Canine hip forces: The ups and downs of project-based learning of static equilibrium

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Introduction

Engineering students are often adept at solving highly defined problems such as the forces in the trusses of a bridge, but falter when asked to solve a more open-ended problem and to describe the concepts involved. Further, students who are studying bioengineering may not be intrinsically motivated to analyze bridges and cranes and are more inspired by biological- and medical-related problems. Bioengineering nationally attracts a more diverse pool of students than has been historically observed in engineering as a whole (Hill 2002, Hill 2002). To encourage curiosity and increase students’ conceptual understanding of static equilibrium, we developed and implemented an open-ended project in our introductory biomechanics course.

The formation of the project was based the premise that students gain deeper knowledge and retain it longer when it is presented in a real-world context as demonstrated in the problem-based learning (PBL) literature (Eberlein, Kampmeier et al. 2008). The literature indicates that PBL enhances both the immediate and long-term ability of students to apply their knowledge (Gijbels, Dochy et al. 2005, Pascarella and Terenzini 2005, Kuh, Kinzie et al. 2011). The process of completing the project is inherently student-centered, with students solving the problem at their own pace and the professor serving as a guide and facilitator. The students determine what they need to know and learn to critically evaluate sources of information, and thus develop critical problem solving skills (Barrows 1980).

Despite the prevalence of literature demonstrating improved engagement and learning from active learning techniques such as PBL, it is difficult to find data supporting the impact of short-term team projects in context of classroom. Further, implementing PBL in the classroom can be daunting for faculty (Freeman, Eddy et al. 2014). Descriptions of how to implement PBL techniques in adequate detail, e.g., in (Clyne and Billiar 2016), and evidences of their effectiveness are critical for encouraging faculty members to adopt such techniques (Fairweather 2010).

In this work, we describe a sophomore-level biomechanics project and compare student achievement to that of previous offerings without projects. The goal of implementing the project was to guide students towards adaptive expertise, the combination of factual and conceptual knowledge and ability to transfer that knowledge to new and novel situations (Bransford et al. 2000). Here we provide details of the implementation of the project including tools for assessment of student learning and also present student outcomes.
Methods

The project was assigned at Worcester Polytechnic Institute in the Fall 2016 offering of a sophomore-level biomechanics course (BME2511). To reduce the burden on the students, the project took the place of the first two homework assignments from the previous offering of the course. The objectives of the assignment were to assess the students’ ability to 1) set up a static biomechanics problem effectively, 2) apply static equilibrium equation to estimate joint forces, 3) predict uncertainty, 4) assess if solution is realistic, 5) work well on a team, 6) communicate effectively, and 7) identify unexpected opportunities.

To engage the interest of the students in the project, they were told that veterinarians are reporting higher-than-acceptable cracking of the plastic portion of the acetabular cups in a total hip replacement products causing undue pain and suffering to many dogs, especially large breeds. Seventy-five students, mostly sophomore biomedical engineers, were randomly assigned into three-person teams and challenged to analyze the mechanics of the canine hip to determine the force that the femoral head (ball) applies to the acetabular cup and, if possible, to come up with a better design or alternative solution that could potentially reduce failure of the component.

Assessment: Formative Assignment

To get the students started, an initial formative assignment was assigned. Feedback was provided (no grades given), and the student groups met in class to discuss their initial solutions with other groups. The students were encouraged to observe similarities and differences in how they set up the problem and obtained anatomical parameters. For the formative assignments, the students were asked specifically to do the following:

- Draw a clear schematic showing position of “your” dog with main bones and main muscles acting at the hip joint.
- Draw a close-up simplified schematic of the hip joint with only a single muscle acting on the leg bone.
- Draw an accurate free-body diagram (FBD) with clear labels and coordinate frame indicated
- State the assumptions that allow you to simplify the joint system to only three unknowns (muscle force, joint force magnitude, joint force direction) with rationale for why they’re reasonable
- Using multiple sources (web/text), determine the joint center of rotation and indicate it on the schematic for your dog type (small, medium, large).
- Using these sources, determine the locations of the muscle origin on the leg bone and insertion in the pelvis/trunk. Calculate the force vector direction (unit vector) relative to your coordinate frame. Indicate the range of values (uncertainty) due to difficulty in estimating exactly where the origin and insertions are located i.e., calculate multiple unit vectors representing the range.
- Determine the distances from the joint center of rotation to the origin of the main muscle in both x- and y-direction (be careful of the sign (positive/negative)). Write out “radius vectors” from the center of rotation to your best estimate of the muscle insertion location. Also note
the closest and furthest the insertion location could be (range of locations for uncertainty analysis).

- Calculate the moment about the center of rotation due to the muscle in variable form (you don’t know the magnitude of muscle force yet...).

They were also asked conceptual questions:
- Is the force in the muscle positive (tension)? Can muscles push, and thus be in compression?
- By just looking at the schematic can you tell if the joint is in compression or tension?
- What direction is the moment due to the muscle?
- Based on the uncertainty in measurements, how many significant digits should you use in your calculations and answers?

Assessment: Summative Report

For the second and final portion of the assignment, the student teams were tasked with writing a two-page report with appendices containing individual students’ diagrams and calculations. The project was assessed using a detailed rubric. The rubric was provided to the students with the assignment to provide guidance on what was expected of their report. The groups were also asked to assess their own reports using the rubric so they could identify areas of improvement before handing in their reports.
**Table 1: Rubric for project report.**

<table>
<thead>
<tr>
<th>Project objective</th>
<th>Expert level (full points)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Set up static biomechanics problem effectively (20pt)</strong></td>
<td>• Clear schematic showing position of animal with main bones and main muscles acting appropriately&lt;br&gt;• Accurate FBD with clear labels and coordinate frame indicated&lt;br&gt;• Simplifying assumptions defended with rationale&lt;br&gt;• Information integrated from multiple sources</td>
</tr>
<tr>
<td><strong>Apply static equilibrium equation to estimate joint forces (30pt Individual)</strong></td>
<td>• Equations written out in variable form (based on FBD labels and definitions)&lt;br&gt;• Vector direction of muscle force defined based on muscle origin and insertion&lt;br&gt;• Joint force solved in variable form&lt;br&gt;• Calculation for magnitude of joint force for each individual (dog size) in appendix&lt;br&gt;• Summary table of results for a wide range of dog sizes (at least three) in body of report&lt;br&gt;• Units and directions indicated clearly</td>
</tr>
<tr>
<td><strong>Predict uncertainty (10pts Individual)</strong></td>
<td>• Anatomic diagrams with origin and insertion sites for muscles and axis of rotation for joint clearly shown with range of locations indicated&lt;br&gt;• Calculations for range of muscle origins and directions presented clearly with relative values (e.g., % difference from best case) in appendix for each individual and summary in table in body of report</td>
</tr>
<tr>
<td><strong>Assess if solution is realistic (10pts)</strong></td>
<td>• Joint force magnitude realistic compared with body weight considering chosen position and muscle force magnitude&lt;br&gt;• Direction of joint force explained correctly&lt;br&gt;• Force magnitudes compared to literature values (and realistic)</td>
</tr>
<tr>
<td><strong>Work well on team (10pts)</strong></td>
<td>• Complete agreed-upon tasks (fair share) on time&lt;br&gt;• Always positive attitude&lt;br&gt;• Listens attentively&lt;br&gt;• Contributes to discussions&lt;br&gt;• Makes all meetings on time</td>
</tr>
</tbody>
</table>
| **Communicate effectively (20pts)**                                             | • Descriptive title; author info; section headings<br>• Statement of problem/significance/gap<br>• Reasonable objective/goal (clear!)
  • Concise methods with diagrams & eqns<br>• Quantitative and qualitative results (clear table and sensitivity analysis included)<br>• Persuasive discussion and conclusion<br>• Terms/jargon are properly defined when first used<br>• Proper grammar and spelling; page numbers<br>• References in proper format (others’ data should be cited!!)<br>• Proper use of sig figs<br>• Table headings/figure captions clear                                                                                                                                                                                                 |
| **Bonus (10 pts): Identify unexpected opportunities**                             | • Identified alternative solutions not currently available for dogs<br>• Applied solution to other patients/situations<br>• Normalized values for dog/joint size                                                                                                                                                                                                                                                                         |
Assessment: Quiz

A quiz was administered to assess the students’ ability to perform basic static analyses and describe static equilibrium concepts in writing; the question type and difficulty were equivalent to those on the quiz in the previous course offering.

Quantitative questions: The purpose of the quantitative questions is to test the students’ ability to set up a biomechanics problem and solve for the forces and moments in a joint (e.g., hip, knee, shoulder). To focus on the concepts rather than ability to plug numbers into a calculator and use proper significant figures, the students give their answers in variable form (I still consider the questions to be quantitative even though no numbers are provided in the problem). In this offering, a picture of a hip joint was provided with center of rotation and muscle origin and insertion locations (with coordinates, $x_i$, $y_i$), and the students were asked to calculate the forces acting on the joint in terms of the magnitude of force and the aforementioned coordinates. A similar problem wherein the students were asked to calculate the forces in a knee joint was also asked. In previous offerings, different loadings on these joints and other joints (shoulder, elbow, etc.) have been assigned.

Qualitative questions: The purpose of the qualitative questions is to test the students’ understanding of the basic concepts and ability to communicate their understanding in writing. The following questions were asked in the current offering, followed by comparisons to questions in previous offerings:

“To raise the leg outward and up (adduction) in problem 1 [picture of a hip joint], is the force in the muscle tensile or compressive? Explain how you know this in one sentence as if you are explaining it to a middle school student.” Similar questions to this on the concept of muscles only providing tensile forces were asked in 2012, 2013, 2014, and 2015 as well, and a very similar question was asked on homework in these offerings as well. The homework assignments were provided to the students in the current offering but not assigned for credit.

“What major assumption(s) did you make in problem 2 [holding the shank of the leg in the air] to make the problem tractable (able to calculate the muscle force) and describe in one sentence why this is/these are valid?” Essentially the same question regarding simplifications (single muscle acting at a point, frictionless joint) was asked in the four previous offerings.

“The way our bodies are structured, the forces in the muscles and bones are very high for relatively low external forces (e.g., the 5 lb. weight I held out at arm’s length in class resulted in tens of pounds of force on a volunteer’s deltoids). What is the benefit of such a design?” The same question was asked on the quizzes in 2012, 2014 and 2015.

“How many unknowns can one have in a 2D equilibrium problem (without being statically indeterminate)? How many in a 3D equilibrium problem? Explain why we can only have this many unknowns.” And “For vectors $\mathbf{a}$ and $\mathbf{b}$, what is the difference between $\mathbf{a} \times \mathbf{b}$ and $\mathbf{b} \times \mathbf{a}$?
Statistics: Results from the three offerings were compared using one-way ANOVA on ranks with p<0.05 considered significant. When significant effect found, pairwise comparisons completed using Dunn’s method. (SigmaPlot v.13, Systat Software, Inc.).

Results

Overall the students performed well on the project, submitting clearly written two-page reports completed in professional word processing software with legible figures, tables, typed equations, and proper citations. The appendices consisted of relatively clear hand-drawn schematics and free-body diagrams (FBD) and hand-written equations in variable form with example numerical calculations. While proper significant figures and units were utilized in most reports, approximately one-third of teams (not quantified) had trouble with these basic aspects of professional communication.

Prior to submission of the project, at least one member of the majority of teams attended office hours to gain clarity on project objectives, position of the dog for static analysis, how to construct their FBDs, and how to perform the uncertainty analysis. Despite the formative feedback, six students had fundamentally flawed FBDs and most teams had difficulty with the estimating the error associated with their approximating the joint center of rotation and muscle origin and insertion locations.

Project and homework assignment grades: The average score of the projects were higher than those of the homework assignments in the previous offering (Figure 1).

![Figure 1. Comparison of the average score from Homework assignments 1 and 2 for previous offerings (2012-2015) with the project report score in the current offering (2016). * indicates different from all](image-url)
other groups; ** indicates different between specific groups below horizontal lines: p<0.001 ANOVA on Ranks.

**Quiz grades:** The scores on question 1 (forces and moments) and question 2 (rotational static equilibrium) from the quiz were significantly lower for the students completing the project compared to those completing the homework assignments in the previous offering (Figure 2). The exact same Question 2 was asked in 2012 and 2016, with substantially lower scores in 2016 (79% ± 18% vs. 59% ± 23%).

![Quantitative Quiz Score (%)](image)

*Figure 2. Comparison of the average score from quantitative questions (1 and 2) of the quiz for four offerings of the course. A project was implemented in the current offering (2016). * indicates different than all other groups; p<0.001 ANOVA on Ranks.*

In contrast, the students did significantly better in describing the concepts of static analysis following the project compared to doing homework assignments (Figure 3). Interestingly, in 2015 the students were given the option of answering 5 out of 6 qualitative questions (rather than having to answer all five questions in the other offerings), and they did perform significantly better than in 2013 and 2014, but did not perform as well as in 2016. Almost exactly the same qualitative questions were assigned in 2012 with higher scores in 2016 (81%±16% vs. 94.8% ± 11%).
Figure 3. Average score from five qualitative questions of the quiz for five offerings of the course. * indicates different than all other groups; p<0.001 ANOVA on Ranks. 2013 and 2014 were not significantly different as indicated by n.s. Note: in 2015, the students were allowed to answer 5 of 6 questions.

Entrepreneurial mindset: Over 75% (19 of 25) of the teams received extra credit for identifying unexpected opportunities. This aspect of creating value is a key part of the entrepreneurial mindset as defined by the Kern Entrepreneurial Engineering Network (KEEN) (engineeringunleashed.com/keen/em101/). In addition to calculating the forces in the joint, the majority of teams suggested using more robust material for the acetabular cup. Hip resurfacing (metal-on-metal) rather than total hip replacement is utilized in certain human populations, and ceramic-on-ceramic implants are being investigated for humans, and some students suggested that these innovations may be used in dogs as well. Other groups suggested patient-specific implants e.g., bioprinted using data from noninvasive imaging. Finally, a few groups suggested mechanical solutions to reduce forces such as the use of an exoskeleton or changing the geometry to alter the gait patterns. All of these solutions go beyond the stated scope of calculating joint forces for the project. The solutions indicate that the students are willing and able to think creatively to generate value in addition to what is gained from solving for the variables explicitly required in the client statement.

Student comments: In general, the students indicated that they enjoyed doing a project with real-world implications. A few students reported that they thought project was too vague and/or too large e.g., one stated “Personally, I felt that there were too many unknowns, and I understand that is the purpose, that we design our own project, but I would rather have a more structured project.” The rubric was provided after the initial formative assignment, and some students commented that they would have liked to have had it when the project was first assigned to clarify expectations rather than “leaving it vague.” Finally, although the idea of helping dogs was liked, a few students found it difficult to find information on canine anatomy and would have rather focused on human hips.
Discussion

With the addition of a short project, the students in our introductory biomechanics course were able to transfer static analysis knowledge to a novel situation (canine hip) as evaluated by the project grades. However, students had significantly lower quantitative scores on the quiz, a basic assessment of “factual knowledge,” than the previous five course offerings. In contrast, they had significantly higher qualitative scores, an assessment of “conceptual knowledge,” than all other offerings.

Both the project and homework assignments are fundamentally formative assignments designed to motivate and aid student learning. Grades are given more to encourage completion than for summative evaluation. High scores on the project report were to be expected, since the students were encouraged to utilize the rubric to assess their own work while completing the project, and they could ask the instructor and teaching assistant for specific feedback before handing in the reports. Further, they could earn up to 10 points extra credit for offering additional impact demonstrating an entrepreneurial mindset (over 75% of the teams received extra credit). Yet high scores were also relatively easily attainable in previous offerings since students were permitted to work on homework together, and it is likely that many had access to similar homework solutions from previous offerings. Thus, it was not obviously a priori that the scores on the project would be significantly higher than for the homework assignments, and the high project grades suggest that the students took the project more seriously than completing homework assignments (average grades for other homework assignments in the course ranged from 80 to 97 out of 100).

As for the quiz, the significantly lower grades on the quantitative problems indicate that the project was not as effective as previously assigned homework assignments in aiding the students in performing basic static analysis. Not requiring the students to do multiple highly defined problems for homework similar to the basic statics questions in the quiz yields lower performance in solving this type of problem. Our findings are consistent with reviews of medical education programs which find that PBL produces better clinical management, but no better or even inferior gains in factual knowledge (Albanese and Mitchell 1993, Berkson 1993, Vernon and Blake 1993, Colliver 2000). More recent meta-analyses of PBL in various fields also yield variable results depending upon knowledge level, with significant enhancements in students’ learning and retention but only at mid- and high-levels. Understanding of principles and linking concepts (mid-level knowledge) and linking of concepts and principles to application (higher level knowledge structure) showed gains relative to understanding of concepts (lowest level knowledge) (Dochy, Segers et al. 2003). Specifically in introductory biomechanics courses, there is evidence that PBL and other approaches based on “how people learn (HPL)” do not produce significant differences in factual knowledge. In one case, for the same course taught in both traditional and challenge-based instruction modes with controls for student demographics, the authors report no significant difference on the less difficult knowledge-based questions on the final exam (Roselli and Brophy 2006). In a more recent comparison of HPL and standard instruction, there was no significant difference in factual knowledge between the groups (Gijbels, Dochy et al. 2005).
In contrast to the basic factual (quantitative) knowledge, we found significant increase in conceptual knowledge. This finding is consistent with previous comparisons of standard and HPL instruction (Pandy, Petrosino et al. 2004), and in comparisons of standard and challenge-based instruction biomechanics class where students performed significantly better on more difficult knowledge-based questions (Roselli and Brophy 2006).

To assess whether the comparison of scores between quizzes from the various offerings is valid, two biomechanics professors at our institution compared the quizzes from the six years in terms of difficulty and clarity. One professor commented that the quantitative question from 2014 was somewhat less clear and more difficult. The other professor commented that they did not find any of the questions more difficult between the quizzes, “it was more a matter of how easy was it for a student to figure out how to give you what you want.” Of note, this year’s quantitative questions were found to be better in terms of the clarity of figures than 2013 and 2014 and less detail oriented than 2015, thus one would have expected the students to do better in this offering. The conceptual questions from 2012 (which were essentially the same as 2016) were found to be the best at helping the students link the math with conceptual knowledge. In these offerings, the final two qualitative questions were relatively straight-forward and mathematical compared to some of the questions asked in the three previous offerings. Questions about sources of error in the class demonstrations, which major muscle is acting in a particular movement, and if muscle forces increase or decrease with a particular change in distance or angle were asked in previous offerings, but not in this offering. This difference may, in part, explain the higher qualitative scores for these two years compared to 2013-2015, yet the students who completed the project in this offering scored significantly better than in 2012 indicating that the results of increased conceptual knowledge with the project are valid.

In terms of the implementation, it is possible that the differences between this year and previous offering could have been how hard the quizzes were graded. The average scores from all four quizzes were somewhat higher this year, but not significantly different (paired t-test, 76.2 vs. 81.4, 2015 vs. 2016, p = 0.36). Further, based on best practices from the PBL literature, the project description was introduced before the theory to motivate learning of the subject material and curiosity (Barrows 1996). The fact that the students were learning the theory while applying it may have hindered the ability of some students from effectively practicing solving basic statics problems. In the present course, multiple students commented that they would have liked the project assigned later in the term after they had already learned the theory.

In future offerings, it will be important to clearly identify what minimum quantitative knowledge is required of the students, i.e., what is the simplest static analysis problem that should be able to be completed by all students. We also plan to examine if the results from the current offering are repeatable in the upcoming offering, and control questions to be more directly comparable. We recognize the value of evaluating long-term retention, but this type of assessment is difficult as this course is not part of a required sequence of courses; in fact, there are no required courses at our institution.
In conclusion, our findings suggest that assigning an open-ended project in lieu of completing multiple basic statics problems may not produce gains on this low-knowledge-level type of analysis; however, even limited project-based learning can have a positive impact on the students’ ability to describe basic statics concepts in writing.

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References


