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Group Problem Solving Coupled with Hands-on Activities: Conceptual Gains and Student Confidence in an Introductory Biomechanics Course

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Introduction

Introduction to Biomechanics is a required sophomore-level course focusing on the application of statics and mechanics to biologic tissue at the University of Pennsylvania. To succeed, students must have an understanding of both mathematical and applicable physical/biologic constraints. While statics and 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. In past course offerings, it has been noted 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 derivations presented in class and in the textbook, which often leads to solutions without physical context.

Previous studies have demonstrated that well-planned, student-centered, active, learning modules can enhance problem-solving abilities, improve academic achievement and create more positive attitudes toward learning.[1-3] Many of these studies have focused on activities such as group problem solving, interpreting data or evidence, or engaging in practices of the field. Traditionally topics in a mechanics/biomechanics course are introduced using derivations with subsequent assignments using the results of these often non-intuitive mathematical procedures. However, few studies have looked at the use of hands-on activities to replace or supplement mathematical derivations in an effort to connect physical concepts with mathematical equations. Therefore this course was modified in 2014 from its original lecture-centered format to include group problem solving coupled with kinesthetic, hands-on, discovery based activities. This unique combination of active learning principles was hypothesized to increase conceptual understanding and student confidence in their biomechanics and problem solving skills.

Background

Structured, active, in-class learning (SAIL) is a term used to describe classroom education with an emphasis on learning-by-doing. Class time is built around a variety of student-centered activities with clear educational goals meant to engage students in the learning process. Activities are often performed in groups further enhancing the learning environment by providing opportunities for peer instruction.

One specific type of SAIL activity is in-class problem 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.[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 the "correct" answer.[2,5-7] Even when the work is done in groups, individual performance, attitudes and retention have been shown to increase with collaborative instructional methods.[3,8,9] 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 with a kinesthetic component. Students are encouraged to interact with objects, notice patterns and ultimately discover information within the provided materials, but without explicit, instructor-led instruction.[10,11] These types of activities have been shown to benefit both kinesthetic and non-kinesthetic learners.[12] There is some debate on the effectiveness of unassisted discovery based learning; however, guided or enhanced discovery has been shown to lead to greater learning than explicit instruction.[10,13] 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.[14,15] 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. It is important to note that in this paper we use the term kinesthetic learning or hands-on activities to mean a physical activity that is meant to teach a concept and develop a deeper understanding of the material, not just the performance of a skill or observation of a phenomenon.

The scope of this paper focuses on the conceptual gains in a SAIL version of the course compared to a traditional, lecture-based version as well as the underlying student attitudes in this combined group problem solving/hands-on learning style. We hypothesized that the SAIL format would improve student learning of biomechanical concepts. A brief summary of the details of the activities is reported here but for more information on the development and implementation of the SAIL techniques discussed in this study, including examples, the reader is referred to Dourte-Segan & Rooney, 2015.[16]

Methods

In 2014 the Biomechanics course was restructured from its lecture-only format so that approximately 50% of class time was spent on collaborative group problem solving and group hands-on activities while the remaining 50% was spent on lecture interspersed with instant feedback questions. This resulted in a total of 7 group problem sets and 4 hands-on activities administered during the 1.5 hour class time. Both the 2014 version of the course and the previous 2013, lecture-only version were taught by the same instructors. A total of 69 students were enrolled in 2013 and 55 students in 2014.

A brief overview of the group problem solving and hands-on activities is presented here, however, a more complete description can be found in our previous publication.[16] 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 for the activity students were asked to analyze the problem within the context of the information they had already learned. A problem-solving outline was 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. Thus, these activities emphasized application and practice of concepts. Outlines contained more detailed guidance in the beginning of the semester (see Appendix A) and became less detailed as the semester progressed (see Appendix B).

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. A hands-on activity for each major course topic was created (reactions, stress/strain axial loading, torsion, and bending) to introduce the basic concepts. A provided outline for these "discovery labs" aimed to help the students to first observe and describe a physical phenomenon and then represent it mathematically. For example, students were asked to build models of different joints in the body using wood, screws and hardware, i.e. the elbow as a hinge between two pieces of wood (see Appendix C). They were then asked how these joints resisted translational and rotational motion – the physical corollary to "reactions" in mechanics, and how you might denote them mathematically and on a free-body diagram. While this likely was a term they had never heard before, they could gain a physical understanding of what it represented. Other hands-on activities included deriving the quantities of stress and strain using elastic and a spring scale (see Appendix D), observing shear strains under torsional loading in a foam pool noodle and exploring beam bending with a piece of Neoprene. In contrast to group problem-solving sessions, these activities facilitated learning of new concepts. Following the activity, students were assigned an out of class, ~15 minute video with follow-up quiz to reemphasize the concepts learned in class.

During the activities, two faculty members and two graduate TAs circulated throughout the room to 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). Again, the reader is referred to our previous publication[16] for further details on the development and implementation of the SAIL activities.

The effectiveness of the SAIL activities was assessed using a pre- and post-instruction concept assessment based on previously published concept inventories.[17,18] Questions were chosen that reflected the major course topics and new questions in the same style were created for

biomechanical concepts not covered in the previously published inventories. Conceptual questions were administered to students in both the lecture-only (2013) and SAIL (2014) courses during class time. Two versions of the assessment were created so students did not have the same questions pre- and post- instruction. To help account for any possible differences in versions, approximately half the class was given the first version and the other half the second version pre-instruction. For the post-assessment, the versions were switched. The material was categorized into fundamental, prerequisite material (e.g. Newtonian physics), and material learned during the course, (e.g. statics and mechanics of materials). Only participation in the assessment counted toward the students' grades. Differences between the pre- and post-concept assessments were calculated and normalized based on pre-instruction scores to measure gains in conceptual understanding over the semester using the formula (post - pre)/(HighestPossibleScore - pre) for positive gains and for negative gains (post - pre)/(pre).[19,20] Differences between course formats, gender, ethnicity, and student confidence level were analyzed using a one tailed t-test with significance set at $p<0.05$. Comparisons across more than two groups were analyzed using one-way ANOVA, with significance set at $p<0.05$.

To further understand student attitudes and confidence in skills associated with success in the SAIL course, a total of two surveys were administered for participation credit; one at the beginning and one at the end of the semester. To encourage honest, open responses, the survey results were obtained and aggregated by the University of Pennsylvania's Center for Teaching and Learning, and matched to students' grades and scores on concept assessments. Instructors only received aggregate, anonymous results. The survey covered topics ranging from confidence in particular skills to effectiveness of activities and self-reflection on group dynamics. Survey items included multiple choice 5-level Likert-type items and open-response questions modified from the Student Assessment of their Learning Gains instrument (SALG)[21] and those designed by the researchers. Survey questions analyzed for this manuscript are included in Appendix E. Student responses to Likert-type items are represented by frequency of response or median responses throughout. Post-instructional gain in confidence in overall problem-solving skills was calculated by summing Likert item responses from the seven 5-level survey items querying gain in problem-solving skills after instruction. Cluster analysis was also performed grouping students' skill confidence responses using Ward's minimum variance method (agglomerative hierarchical, squared Euclidean distance).[22,23] The number of clusters was determined by scree plot. These clusters were used to assign students to moderate or high pre-instructional confidence groups. Differences in ordinal data, including student responses to Likert items and scales, across groups were analyzed via Mann-Whitney U test, with significance set at $p<0.05$. Open-response comments directly related to hands-on activities and group problem solving sessions were identified by the word roots and common misspellings of: activity, group, problem, solve, hands, collaborate, work with, and interact. Responses to open response questions were open-coded.[24]

Results

Results from the concept assessments showed a significant increase in conceptual gains on course material taught in the SAIL format compared to the traditional format (Figure 1, p = 0.023). Gains in prerequisite, physics knowledge did not differ between instruction formats (Figure 2, p = 0.066). In addition, course grades were increased in the SAIL course compared to the lecture-only course (Figure 3). Although course grades are difficult to compare across years given variations in exams and grading, therefore precluding us from performing statistics on the grades, this result supports the finding that students had an increased understanding of the material in the modified course.
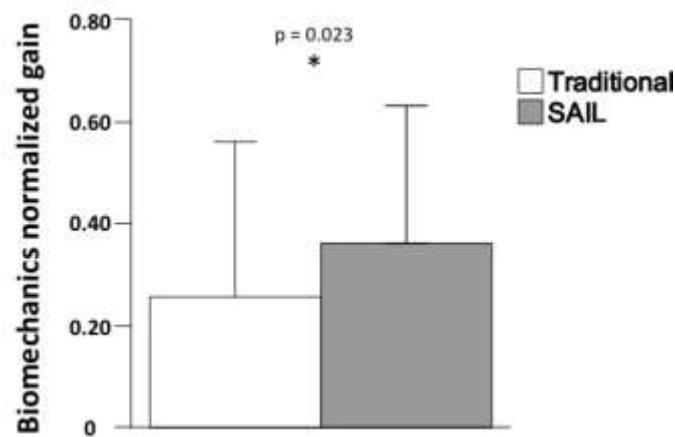
Figure 1: Normalized changes in conceptual gains in Biomechanics knowledge in Traditional vs SAIL instruction (mean +SD). A significant increase in conceptual gains in the SAIL course versus the Traditional course was noted (p<0.05).
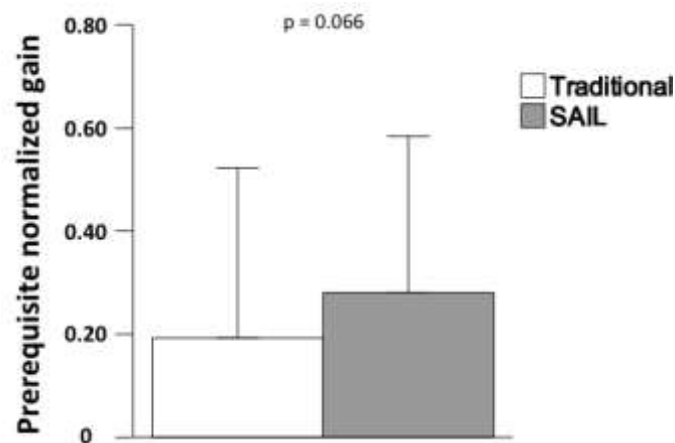
Figure 2: Normalized changes in conceptual gains in Prerequisite knowledge in Traditional vs SAIL instruction (mean +SD). No differences were seen in conceptual gains in the SAIL course versus the Traditional course.
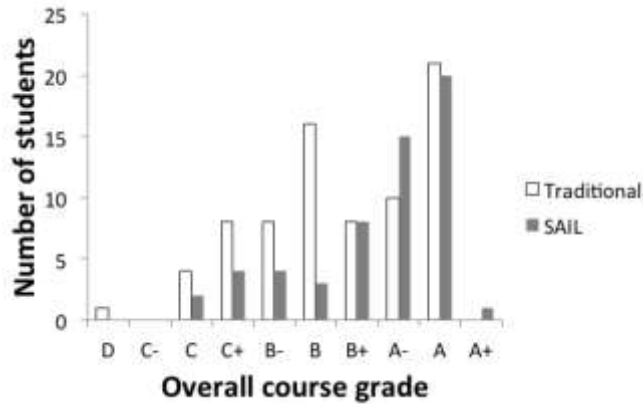
Figure 3: Letter grade distribution in Traditional vs SAIL.

There were no differences in conceptual understanding for under-represented groups (p = 0.421) or across genders (p = 0.167) in the SAIL course (data not shown). Negative gains in biomechanical concepts were seen in 23% of students in the traditionally formatted course and only 7% in the SAIL course. In prerequisite conceptual gains, 36% of students in the traditional format showed negative gains whereas in the SAIL format, 20%.

The SAIL course surveys demonstrated that 84% of students found the course structure an effective way to learn the material (84% of students rated the course structure effective at 4 or 5 on a 1-5 scale) (Figure 4). As very few students provided course ratings between 1 and 3, these responses were condensed into one category, resulting in a 1-3 scale (ineffective, effective, and very effective). There were no significant differences in conceptual understanding or course grade between students among these different course-rating groups (biomechanics conceptual gain p = 0.17; prerequisite conceptual gain p = 0.72; course grade p = 0.67, data not shown). Students reported good gains (median = 4) in categories pertaining to content understanding, skills related to general problem solving and analysis, and confidence. Lower gains were reported in math-specific skills, enthusiasm, interest, and enjoyment (median = 3, data not shown). The majority of students reported increased confidence specifically in their ability to solve problems in their science courses and their ability to work well in a group (Figure 5 A and B).
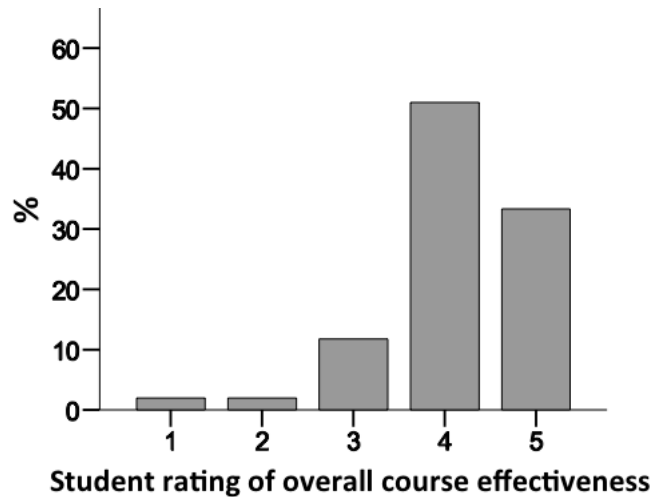
Figure 4: Student ratings of the effectiveness of the SAIL course format. Responses range from 1 (very ineffective) to 5 (very effective).
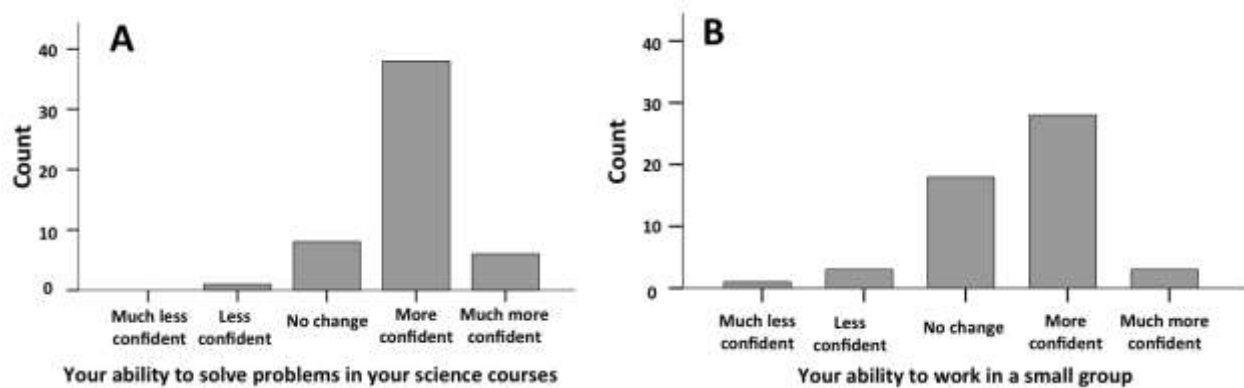

Figure 5: (A) Post-instruction student confidence levels in ability to solve problems in science courses. **(B)** Post-instruction student confidence levels in ability to work in a small group.

Cluster analyses grouping students by pre-instructional confidence separated students into two groups; those with moderate pre-instructional confidence and those with high pre-instructional confidence. Students with moderate pre-instructional confidence showed fewer gains in prerequisite skills than those with high pre-instructional confidence (Figure 6, p=0.028). In contrast, students that entered with moderate pre-instructional confidence showed similar biomechanics confidence gains over the semester compared to their peers (Figure 7, p = 0.187). However, these gains in conceptual understanding were not always reflected in course grades; students that entered the course with low confidence tended to receive lower grades than their peers (p = 0.004, data not shown). Students who entered the course with moderate pre-instructional confidence reported problem solving skill gains equal to their peers (Figure 8A, p = 0.187); however, these students were more likely to report gains in their ability to work in a group (Figure 8B, p = 0.005).
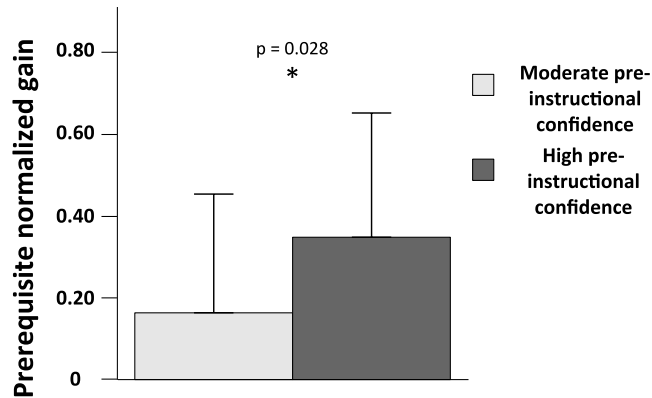
Figure 6: Normalized prerequisite material score gain by student pre-instructional confidence level (mean +SD). A significant increase in prerequisite conceptual gains in the high starting confidence cluster was noted (p<0.05).
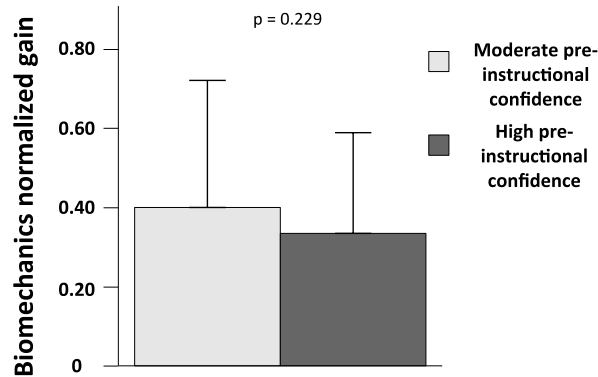

Figure 7: Biomechanics conceptual score gain (mean +SD) grouped by student pre-instructional confidence shows pre-instruction confidence did not affect ability to gain conceptual biomechanics knowledge.
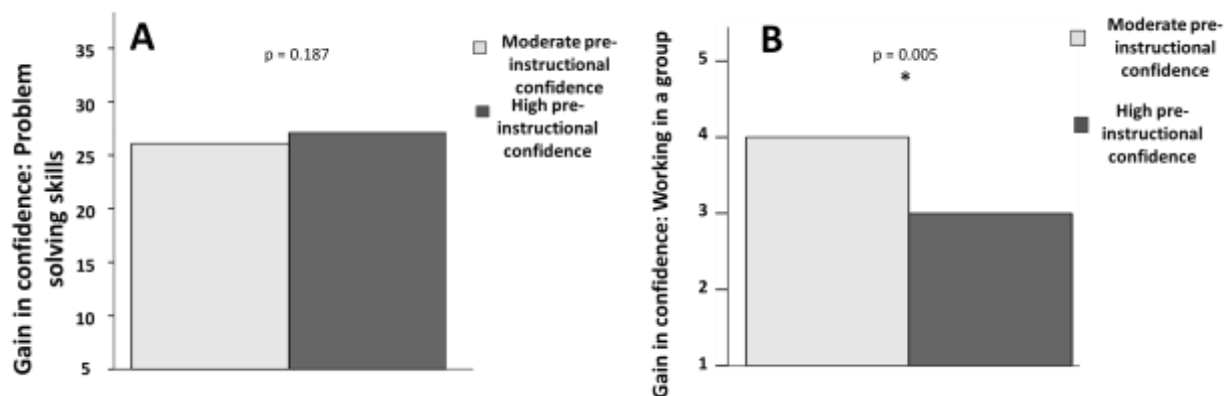

Figure 8: Students are grouped by pre-instructional confidence. (A) Median summative scales of seven survey items querying confidence gain in problem-solving and problem-solving related skills. Students in the moderate starting confidence cluster demonstrated similar gains in problem solving confidence. **(B)** Gain in student confidence in working with a group after instruction. Median reported gain on a 1 (much less confidence) to 5 (much more confidence) scale. Students

in the moderate starting confidence cluster reported significantly higher gains in confidence in group work compared to students in the high starting confidence cluster ($p<0.05$).

The majority of students (90%) reported moderate to great gains in their own enjoyment of learning biomechanics concepts and ideas as a result of the course. Similarly, most students (85%) reported moderate to great gains in enthusiasm for biomechanics in general. As very few students reported either no gains or little gain, these two responses were combined for analysis. Students who reported low to no gains in enjoyment of learning biomechanics ideas and concepts had slightly lower biomechanics score gains compared to their peers, but these differences were not significant (Figure 9, $p = 0.267$). Students who reported low to no gains in enthusiasm for biomechanics had similar biomechanics score gains compared to their peers (Figure 10, $p = 0.845$). Thus, gains in enjoyment of learning and enthusiasm do not correlate with student learning in the course.
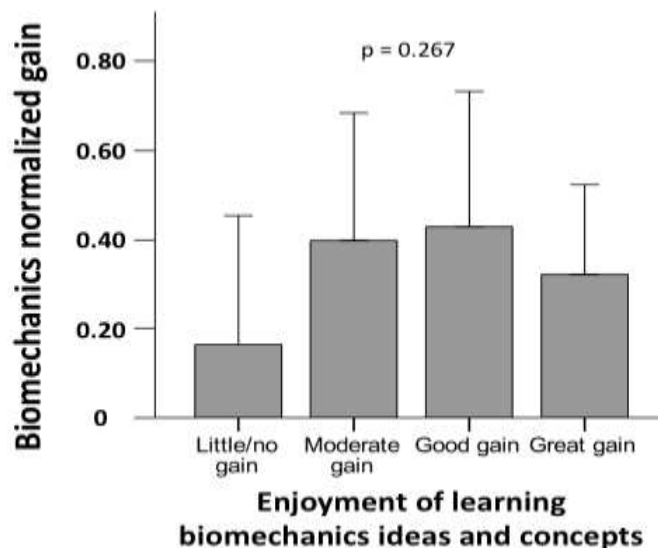

Figure 9: Amount of gain in the enjoyment of leaning biomechanics ideas and concepts showed no effect on biomechanics conceptual gains (mean +SD).
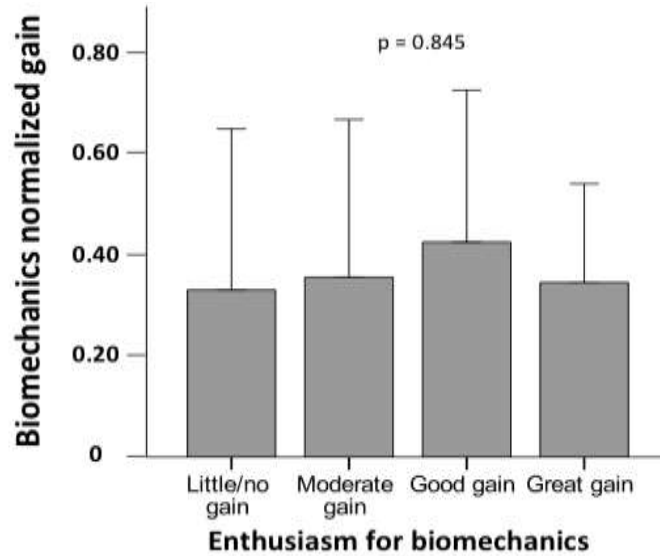
Figure 10: Amount of gain in enthusiasm for biomechanics showed no effect on biomechanics conceptual gains (mean +SD).

The majority of students (78%) reported spending between 4 and 6 hours per week outside of class (data not shown). Within work done outside of class, students found reading the textbook least effective on a scale of one to five (Table 1, median = 2), while homework was the most effective (Table 1, median = 5). Women tended to find reading the textbook ineffective, but were more likely to report doing so (72% of women vs. 52% of men). Office hours, recitation, and studying out of class were found effective as well (Table 1, median = 4). During course time, students found lecture notes and materials most effective (Table 2, median = 4), while all other elements were found to be moderately effective (Table 2, median = 3), including group problem sets, hands on activities, and group work. Women found the hands-on activities less effective on average (median = 3) compared to men (median = 4).

Table 1: Student reported effectiveness of out-of-class course elements from 51 respondents. "N" excludes students who reported that they did not do/participate in the activity.

	N	Median	Mean	Standard Deviation
Reading the textbook	31	2	2.55	1.312
Homework	50	5	4.40	0.756
Recitation	50	4	3.62	1.123
Office hours	36	4	4.14	0.990
Working with a tutor	12	4	3.75	0.965
Studying on my own outside of class	48	4	3.79	0.944
Studying with a group outside of class	41	4	4.00	1.049

Table 2: Student reported effectiveness of in-class course elements. "N" excludes students who reported that they did not do/participate in the activity.

	N	Median	Mean	Standard Deviation
Lecture notes and materials	50	4	4.02	0.937
Hands-on, physical activities	50	3	3.44	0.951
Group problem sets	49	3	3.41	1.019
Working as part of a group, as opposed to individually	50	3	3.30	1.147

Out of 363 total open-response comments provided by students, twenty-two directly discussed hands-on activities. About 23% of those comments emphasized the importance of each group member engaging and communicating. Thirty-two percent of those comments discussed how the hands-on activities helped them conceptualize the ideas, such as by making the ideas seem more intuitive. For example, "It was veyr (sic) hands on, and allowed us to transform our intuitions into knowledge"; and "I liked having in class group work to present new material. It gave us a chance to really see the physical deformation and visualize what all the equations we were learning were doing..." One comment discussed the intuitive nature of the hands-on activities as a negative: "…physical behaior (sic) like bending and torsion are fairly intuitive… I don't need equations to tell me that the geometry of an object affects how easily it bends…"

Sixty-two comments specifically mentioned group problem solving sessions. Seventeen percent of these comments again emphasized the importance of each group member engaging and communicating: "Effective groups have a lot of discourse throughout the problem solving process. Whenever two people disagree, they talk through the different ideas to figure out what the right/better approach is. When someone doesn't understand something, the rest of th (sic) group stops what they're doing and focuses on explaining it until they know that that group member genuinely understands the problem". Fifteen percent of the comments indicated that it was particularly helpful to solve problems when they could get quick feedback, either from a TA or their peers: "There were other people there (classmates, TAs, professors) for support". A total of 8.1% of students who commented on group problem-solving indicated that group problem sessions were stressful, sometimes due to a time crunch, and another 8.1% responses indicated that group problem solving was inefficient. However, 6.45% of comments on group problem-solving sessions stated that group interaction was beneficial in general. Another 6.45% stated that it was specifically helpful to hear multiple different perspectives from their peers, and another 6.45% stated that they found teaching or explaining during group work an effective way to learn. A total of 6.45% of comments indicated recognition of the importance of group work skills, and indicated that course activities improved those skills. Of all the comments related to both hands-on activities and group problem sets, three expressed appreciation for a comfortable, low stress environment.

Discussion

Overall students showed significant positive conceptual gains in the SAIL course versus the traditional course. However, as is common in assessment using concept inventories,[19] some negative gains were observed. While it is encouraging to note that the number of these negative gains decreased in the SAIL course, it is still an area of concern. Fully interpreting this result is difficult given that students were not graded on the assessment but rather given participation points for completion. Students may have rushed through the post-assessment or did not thoroughly read the questions once they realized that they were not being graded and rather wanted to get out of class faster. Future analysis will examine the data for trends in incorrect answers to try and pinpoint remaining areas of confusion.

Students entering the course clustered into two groups based on pre-instructional confidence in problem-solving related skills: the moderate pre-instructional confidence group and the high pre-instructional confidence group. Students in the moderate pre-instructional confidence group showed significantly lower prerequisite conceptual gains (Figure 6). Though improved understanding of this prerequisite material was not an explicit course objective, these ideas were reinforced throughout the semester as these concepts were applied to biomechanics examples and problems. These results suggest that students with low confidence, perhaps as a result of previous experiences with learning physics, may have a disadvantage when it comes to learning new related material. Future studies may reveal whether lack of confidence is due to accurate student assessments of their own skill, and/or serves as a direct impediment of learning. It is notable that students in the moderate pre-instructional confidence cluster showed equal biomechanics conceptual gains (Figure 7) compared to their peers, suggesting that this barrier can be overcome.

While students reported good gains in almost all categories pertaining to content understanding, skills, and confidence, lower gains were reported in math skills, enthusiasm, interest, and enjoyment. The lower values on the latter three could be explained by the fact that this is a required course for majors and that students often have difficulty connecting what they consider "math skills" to the general problem solving strategies emphasized in this course. Instead of general math skills, student often think of calculus skills – the course the majority of them are concurrently enrolled in.

In the literature student learning usually improves in active courses,[7] however, this is not always reflected in student perceptions of the course.[25] This may be related to student understanding of what learning is and the learning process. If so, this is not an issue with active learning per se, but rather with a mismatch between student expectations and the course structure. Further, students are not always able to accurately identify their own skill level and effective learning practices.[26,27] While it's encouraging to see that many students found active learning helpful in this course, student responses on perceived learning may be best used to think about how to orient students to the course structure and identify where students find themselves struggling.

Finally, students who reported the greatest gains in enjoyment of learning biomechanics did not have significantly higher gains in conceptual understanding. This suggests that even students who struggled with the material found that the course positively influenced their enthusiasm and interest in the subject.

Though the average student rating of group problem-solving and hands-on activities were similar, there was more variation in student reports on group problem-solving (Table 2); while some students found this element effective others did not. This was reiterated in student comments; a small but notable minority of comments indicated that group problem-solving was either stressful or inefficient. Based on this feedback, possible improvements include shorter group problem sets with optional extension problems for faster groups. Additionally, students who find this problem solving tedious may benefit from more explicit instruction on what students should try to take away from these problem-solving sessions.

One limitation to this study is the inability to fully separate the effect of the hands-on activities from the group problem solving. However, since the hands-on activities were designed to specifically address conceptual understanding, as opposed to the problem solving skills emphasized by the group problem solving, hands-on activities were likely at least partially responsible for the increased conceptual gains found in the SAIL course. Thirty-two percent of student comments related to hands-on activities noted that these assignments helped to conceptualize the material, suggesting that students perceived the link between hands-on activities and conceptual understanding as well.

One future course improvement is the restructuring of feedback on the in-class activities. In its current format, group problems and hands-on worksheets were placed in the mailbox of one student in the group with written feedback. However, it was noted at the end of the semester that these assignments were rarely picked up from their mailboxes, despite numerous reminders that they were there. Possible solutions include posting the feedback online so all group members can access it, providing a summary of common misconceptions in the class following the activity, or creating an assignment where students reflect on their in-class work.

In conclusion, a combined group problem solving/hands-on activity approach was shown to positively increase biomechanics conceptual learning. In general, students found hands-on activities helpful in understanding the physical meaning behind the mathematical equations and that the course format was an effective way to learn the material. Incoming confidence levels may influence students' ability to master some course material, especially that directly related to prerequisite material, and further efforts will focus on identifying ways to overcome these perceived barriers.

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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).
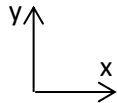
**Question you are trying to answer using the outline provided:**
1. Considering a 2D scenario, simplify the complex anatomy of the left arm and model the equilibrium scenario shown above. Calculate all loads acting on the arm. Use the provided anthropometry figures to estimate measurements necessary 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.

IN-CLASS GROUP PROBLEMS: BENDING
Primary Cilia Bending

The primary cilium is a structure that extends from the surface of nearly every cell in the body. It plays important mechanosensory roles, where cilium deflection under mechanical loading triggers a cellular response. The bending behavior of primary cilium has been modeled as a uniform cylindrical cantilevered beam subjected to a unidirectional load perpendicular to its long axis (due to fluid flow).
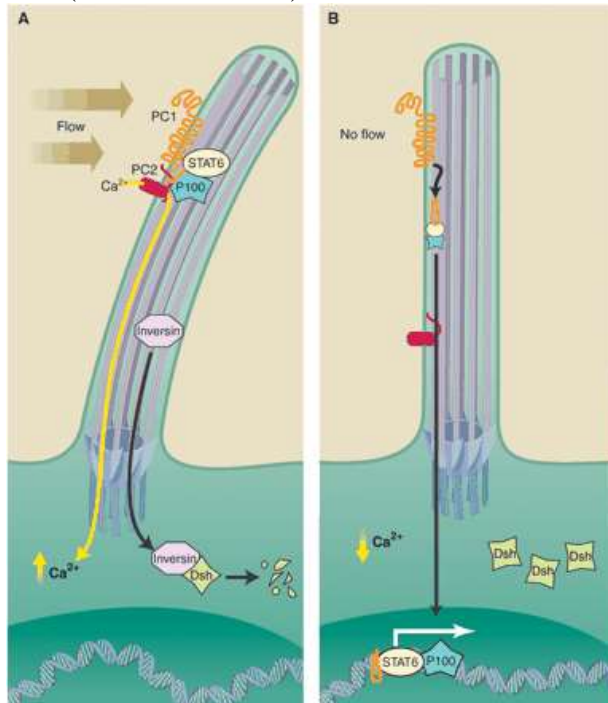
Hoey DA, Downs ME, Jacobs CR. The mechanics of the primary cilium: An intricate structure with complex function. J Biomech, 2012, 45:17-26.

Singla V, Reiter JF. The primary cilium as the cell's antenna: Signaling at a sensory organelle. Science 2006, 313(5787):629-633.

Hill DB, Swaminathan V, Estes A, Cribb J, O'Brien ET, Davis CW, Superfine R. Force generation and dynamics of individual cilia under external loading. Biophys J, 2010, 98(1):57-66.

Goetz JG, Steed EM, Ferreira RR, Roth S, Ramspacher C, boselli F, Charvin G, Liebling M, Wyart C, Schwab Y, Vermot J. Endothelial cilia mediate low flow sensing during zebrafish vascular development. Cell Reports, 2014, 6(5):799-808.

Spoon C, Grant W. Biomechanical measurement of kinocilium. Methods Enzymol, 2013, 525:21-43.

As the PI of a research lab, you are studying the bending of primary cilia. Consider a single primary cilium that is 8 μm long and 0.2 μm in diameter with a Young's modulus of 14 MPa and a shear modulus of 2 MPa. In order to initiate a calcium release for a biochemical cascade, the cilium tip must deflect at least 5.1 μm. The fluid flow that you are applying to your cilium creates a distributed force along the length of the cilium with no force at the bottom and a max force (in pN/μm) at the tip.
Note: The second moment of area, I, of a circle is $\pi R^4/4$

Questions you are trying to answer using the following outline:
1. What distributed force (in pN/μm) at the maximum of the applied triangular distributed load must you apply in order to initiate the calcium release?
2. What is the resultant (magnitude) of this distributed force?
3. What does the shape of the deformed cilia look like? Graph using your findings.

I.   Observe
       Draw a picture of the loading profile and describe how it will cause deflection of the
       cilium.

II.   Focus the Problem.
       Outline the approach to be taken.

III.   Describe the Mechanics.
       Draw all appropriate FBD(s).
       Identify and record the knowns and unknowns.
       State any assumptions.
       State which mechanics principles/equations you can use.

IV.   Do the Math.
       Translate your mechanics descriptions into equations with variables.

V.   Put in the Numbers.
       Put real numbers into your equations and determine numerical values for your target
       quantities.

VI.   Evaluate the Answer.
       Are the units correct?
       Is the answer unreasonable? Justify.

VII.   Answer the Questions.
       1. What force (in pN/μm) at the maximum of the applied triangular distributed load
          must you apply in order to initiate the calcium release?
       2. What is the resultant (magnitude) of this distributed force?
       3. What does the shape of the deformed cilia look like? Graph using your findings.

APPENDIX C: Sample 1 Hands-On Discovery Lab: A total of 4 supports/joints were analyzed in this activity. Support 1 is provided as an example.

HANDS-ON ACTIVITY: SUPPORTS AND JOINTS
Background
- Recall Newton's Third Law: For every action, there is an equal and opposite <u>reaction</u>.
- A FBD (<u>free</u> body diagram) requires that the object of interest is completely isolated. A complete FBD includes all reactions, external forces/moments (torques), and a labeled coordinate system.

Goals
1) Understand how we can use mechanical supports to model physical and biological structures
2) Define the term "reaction" as it pertains to mechanics
3) Deduce how different supports result in different reactions

Materials
Screw driver
Hinge
Screws
Different pieces of wood
Twine
Eye hooks

At the end of this hands-on activity, you should be able to:
1) Describe in your own words the definition of a "reaction" as it pertains to mechanics
2) Use deductive reasoning to represent on a FBD the reactions due to various supports

Note: In this activity, you will be re-using the materials provided. Make sure any model you create can be easily taken apart. When you are finished, please completely disassemble your structures and put all parts back in the bag.

SUPPORT #1: FIXED SUPPORT

In human newborns, the bones in the skull are able to shift to allow for birthing and growth. By the time we reach adulthood, these bones are fused together through mostly rigid joints known as "sutures."
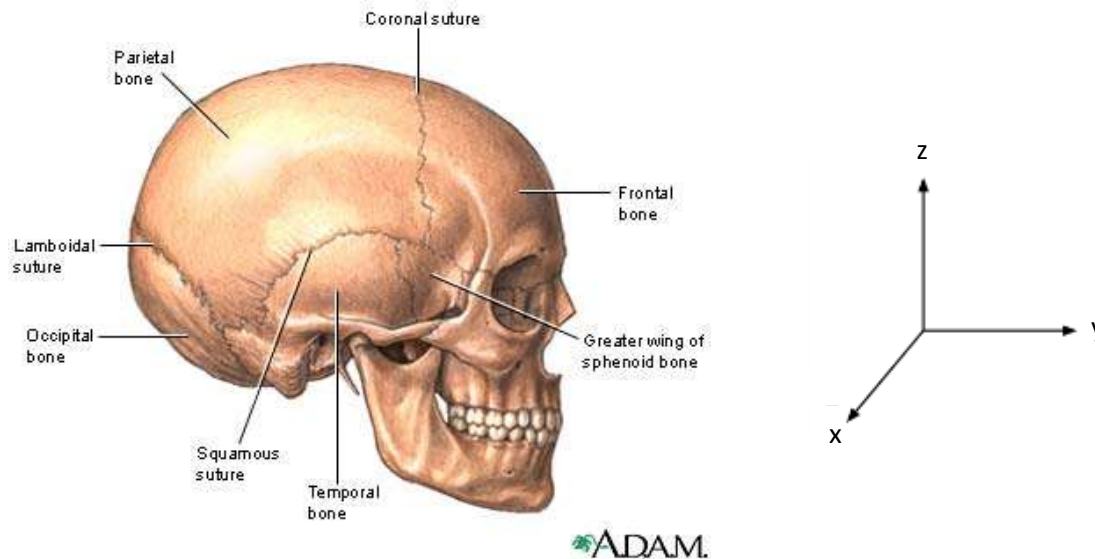
1. **Using the materials and tools in front of you, create a model of a rigid, fixed joint.** Hint: How many screws do you need to make sure no translation or rotation is possible? Even if you use multiple screws, can you simplify this to represent a "single" support?
2. **Try rotating, pushing, and pulling on your model in all 3 planes.** Describe/list what is happening. Specifically, is there is a resistance to translational or rotational motion? Be specific which direction the resistance is in or about. Is there a reaction (recall Newton's 3rd law) that prevents rotation or translation in a particular direction?
3. **Using your own words, define the term "reaction" as it pertains to mechanics.**
4. **At a point where the fixed support is acting, what mechanical reactions does this joint produce in 3D?** Remember to think about rotation and translation. How are you going to represent a resistance to rotation?
5. **Draw a FBD to represent the possible reactions produced by a 3D fixed support.** Isolate one piece of your model for the FBD and represent the fixed support at a point. Since we do not know any specific loading, do not worry about positive or negative directions and instead assume positive since the direction is currently an unknown.
6. **What possible mechanical reactions would this fixed joint produce in 2D?** Choose any plane. Remember to think about rotation and translation. Draw a FBD to represent the reactions produced by a fixed support simplified to 2D.

Record answers to all the above discussion questions to turn in. Raise your green flag to have your answers reviewed by an instructor or TA. Move onto the next part while you are waiting.

APPENDIX D: Sample 2 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.

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 <u>unloaded</u> 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, <u>repeated</u> 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 (~1.275×10^{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.

APPENDIX E: Pre and post survey sample questions

Sample Pre-instructional Survey Questions:

How confident are you in:

	1: Not at all confident	2	3	4	5: Very confident
Your ability to solve problems in your science courses.	○	○	○	○	○
Your ability to solve physics problems in particular.	○	○	○	○	○
Your math skills.	○	○	○	○	○
Working with complex, difficult ideas.	○	○	○	○	○
Your ability to use systematic reasoning in your approach to problems.	○	○	○	○	○
Your ability to use a critical approach to analyzing data and arguments in your daily life.	○	○	○	○	○

Sample Post-Instructional Survey Questions:

Questions about problem solving skills: Note: Responses to the following seven items were summed to create an overall scale of post-instructional gain in student problem-solving confidence.

How has this course impacted your confidence in the following:

	Much less confident	Less confident	No change	More confident	Much more confident
Your ability to solve problems in your science courses.	○	○	○	○	○
Your ability to solve biomechanics problems in particular.	○	○	○	○	○
Your ability to solve problems in your math courses.	○	○	○	○	○
Your math skills in general.	○	○	○	○	○
Working with complex, difficult ideas.	○	○	○	○	○
Your ability to use systematic reasoning in your approach to problems.	○	○	○	○	○
Your ability to use a critical approach to analyzing data and arguments in your daily life.	○	○	○	○	○

How has your confidence in your ability to work in a small group changed as a result of this course?

- ○ Much less confident
- ○ Less confident
- ○ No change
- ○ More confident
- ○ Much more confident

Questions about conceptual gains:

	No gains	A little gain	Moderate gain	Good gain	Great gain
The main concepts explored in this class.	○	○	○	○	○
Connecting key biomechanics ideas with other knowledge.	○	○	○	○	○
Connecting what you know about biomechanics with events in your daily life.	○	○	○	○	○
A basic understanding of how biomechanics relates to real world problems.	○	○	○	○	○

Questions about enthusiasm and enjoyment:

As a result of this class, what kind of gains have you made in the following?

	No gains	A little gain	Moderate gain	Good gain	Great gain
Enthusiasm for biomechanics.	○	○	○	○	○
Enjoyment of learning biomechanics ideas and concepts.	○	○	○	○	○
Interest in discussing biomechanics with friends and family.	○	○	○	○	○

Questions on student engagement in the course and effectiveness of activities:

How many non-classroom hours per week did you spend working on material for this course (including reading text, doing homework, studying, etc.)

- ○ 1 hour or less
- ○ 1-2 hours
- ○ 2-3 hours
- ○ 3-4 hours

- ◯ 5-6 hours
- ◯ More than 6 hours

	I did not do this	1: Not at all effective	2	3	4	5: Very effective
Reading the textbook	◯	◯	◯	◯	◯	◯
Lecture notes and materials	◯	◯	◯	◯	◯	◯
Learning Catalytics questions	◯	◯	◯	◯	◯	◯
Discussions with classmates in class	◯	◯	◯	◯	◯	◯
Hands-on, physical activities	◯	◯	◯	◯	◯	◯
In-class problem sets	◯	◯	◯	◯	◯	◯
Working as part of a group, in class on problems, as opposed to individually	◯	◯	◯	◯	◯	◯
Homework	◯	◯	◯	◯	◯	◯
Recitation	◯	◯	◯	◯	◯	◯
Studying on my own outside of class	◯	◯	◯	◯	◯	◯
Studying with a group outside of class	◯	◯	◯	◯	◯	◯
Office hours	◯	◯	◯	◯	◯	◯
Working with a tutor	◯	◯	◯	◯	◯	◯
Other (please specify):	◯	◯	◯	◯	◯	◯

How effective did you find this course structure as a way to learn the material?

- ◯ 1: not at all effective
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5: Very effective

Open-ended questions analyzed for comments on hand-on activities, group-problem solving, and group work in general:

1. Please comment on how this course has affected your confidence in your skills.
2. Please comment on this course has impacted your attitudes towards biomechanics:
3. Please comment on how this course has impacted your confidence in your group work.
4. Please comment on what you feel you have gained from this course overall.
5. What do you see as the benefits, or upsides, of the structure of this course? What are the challenges?
6. What advice do you have for future students who wish to do well in this course?
7. Do you have any other comments about this course?
8. Has this course impacted your confidence in completing your desired major, and how so?
9. What did you find most helpful about working on questions/problems in class? What was ineffective?
10. Please comment on which elements of the course and assignments you find most helpful, and why.
11. How effective have the following assignments and materials been for helping you learn and understand the material in this course?