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Structured, Active, In-Class Learning: Connecting the Physical to the Mathematical in an Introductory Biomechanics Course (Work in Progress)

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Introduction

Introduction to Biomechanics is a required sophomore course in the Bioengineering curriculum at the University of Pennsylvania focusing on the application of statics and mechanics to biologic systems. To be successful, students must have an understanding of both mathematical and applicable physical/biologic constraints. While mechanics of materials is traditionally taught from an instructor-led, problem solving approach, a complete understanding of the material covered in a biomechanics course should also include a conceptual component which is constrained by the physical world and human biology. Over the past three years of this Introduction to Biomechanics course, it has been observed that students excel at problem solving when the problem resembles an example they have encountered before, but often struggle adapting their problem-solving process when presented with a novel or more complex scenario. Additionally, students struggle to explain the physical meaning of the mathematical formula and have difficulty approximating solutions within the physical bounds.

Previous studies have demonstrated that student-centered, active, inductive learning activities can enhance problem-solving abilities, improve academic achievement and create more positive attitudes toward learning.[1-3] There is particular interest in incorporating active learning principles into this course because of the dual need to understand both physical concepts and complex mathematics. Historically, the course met twice a week for passive, instructor-led lectures with weekly, small-group, TA-supervised problem solving recitations. Given the previously mentioned student challenges, the course with an enrollment of 58 students was redesigned for the Fall 2014 semester to incorporate active learning principles, with an emphasis on problem scaffolding and connecting mathematical concepts to physical reality. This paper presents a *work in progress* of the modified course. The course was developed with the following goals which were hypothesized to produce better outcomes using a structured active learning environment.

1. Students should develop a problem-solving framework flexible enough to accommodate new problems and deviations from examples, while still understanding the concepts well enough to effectively communicate their thought process, including explicitly stating the limitations associated with their answers and communicating these assumptions verbally and numerically.
2. Students should gain physical insight into the mathematical equations and develop a contextual instinct for the solution (e.g., magnitude of an answer, tension or compression)

Specifically, we utilized in-class, collaborative group problem solving activities, hands-on, guided “discovery labs” and an instant feedback clicker system.

Background

Structured, active, in-class learning (SAIL) is a term used to describe classroom education with an emphasis on learning-by-doing.[2] Class time is built around a variety of activities with clear educational goals meant to engage students in the learning process. These may include group problem solving, interpreting data or evidence, or engaging in practices of the field, such as justifying simplifications or estimating magnitude of an answer.

One specific type of SAIL activity is small-group, in-class solving of a problem based on real-world applications. Students work in small groups to accomplish a common learning goal and are encouraged to use the problem solving process of experienced decision makers: define the situation, state the goal, generate ideas, prepare a plan, take action and check to see if the goal was achieved.[4] This type of collaborative learning activity has been shown to positively engage students in the classroom and emphasize the process of solving a problem, not just the end-goal of obtaining a solution.[2,5,6] Even though the work is done in groups, individual performance, attitudes and retention have all been shown to increase with collaborative instructional methods.[3,7,8] This technique also provides a support system for struggling students and develops collaborative teamwork skills necessary for success in the engineering field.[5,6]

Another type of SAIL activity is guided, discovery based learning. Students are encouraged to interact with objects, notice patterns and ultimately discover information within the provided materials, but without explicit, instructor-led instruction.[9,10] Debate continues as to the limitations of unassisted discovery based learning; however, guided or enhanced discovery has been shown to lead to greater learning than explicit instruction.[9] Cooperative, hands-on activities designed to serve as "discovery labs" can be used as a means to lead students from a physical description of mechanics to a mathematical description. These kinesthetic/tactile activities can be directly connected to deeper thinking about the *how* and *why* of the results.[11,12] This type of activity reflects a fundamental aspect of the engineering modeling process where an engineer observes a physical phenomenon, e.g. mechanical behavior of a material, and develops ways to quantify the behavior to use in a predictive manner in the future.

The scope of this paper focuses on the development, implementation and planned assessment of SAIL techniques in a Biomechanics course to address our goals and is a *work in progress*. We dedicated 50% of class time to group problem solving sessions and physical, hands-on activities, and 50% to lectures supplemented with discussion and short feedback questions.

Implementation

To improve students' problem solving abilities, the class was divided into groups of three with each member assigned a specific role (Appendix A). Both groups and roles rotated throughout the semester. For the group problem solving sessions, a biologically motivated mechanics problem with a design and/or estimation component was distributed to each group. The fundamental mechanics concepts needed to solve the problem were presented in class in the preceding lectures and now students were asked to analyze the problem within the context of the information they had already learned. A problem-solving outline was also provided and began with an estimation of the expected answer and/or a question about simplifying the given information into a solvable statics or mechanics problem to reinforce the course goals. Additional steps required groups to express their equations symbolically before plugging in numbers, identify assumptions and limitations of their methods, and evaluate the practicality of their final answer. Outlines contained more detailed guidance in the beginning of the semester (see Appendix B) and became less detailed as the semester progressed. Students were encouraged to discuss and develop conclusions together and to ensure all members of the group were confident in the steps before moving forward. During the problem solving sessions, two faculty members and two graduate TAs circulated throughout the room to help answer questions. To aid in gauging class progress, groups had access to a flag system (e.g. green, yellow and red flags in a block on the table). This method helped identify if there was a particularly difficult step which the class as a whole needed to regroup and clarify or if students were progressing rapidly through the material and future problems should be made more challenging. Solutions to the problems were posted online after class, and assignments were graded with emphasis on the problem solving process instead of the final answer.

Hands-on activities introduced concepts that the students had not previously studied. Rather than presenting the mathematical derivation as the introduction to a topic, students were again divided into groups and given materials and actions to impose on these materials, e.g. loading in bending. A provided outline for these “discovery labs” aimed to help the students to first observe and describe a physical phenomenon and then describe it mathematically. For example, this past semester we had students build different types of supports out of wood, screws and string to represent different joints in the body, i.e. the elbow as a hinge between two pieces of wood. They were then asked how these joints resisted translational and rotational motion – the physical corollary to reactions in mechanics. Other hands-on activities included deriving the quantities of stress and strain using elastic and a spring scale (see Appendix C), observing shear strains under torsional loading in a foam pool noodle and exploring beam bending with a piece of Neoprene.

In order to transition these activities into the course, some of the traditional lecture material was moved outside of class time. Three video lectures were created to follow some of the hands-on activities for online, post-class viewing. These lectures were limited to a maximum of 15 minutes and focused on connecting the hands-on activity performed by the students to the mathematical description of the phenomena. In order to encourage students to take an active role in their own learning and to ensure students were participating in the out-of-class material, we also instituted short, online comprehension quizzes to be completed after viewing the videos for a minimal portion of the final grade. Material that had previously been identified as problematic for introductory students remained in lecture format punctuated by interactive questions. To engage the class, Learning Catalytics, an instant feedback system where answers are recorded using a student's laptop, tablet or smartphone, was utilized. Questions ranged from stating a basic concept to computing a mathematical answer for a simplified problem.

Assessment

Three exams were administered during the semester and incorporated "big-picture" concept questions in addition to traditional, numerical mechanics problems. Throughout the semester, instant feedback "clicker questions" in multiple choice or short answer format were utilized to review material, assess student understanding and prepare for the concept questions on the exams. Because exam solutions are released each year, matched exam questions with previous, non-SAIL formatted years are not feasible. However, the topic(s) and goal for each problem along with the average problem score will be tabulated and compared across years to identify if any patterns exist.

A variety of non-exam assessments were also administered in collaboration with the University's Center for Teaching and Learning. A concept inventory quiz was administered at the beginning and end of the semester based on previously published question inventories.[13,14] The questions included concepts that should have been recalled from prerequisite courses as well as material that would be learned throughout the course of the semester. These same concept inventories were administered the year before in the non-SAIL formatted course and will be compared to the SAIL formatted course. The concept inventories will be evaluated for increases in new knowledge (beginning to end of the semester) but also for trends in solidifying fundamental physics concepts that may have been forgotten coming into the semester.

Additional evaluation will be conducted using a pre-, mid- and post-semester survey distributed using the online survey system Qualtrics. Once compiled, this software will allow for correlation between student comments, ratings, confidence in their abilities, preparation for class and global trends associated with final grades in the course blinded to the instructors. The survey will also evaluate if previous exposure to a SAIL formatted course influences student expectations. Since SAIL freshman course offerings are becoming more common at our University, we plan on continuing to evaluate the results in the years ahead.

Summary

Moving forward, the assessment data associated with the Fall 2014 semester will be analyzed and faculty impressions recorded before deciding which aspects of the course were most successful. Preliminary qualitative feedback suggests that while students were initially wary of the new format, as the course progressed they found the activities beneficial. Students often reflected on how much they liked the support of their peers in group sessions and how it was encouraging to know that there were others struggling with difficult concepts. Initial faculty impressions are that the SAIL activities deepened student understanding and while there is always room for improvement, the general concepts will be reused in future iterations of the course.

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Appendix A: Group Member Roles

Manager	Recorder/Checker	Skeptic
• Directs the sequence of steps in the problem • Manages time • Reinforces the merits of everyone's ideas • Ensures that each group member participates Sounds like: "Does anyone have an idea what approach we could take for this problem?" "We have to move on. If we have time, we'll come back to this discussion later." "That's an interesting idea. Does anyone else have a suggestion before we evaluate it?"	• Writes actual steps on the paper you will turn in • Checks for understanding of all group members • Makes sure all group members agree on each step of the problem Sounds like: "Do we agree that this drawing is accurate?" "Before I go on, do we all understand what is written so far?" "I'm hearing more than one idea. I'm not sure what to write. Can we agree on how to proceed?"	• Makes sure all possible problem-solving strategies are explored • Suggests alternative approaches or concerns with suggested processes • Provides reasoning and explanations of steps to group members as necessary. Sounds like: "Can we visualize this problem differently?" "Does anyone want me to explain what's helpful about this diagram?" "It feels like we're spinning our wheels. Let's take another look at this previous step."

Appendix B: Sample Group Problem and Provided Outline: Higher level of detail as presented in the beginning of the semester

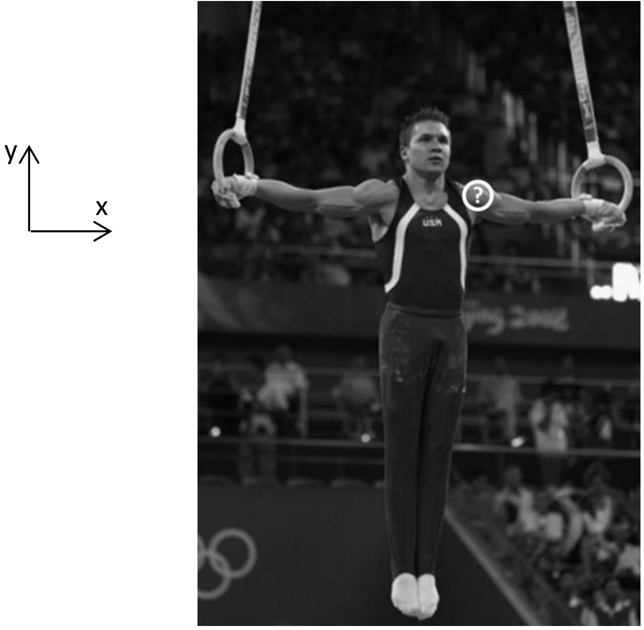
	Name (printed)	Name (signed)
Manager:	________________________	________________________
Recorder/Checker:	________________________	________________________
Skeptic:	________________________	________________________

IN-CLASS GROUP PROBLEMS: MUSCULOSKELETAL ANATOMY AND STATICS

To be completed during class. Please pay particular attention to the recommended times for each section and contact an instructor if your group is significantly surpassing these time recommendations.

Iron Cross Shoulder Model (read and discuss problem statement, 5 minutes)

Jonathan Horton was a member of the 2008 Olympics USA gymnastics team. Jon earned a silver medal on high bar and the team earned bronze overall. This image shows Jon performing the infamous "iron cross" skill on the rings. The goal of this skill is to stay as steady as possible; it requires tremendous upper body strength, particularly in the shoulders. Like most gymnasts, Jon has a small frame (5'1", 126 lbs).



Question you are trying to answer:

1. Considering a <u>2D</u> scenario, simplify the complex anatomy of the left arm and model the equilibrium scenario shown above. Calculate all loads acting on the arm. Use the provided anthropometry figures to estimate measurements necessary for your calculations.
2. Discuss and record what anatomy was neglected and what needed to be included to maintain equilibrium.

I. Estimate (5 minutes)
Does your shoulder joint resist translational motion in the xy plane? Does it resist rotational motion within the xy plane (be clear which axis this is about)? Record your observations. What reactions will be involved at the shoulder?

II. Focus the Problem (5 minutes)
Draw all appropriate FBD(s) to determine all loads acting on the arm.

- Don't even look at the anthropometry data yet, just label the distances as variables and assume you'll be able to find them.
- (Hint: what FBD must you draw before drawing the FBD of the shoulder?)

Outline the approach to be taken. Be specific.

III. Describe the Mechanics (15 minutes)
Identify and record the knowns and unknowns.
State which mechanics principles/equations you can use. How many equations is this?
Specifically consider rotational equilibrium, $\sum M = 0$

- With your current FBD of the arm, will it be satisfied? Justify.
- If you answered yes, discuss with your group conceptually what is physically maintaining equilibrium when you sum moments at the shoulder. Record your answer.
- If you answered no, discuss with your group what you need to add to your model. Be specific (with words) if you are modeling an applied moment (something created by a force on your FBD) or a reaction moment (resistance to rotation provided by a support). Record your answer. Include your conclusions on your FBD.

IV. Do the Math (10 minutes)
Translate your mechanics descriptions into equations with variables.
Combine these equations to get the equation(s) for your target variable(s) (don't substitute in your numbers yet!).

V. Put in the Numbers (15 minutes)
Put real numbers into your equations and determine numerical values.

VI. Evaluate the Answer (10 minutes)
Are the units correct?
Is the answer unreasonable? Justify.

VII. Answer the Questions (10 minutes)

1. Considering a 2D scenario, simplify the complex anatomy of the left arm and model the equilibrium scenario shown above. Calculate all loads acting on the arm.
   - Double check that your work above answers these questions.
2. Discuss what anatomy was neglected and what needed to be included to maintain equilibrium.
   - Double check that these assumptions have been appropriately discussed above or restate here as needed.
   - Use your own arm and knowledge of arm anatomy to discuss what may have been neglected.

Appendix C: Sample Hands-On Discovery Lab: Students were provided with elastic measuring 5, 10, 15 and 20 cm in length each with a safety pin through each end as well as three pieces 10cm long pinned together at their ends.

	Name (printed)	Name (signed)
Manager:	______________________	______________________
Recorder/Checker:	______________________	______________________
Skeptic:	______________________	______________________

HANDS-ON ACTIVITY: STRESS-STRAIN

Goals

1) Understand why stress and strain are important engineering calculations
2) Deduce the strain equation
3) Deduce the stress equation

Materials

Elastic	Ruler
Spring scale	Safety pins

Background

- So far, we have been doing rigid body mechanics; however, we know that in reality, all materials undergo some finite amount of deformation when loaded. Now, we will learn about deformable bodies and mechanics of materials.
- The length of an unloaded material is known as the original or "gauge" length, L_o. Your gauge length is between the applied loads exerted by the safety pins.
- The term "load" can mean an applied force or moment. If you are talking about deformation along an axis, the "load" is a force.
- Reminder: To reduce error, repeated measurements are needed

At the end of this hands-on activity, you should be able to 1) understand how material geometry may play an important role in mechanics and 2) write the equations for stress and strain.

PART 1: STRAIN (30 minutes allotted)

"Strain" is an engineering term used to describe how much a material deforms. Using the materials in front of you, explore how the length of the material influences the amount of axial deformation when a load is applied. You will develop a relationship between length and deformation.

1. In front of you, you will find 4 pieces of elastic cut to different gauge lengths. Apply **2N** of load to each piece of elastic and measure the corresponding deformation. The length of the material should be measured from the pins. Record your findings in a table. Note any sources of error in your measurements.

2. Using the provided graph paper or your computer, create a graph that demonstrates the relationship between the deformation of the elastic (change in length, ΔL, y-axis) and the gauge length (L_o, x-axis). Determine the linear relationship.
3. **Fact: All of these materials underwent the same amount of strain. The symbol for strain is ε.** Using your graph, discuss what this must mean and use your observations to write the equation for strain in terms of ΔL and L_o. How much strain did your specimens undergo?
4. What are the units of strain?
5. For the same strain as this experiment, use your equation to predict the axial deformation of a piece of elastic that is the length around the equator of the earth (40075 km). What is the total length of the stretched elastic?

Record answers to all the above questions to turn in. Raise your green flag when you are finished and begin Part 2. When the entire class has completed Part 1, we will momentarily pause to discuss your results as a class.

PART 2: STRESS (20 minutes allotted)

"Stress" is an engineering term used to describe the load a material experiences when it is deformed. Using the materials in front of you, you will explore how the cross-sectional area of the material influences the amount of load that can be applied to achieve the same deformation. You will develop a relationship between area and load.

1. In front of you, you will find 3 pieces of elastic that are the same gauge length safety-pinned together. What is the cross-sectional area of your material? Given the small thickness of your elastic and the limited resolution of your ruler, what can you do to increase the thickness dimension to reduce error in your measurement? Determine the amount of load required to deform the material by 1 cm. Record your findings in a table. Note any sources of error in your measurements.
2. Now, **without changing the gauge length of the material**, remove one piece of elastic. What is the new cross-sectional area of your material? Determine the amount of load required to deform the material by 1 cm. Add your findings to your table.
3. Finally, repeat the above steps with a single piece of elastic. What is the cross-sectional area? What is the load required to deform the material by 1 cm? Add your findings to your table.
4. Using the provided graph paper or your computer, create a graph that demonstrates the relationship between the cross-sectional area of the elastic (x-axis) and the load required to achieve the same change in length (y-axis). Determine the linear relationship.
5. **Fact: All of these samples experienced the same amount of stress. The symbol for stress is σ.** Using your graph, discuss what this must mean and use your observations to write the equation for stress. How much stress did your specimens experience?
6. What are the units of stress?

7. Using your equation, predict the load required to deform 1 cm a piece of elastic the same length as you tested in this section of the assignment with the same cross-sectional area as the earth (~1.275 x 10^{14} m^2).

Please put all supplies back in the bag. Record answers to all the above questions to turn in. Raise your green flag when you are finished and begin Part 3.

PART 3: SUMMARY QUESTIONS (15 minutes allotted)

1. In part 2, were your 3 samples experiencing the same amount of strain? Explain.
2. In part 1, were your 4 samples experiencing the same amount of stress? Explain.
3. You know from experience and physics that load and deformation are related, often linearly as in the case of a linear spring. The term relating force and deformation is called stiffness, k. Recall Hooke's Law: $F = k * \Delta L$. A similar relationship between stress and strain exists, and when linear, is called the Modulus of Elasticity, E. $\sigma = E * \varepsilon$.
    a. Consider a piece of steel and a piece of elastic with **the same amount of load** applied to each. Using what you know about the difference between steel and elastic, describe in relative terms (not numbers) what the **geometry** of these two materials must be to experience the **same amount of strain under the same amount of load**.
    b. Describe the relative **geometry** of the two materials when they experience the **same amount of stress** as they are undergoing the **same amount of deformation**.
4. Explain why stress and strain are important engineering concepts in addition to load and deformation. To aid in your discussion, consider describing to a fellow engineer the failure stress, failure strain, failure load and failure deformation of a specific piece of hair (geometry known) versus hair in general.

Record answers to all the above questions to turn in.