stony Brook, the undergraduate Bioengineering program was formed (formally in the Fall of 1997) primarily to provide an alternative track for Life Science majors. The design and problem solving concepts, which are fundamental to engineering, are not typically introduced to science students, yet scientists are moving ever closer to the process of technology development. This is evident in gene engineering, tissue engineering, biosensor development, drug delivery systems, and the development of cell systems for the production of biologicals. These are all areas where individuals with their primary training in the sciences are on the cutting edge of product development. These areas, therefore, serve as excellent contexts to introduce the basics of the physical sciences, as well as engineering design and analysis concepts to Life Sciences students. It has become clear to us over the past year that a similar Context Based Learning approach should be equally effective in a curriculum for Bioengineering majors as well.

In Contextual Based Learning, the fundamental biology and physiology required of Bioengineers can be introduced to the students in the context of design problems, the solution of which requires an understanding of specific engineering concepts. In such a modular learning environment, an integrated understanding of the science, along with the analytic skills and how they are utilized to solve design problems, are presented in a coherent context, providing the students with incentive to learn material which in a traditional content based approach may appear arbitrary and dull. Importantly, the fundamental engineering knowledge can be introduced over an extended period of time (multiple learning modules) rather than being blocked into arbitrary time frames (e.g. the introduction of all of fluid dynamics concepts in a one semester course). Through this repeated exposure, we believe that students will retain more of the information than they do in traditional courses. Furthermore, the emphasis on student acquisition of knowledge will teach students how to learn, an activity in which they will be engaged throughout their careers. Students should be working in teams on design projects throughout their college years. We incorporate, for example, the ideas of Eric Mazur's Peer instruction, an approach initially developed to teach physics in an interactive fashion, concentrating on an understanding of physical concepts rather than rote memorization of formulae[6]. Repeated opportunities must be given to students to do "back of the envelope" calculations and to learn to use basic principles to derive new concepts rather than to simply master a body of existing knowledge.

II. Contextual Learning Modules as a Pedagogical Approach to Teaching Engineering Themes in Undergraduate Biomechanics

We have previously reported on our approach at Stony Book to develop contextual learning modules (CLMs) as a general approach to teaching bioengineering[7]. Here, we further show the development of this approach by teaching broad engineering themes in an undergraduate course in biomechanics. In particular, we incorporated within different CLMs the following themes: safety, usability, buildability, optimization, adaptability, and reliability. Each CLM was presented over three to five class periods (80 minutes each, twice weekly) depending on the amount and complexity of the material, and concluded with an additional class period devoted to solving a design challenge ("Design Day"). One of our goals was to attempt to push the students to apply their newly acquired and developed knowledge in ways they were not necessarily obvious to the students at first glance. Specifically, we wanted them to use their skills on problems that they had not seen before from class or their textbook.

On Design Day, the class was broken up into different design teams, consisting of three to five members. A list of design challenges was presented to them and as a team they were required to choose one of the challenges not chosen by another team. Hence, making a decision quickly about what challenge they wanted to undertake meant it was more likely that they could in fact work on the one chosen. Each team then spent the next ~50 minutes in class discussing various approaches to solving the challenge, and if they concurred on a specific approach, general strategies that should lead them to a solution. During the last 15 minutes of class, the instructor selected two teams to orally present their solution approaches and the class would critique their proposed solutions. The teams met on their own after class to do further research, work up quantitative analysis, and design a final solution. A detailed written report was handed in to be graded, and the teams were given the option to submit a group consensus report or individual reports. An example of a list of design challenges is presented in section III of this paper.

For each CLM, a portion of, or the entire first class period was spent exploring the general theme by an interactive discussion with the class on their intuitive understanding of it. That is, we wished to develop and explore the students' intuitive understanding of a theme (e.g., safety). This was always followed by a development of how could we *quantify* some way of measuring this. And, this always led to the development of a particular context. The following is a general outline of how this interactive class discussion was directed for the Safety CLM, which led us to the engineering tool of Free Body Diagrams:

<u>Interactive Class Discussion on **Safety**</u>

What is **Safety**?

Consider the concept of safety. What does it mean to you?

We usually define it as the condition of feeling safe from injury, harm or loss.

> Do you feel safe in this classroom?
> Walking across campus in the day?
> Walking across the campus at night?
> Driving to Stony Brook after visiting home?

Why do you think you are or are not safe in these situations?

Can you quantify the level of safety in each of these situations?

Now let's take a more biomechanically relevant example.

> Do you feel you could safely stand up without breaking your leg?
> Could you walk across the room without breaking your leg?
> Could you jump off your chair without breaking your leg?
> The desk top?
> The filing cabinet?
> From a height equal to the height of the ceiling?
> From the roof of your house (assuming two stories) about 20 feet (6 meters)?
> From a three story roof (30 feet - 9 meters)?
> Four stories - 40 feet?
> Five stories - 50 feet?

Try to construct a table of safety jumping on a scale of jump height.

What about for different animals? Is there a difference in safety for jumping height between an elephant (5000 Kg) and a mouse (0.1 Kg)? Interactively (i.e., with student input) construct a table such as the following:

Animal Mass (Kg)	Safe Distance to Fall (animal height)
>100 (10^2)	< 1
10^2 - 10^{-1}	~2
10^{-1} - 10^{-4}	any height
< 10^{-4}	may go up depending on air currents!

Now, why is this so? "A few years ago, at the instigation of my skeptical colleague, Knut Schmidt-Nielsen, I dropped two adult mice from the roof of a five-story building onto pavement. Not only were they uninjured (briefly stunned, though), but they adopted a spread-eagle, parachute-like posture and fell stably. It certainly looked as if the neural circuitry of these small rodents was arranged to deal with the circumstance." (Vogel, *Life's Devices*, 1988, page 6.) How can we quantitatively determine why this is so?

To assist us, let's utilize a tool of engineering (and physics) the <u>**Free Body Diagram**</u>.

After establishing a context for the students' need to know about free body diagrams, the goal of quantifying safety could be achieved. We then proceeded to develop the specific equations that would enable them to answer the mouse puzzle. The following is a synopsis of the learning outcomes, skills, and homeworks that comprised the CLM on safety:

Learning Outcomes
- Understand that Safety is a critical design goal.
- Be able to quantify Safety using *Force* and *Moment*:
- Be capable of developing relationships between Safety and Force &/or Moment
- Be able to describe how safety can be quantified using scaling relationships.
- Be capable of identifying the safety issues in designs, both natural and man-made.

Skills
- Vector math
- Problem formulation
- Performance measures

Homework Assignments
- Identify safety issues in biological systems
- Identify simple scaling relationships in biological systems
- Quantify static forces, develop simple scaling relationships using 2-D free body diagrams
- Answer specific problems in textbook

III. Example Design Challenges for the Adaptability/Testing CLM

Testing a design is at the heart of engineering. That is, we want to know ***quantitatively*** how a particular design will function so that we can compare it to other designs. Nature performs an analogous process in *evolution* as species that don't survive have failed the ultimate test. However, in engineering, we can test a design so that hopefully our own species doesn't have to fail. In each of the design challenges below, you should qualitatively and ***quantitatively*** describe how you would test the design, and how you would change the design based on reasonable different outcomes that you would measure from your testing. As appropriate, you should compare and contrast designs by describing the engineering tradeoffs in the particular design. Describe the specifications. Be certain to explicitly describe the relevant engineering concepts (e.g., safety, reliability, functionality, buildability, etc.) and how they are being tested, and how the information from those tests would explicitly be used to change the design. ***BE QUANTITATIVE!!!!!!***

As always, you may use any and all resources available to you. Prepare an oral presentation of **5 min. duration** to be delivered towards the end of today's class. The oral presentation should concisely describe the problem, main issues, and your solutions. A written (typed) report with sufficient detail is to be handed in by the next class period. The report can be a consensus report and everyone in the group will receive the same grade, or your group may submit individual reports that will be individually graded. The title of your written report should indicate whether it is a consensus or individual report, and if a consensus report, a list of people forming the consensus. (Note: to be part of a consensus group, you must make a *substantial contribution* to the group.)

Select one of the following design challenges not selected by the other design teams.

1) Your company has just developed the ability to bioengineer finger joint replacements suitable for transplantation in people having one or more damaged joints due to trauma or disease. You are responsible for all testing that must be done to meet FDA approval and assure a "quality" product. Describe the tests, show examples of the data that would be acquired, how you would interpret it, and how you might change the product accordingly.

2) Your company has been hired to bioengineer a new drought-resistant variety of corn that could potentially save millions of lives in sub-Saharan Africa. Describe the biomechanical tests that you would recommend to

determine if this new corn plant could meet the required specifications. Show representative data from these tests, how you would interpret the data, and how you might change the product accordingly.

3) Your company has just developed a new synthetic skin (i.e., it is a tissue-engineered product) that is immunologically neutral (i.e., it won't be rejected by the recipients). This product is much less expensive that currently available commercial synthetic skins, and so, could be used in poor countries where burn injuries cost hundred's of thousands of lives each year. What testing must be done, and how will you do it? Show representative data from these tests, how you would interpret the data, and how you might change the product accordingly.

4) Your professor has been attempting to convince you this semester that nature changes biomechanical designs by minimizing stress concentrations. Develop a hypothesis using that concept to explain the location of the eyes in fishes (e.g., salmon). Describe how you would test the hypothesis; show representative data, how you would interpret the data, and how you would arrive at a conclusion regarding the hypothesis.

5) A raging controversy in paleontology has been whether certain species of quadruped dinosaurs could rise up on their hindlimbs for a variety of behaviors ranging from foraging and mating to fighting. Your firm, Biomechanists'R'Us, has been hired to test if this was possible. A complete set of dinosaur bones is presented to you. Describe the tests you would perform, show representative data, how you would interpret the data, and how you would arrive at a conclusion regarding the hypothesis.

6) Your firm is competing for a lucrative contract from the U.S. Government to design a new boot that will eventually be used all combat troops (men and women). Describe your design, what tests you would perform, show representative data from these tests, how you would interpret the data, and how you might change the product accordingly.

7) Pedro Martinez, the ace Boston Red Socks pitcher and two time Cy Young Award winner, has developed pain in his pitching shoulder, which if unresolved would end his $10M year career. His physicians have concluded that the problem is not due to any pathology, infection, or disease per se, but believe that it is a biomechanics problem due to a subtle alteration in his pitching style. Your firm has been hired as consultants to tell the Red Socks what they must do to get Pedro back on the mound so that they can break the dreaded "Curse of the Bambino" and finally win a world series. Describe the tests you would perform, show representative data from these tests, how you would interpret the data, and what recommendations would you make to Pedro and the Red Socks (retirement is not an option!).

IV. Conclusions

Our pedagogical experiences and critiques from the students allow us to continue to evolve the specific information and the sequences in which we deliver the course content. While this approach is still relatively new at Stony Brook, the students report that they are particularly enthusiastic about the immediacy of applying their knowledge in the design challenges. Indeed, their enthusiasm is quite evident during the class periods that are devoted to team-based solving (i.e., Design Days). Our challenge as we work to improve the course is to make sure we incorporate rigor and depth while maintaining contextual intuitiveness that facilitates overall design understanding.

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