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Introducing Uncertainty Analysis in Elbow Biomechanics: A Work in Progress at Two Educational Levels

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Introduction

The educational goal of our research is to facilitate active learning during the introduction of problem-solving while incorporating uncertainty and variability to a biomechanical analysis. In this research, we have defined uncertainty as the inaccuracy in a model that stems from natural variability in input parameters and imprecision in measurement techniques. At the high school level, learning objectives include basic concepts of uncertainty within the context of biomechanics—including moment calculations, weight estimations, and the use of significant figures. At the college level, the learning objectives include application of Analysis of Variance (ANOVA) to conduct sensitivity analyses and to quantify the statistical significance in the observed effects.

High School Level

Methods

Evaluation of our high school teaching model was conducted over two days with 28 high school students from the Upward Bound program at our university (**Figure 1**). The 60 minute module focused on calculating the required force of the biceps muscle to hold up an apple at 90 degrees. Instruction began with a 10-15 minute lecture that introduced uncertainty, elbow biomechanics, anatomy, moment calculations, and the use of significant figures. The active learning component involved three different interactive workstations. Station 1 calculated the biceps force with a PASCO mechanical arm system. Station 2 guided students to calculate the biceps force in models of their own arms and measurements of apples. Station 3 calculated the biceps force for an average, small, and large sized person. Finally, the module concluded with a discussion of the measurements and resulting calculations as well as a video of a recently released prosthetic arm. Uncertainty was introduced in the measurement techniques and tools, as well as in the natural variability found in apples and humans. Effectiveness of the high school teaching module was evaluated based on results from an identical pre- and post- test (See **Figure 2)** that assessed the students' knowledge on moments, significant figures, relative weight dimensions, uncertainty, and interest in Biomedical Engineering. We also assessed their confidence levels by asking if they knew the answers, or if they had simply guessed the answer. Results were evaluated based on a paired t-test ($p<0.05$).

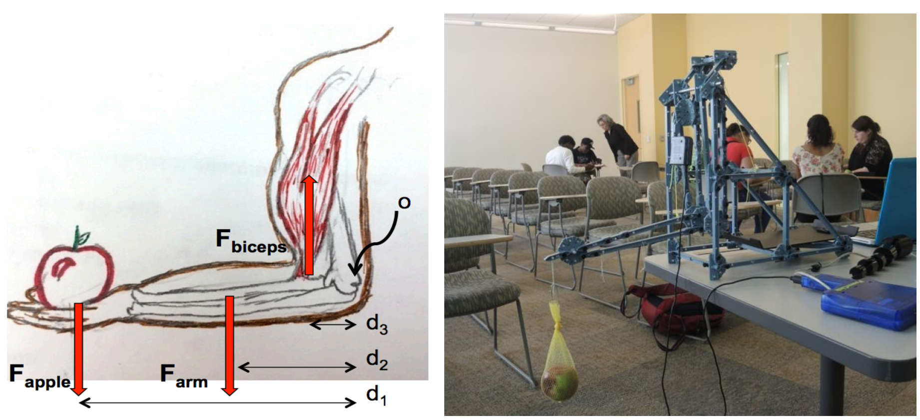

Figure 1: Free body diagram that was used to calculate the force of the biceps (left) and the PASCO mechanical arm system that was used as a class demonstration (right)

Results

Based on time constraints that became apparent on the first day, adjustments were made for the second day. Station 1 (the mechanical arm system) was changed to a class demonstration for all students (See **Figure 1)**, Station 2 was changed to a group activity, and Station 3 was changed to an optional take-home activity. A more detailed explanation of anthropometry was also added to the lecture. Results from the paired t-test reveal statistically significant improvements with $p<0.05$ from both days (See **Figure 3)**. This demonstrates the module is flexible and highly effective at introducing uncertainty analysis in elbow biomechanics. The results also revealed greater interest in Biomedical Engineering.

2. In the picture above, 'F' is a force applied to close a door and 'd' is the distance from the force applied to the point 'o'. The moment about point 'o' can be found using the following equation… $M = F \times d$, true or false? (circle only one)

   True   False   I don't know

3. The following number has how many significant figures? 0.0306 (circle only one answer)

   a. 2   b. 3   c. 4   d. 5

4. What's a reasonable weight for an apple in Newtons or pounds? (circle all that apply)

   a. 50 N   b. 100 N   c. 1.0 N   d. 0.5 lb   e. 5 lb

5. Write down any two factors that can affect the uncertainty and variability in weighing an apple.

Figure 2: Sample questions taken from the pre/post test

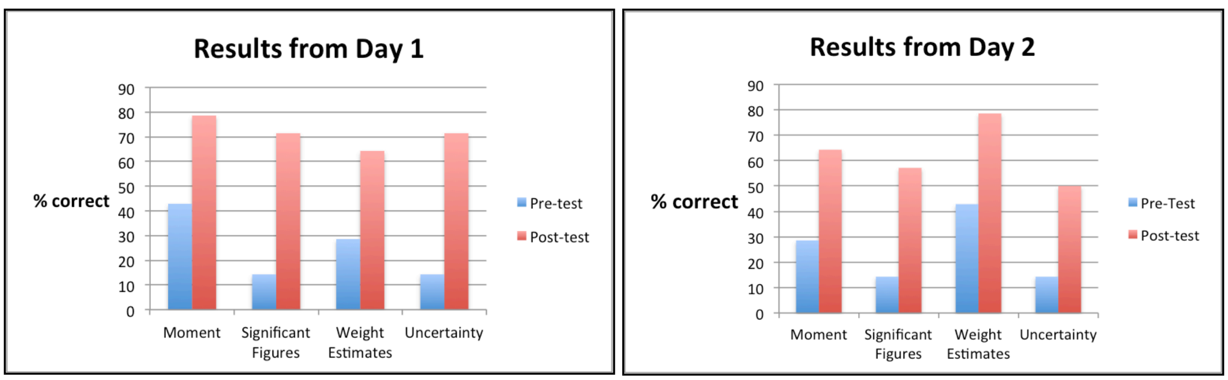

Figure 3: Results from Day 1 (left) and Day 2 (right) of the teaching module with a comparison between the pre-post tests

Undergraduate Level

Methods

Our college level module will be evaluated with juniors in a BME course: Biomedical Computation & Statistics in Spring 2015. The module will follow a similar format, but will emphasize the application of ANOVA statistics to a sensitivity analysis in elbow biomechanics modeling. The module will be incorporated into a lab exercise that introduces human variability, model customization, uncertainity, and sensitivity analysis on total model variance. Implementation of the college teaching module is still a work in progress, however, the lab exercise has been scheduled and the materials have been developed.

The lab will begin with a 10-20 minute PowerPoint lecture that refreshes the typical use of ANOVA and compares it to the sensitivity-based ANOVA analysis that is central to the Design of Experiments (DOE) method used by many medical device industries – and is also emerging rapidly in the biomechanics research field. Examples of the use of DOE in the medical device industry will also be provided to give the students a better sense of the various applications of uncertainty analysis in the

Biomedical Engineering field. The powerpoint lecture will also review basic concepts that will be used such as factors, levels, root mean square error (RMSE), anthropometry, and full factorial designs.

The in-lab activity will have the students create a MATLAB program to calculate the biceps muscle force required to hold up an object (apple, backpack, or milk jug etc.) at 90 degrees based on key input parameters from data found in literature. Students will set up a full-factorial analysis of the elbow biomechanics model, with "high" and "low" levels of each parameter based on the mean ± 1 standard deviation. An Excel sample data sheet will be provided that shows the patterns found within the combinations of the full factorial design. Next, students will perform an ANOVA analysis using MATLAB to idenify the overall mean to report the biceps muscle force for the most generic answer and the RMSE to reflect the uncertainty in this generic model. Using the results from ANOVA, they will then calculate the percent sum of squares (%SS) for each parameter with respect to the total model sum of squares and plot their result in a Pareto analysis bar graph (refer to **Figure 4)** to clearly show which parameters' variances are most critical in the model's calculations. While students are working on these calculations, the instructors will show individual students how to palpate their biceps muscle to locate the insertion point to measure the moment arm of the biceps that will be used later in the post-lab report. Finally, we will introduce JMP statistics software to the students and will briefly show them how to perform an ANOVA analysis on JMP that will also be used in their post-lab report.

The post-lab report will have students repeat the methods described above but with their own personal measurements to create a customized model as opposed to the generic population model done in lab. Students will also be asked to check their work using JMP. Finally, a discussion of uncertainty and variability must be included in the discussion section of the lab report.

Results from the undergraduate teaching module will be evaluated based on an indentical pre/post test with questions that have yet to be determined.

ANOVA TABLE

Source	SS	DOF	P	% SS
F_{apple}	3565.7	1.0	<.0001	**12.2**
F_{arm}	19940.8	1.0	<.0001	**68.3**
d_1	84.5	1.0	0.1	**0.3**
d_2	1408.7	1.0	<.0001	**4.8**
d_3	3585.9	1.0	<.0001	**12.3**
error	618.2			**2.1**
total	29203.8			

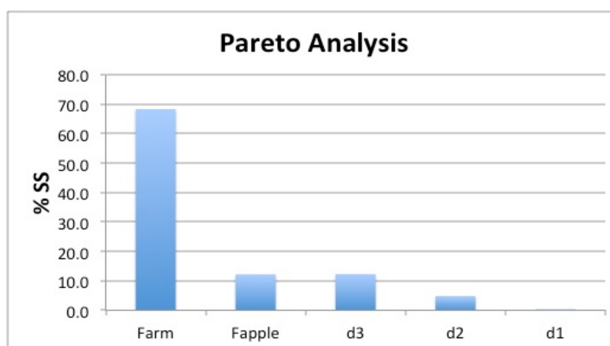

Figure 4: Sample Analysis of Variance table with the degrees of freedom, p-value and percent sum of squares (left) and the corresponding Pareto Analysis bar graph (right)

Conclusion and Dissemination

The ultimate goal of this educational innovation is two-fold. First, we aim to encourage students to think differently about problem-solving and experimental design at both the data collection stage and the analysis stage to consider all possible sources of uncertainty. Second, we intend to teach the advanced students how to analyze the %SS result in the ANOVA table to indentify which parameters contribute the most to the total model variance. Students will be encouraged to move away from the mindset that every problem has a definite answer and will in turn understand that uncertainty exists everywhere. Thus, experiments can be designed and measurement techniques select such that this uncertainty is reduced to an acceptable level. Both teaching modules, high school and undergraduate, have been designed for dissemination to the engineering education community.