Challenge-Based Instruction: The VaNTH Biomechanics Learning Modules

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Abstract - **This paper presents the methodology and results of teaching an engineering course using a challenge-based approach. The challenges consisted of eight biomechanics learning modules developed as part of the VaNTH NSF educational coalition. The pedagogical framework for these modules is based on the widely publicized book "How People Learn" (HPL). The HPL teaching framework presents the learning material as a series of challenges that are posed through a "Legacy Cycle." The VaNTH biomechanics modules were presented in an undergraduate Mechanical Engineering course titled "Biomechanics of Human Movement" in Fall 2004. The class (N=18) was divided into three-member teams. All challenges were performed by the teams using computer-based homework assignments that were supplied by the instructor on a CD. Pre-tests, post-tests, and affect rankings were administered for each modular topic. The students were also surveyed on the learning effectiveness of the various components of each module. At the end of the semester, the students completed a Biomechanics topics matrix that mapped the challenges to the various class topics. Results of this classroom experience and data gathering are presented in this paper.**

Index Terms – Bioengineering Education, Biomechanics, Challenge-Based Instruction, Learning Modules, VaNTH.

INTRODUCTION

The course ME 354M, "Biomechanics of Human Movement," is an undergraduate technical elective in Mechanical Engineering (ME). In the past, the course was taught in a traditional format with chalkboard lectures and overhead transparencies, and with paper handouts distributed as needed. There is no required textbook for the course and the primary lecture content has been prepared over the years by the first author. In the Fall 2004, the course was taught in a different manner using the VaNTH Biomechanics modules.

The participation of this class was part of a much larger educational research consortium, the NSF-sponsored VaNTH Engineering Research Center for Bioengineering Education [1]. The objective of the consortium is to develop a new generation of teaching materials and novel approaches for the education of bioengineering students. The pedagogical motivation for the consortium is based on the widely publicized book "How People Learn" (HPL) by Bransford, et al. [2]. The HPL teaching framework presents the learning material as a series of challenges that are posed through a Legacy Cycle [3]. The Legacy Cycle (Figure 1) methodically marches the students through the challenge-based material. Key stages in the Legacy Cycle are: 1. posing the challenge and learning objectives; 2. asking students to generate ideas; 3. providing students with multiple perspectives; 4. making students research and revise; 5. testing students' mettle; and 6. having them go public.

PREVIOUS RESEARCH

The Biomechanics modules were tested in the classroom in both Fall 2002 and Fall 2003. The primary research question was to determine if the HPL approach increases the students' adaptive expertise in biomechanics, when compared to the traditional lecture approach of earlier years. Student achievement was quantified using pre- and post-test questionnaires designed to measure changes in three facets of adaptive expertise: factual knowledge, conceptual knowledge, and the ability to transfer knowledge to new areas. Statistical analysis of the results showed that the HPL approach increased students' conceptual knowledge as well as their ability to transfer knowledge to new situations [4]. These findings indicate that challenge-based instruction, when combined with an intellectually engaging curriculum and principled instructional design, can accelerate the trajectory of novice to expert development in bioengineering education.

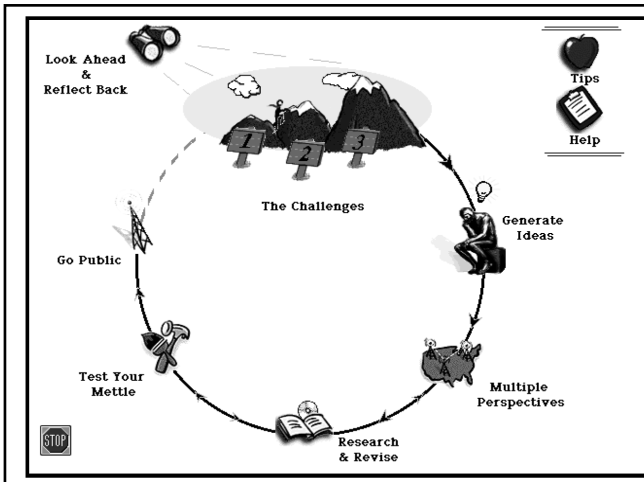

FIGURE 1
THE LEGACY CYCLE FRAMEWORK.

Classroom Instruction and Testing Methodology

Buoyed by these earlier findings, the VaNTH Biomechanics modules were fully implemented for the first time in Fall 2004. A total of 18 students were enrolled in the ME 354M course that semester. At the start of the course, the students were asked to sign a human subject consent form, and they then took a pre-course test. The pre-course test consisted of thirty multiple-choice questions over a variety of Biomechanics topics. The same set of multiple-choice questions was also used at the end of the course as a post-course test. The students were then divided into three-member teams.

While there were eight VaNTH Biomechanics challenges, as shown in Table I, they were organized into four topical areas: The Iron Cross (one challenge); The Virtual Biomechanics Laboratory (three challenges); Jumping Jack (three challenges); and The Knee (one challenge). The same instruction and testing methodology was used for each topical area. First, some background lectures on the topic were given using Powerpoint slide shows. The students took a pre-test and completed an affect survey. They then performed the challenges posed on the CD using the Legacy Cycle. After the completion of each topical area, the students took a post-test and a post-affect survey.

Three times during the semester (Pre, Mid, and Post), a student outcomes survey was administered. These student outcomes were patterned after the requisite ABET outcomes, but were geared towards Mechanical Engineering topics. All tests and exercises were graded using uniform grading rubrics. At the end of the semester, the students also completed a learning effectiveness survey for each of the eight challenges and filled out a matrix that mapped general Biomechanics topics to the modules. A lengthy white paper, summarizing this classroom implementation and testing experience, was prepared by the authors after the course ended [5].

TABLE I
SUMMARY OF THE EIGHT VANTH BIOMECHANICS CHALLENGES

Iron Cross Challenge: "How much muscle strength is required to sustain the Iron Cross position."
Virtual Biomechanics Lab I Challenge: "How does your whole body center of gravity move when you walk?"
Virtual Biomechanics Lab II Challenge: is "What forces do you exert on the ground when you walk?"
Virtual Biomechanics Lab III Challenge: "How do the leg muscles activate during one complete gait cycle?"
Jumping Jack I Challenge: "How high can you jump?"
Jumping Jack II Challenge: "What determines jump height?"
Jumping Jack III Challenge: "What determines who can jump higher?"
Knee Challenge: "Can Voluntary Contraction of the Quadriceps Muscle Group Tear the Anterior Cruciate Ligament (ACL) During an Isometric Knee Extension Exercise."

The VaNTH Biomechanics Challenges

I. The Iron Cross Challenge

The Iron Cross (IC) challenge is "How much muscle strength is required to sustain the Iron Cross position (Figure 2)." The challenge is formulated in the context of a free body diagram (Figure 3). This compels the students to think about the static mechanics of the position, which leads to the major observation: the Iron Cross is a static indeterminate problem due to the multiple muscle actuators that cross the shoulder joint. Thus, the students must make initial assumptions, calculate the moment arms for all muscle actuators at the given arm angle, and solve for the muscle forces needed to maintain the Iron Cross position.

FIGURE 2
THE IRON CROSS POSITION.

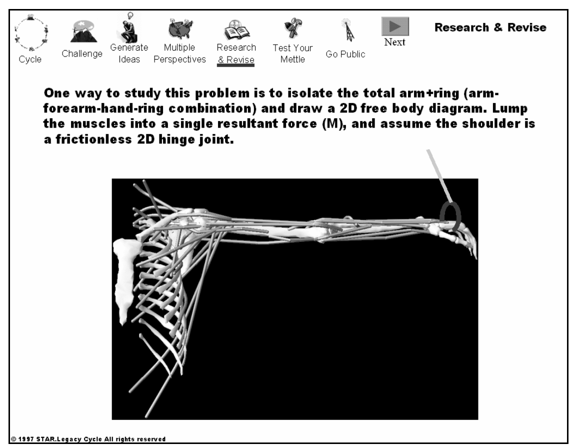

FIGURE 3
THE IRON CROSS IS A STATICALLY-INDETERMINATE PROBLEM.

II. The Virtual Biomechanics Laboratory Challenges

The Virtual Biomechanics Laboratory (VBL) module consists of three challenges, all concerned with experimental observations (kinematics, kinetics, muscle activation) made in a gait analysis lab (Figure 4). Numerous video-audio clips are given as background information on human gait (Figure 5). The students are then presented the main exercise, which is to find the whole body CG using a formula pasted into an Excel spreadsheet. The second VBL challenge continues this inquiry into gait analysis, this time focusing on measurements from a ground reaction force plate. The third VBL challenge focuses on identifying the major leg muscles involved in gait, and then processing the electromyographic (EMG) activity from these muscles using a sliding RMS window.

FIGURE 4
VIRTUAL BIOMECHANICS LABORATORY FOCUSES ON GAIT ANALYSIS.

FIGURE 5
MULTIPLE PERSPECTIVE VIDEO CLIP FROM A PROFESSOR.

III. The Jumping Jack Challenges

The Jumping Jack (JJ) module consists of three challenges, all concerned with the biomechanics of human jumping (Figure 6) and the equations of motion for projectile dynamics. The first JJ I challenge is "How high can you jump?" A spreadsheet is given with experimental jumping data collected from a human subject. The data contains columns for: ground reaction force, and the vertical position, velocity, and acceleration of the subject's center of mass (COM). The students are then asked to calculate jump height in different ways. One way is to integrate the acceleration curve (Figure 7) to get the lift-off velocity using the formula:

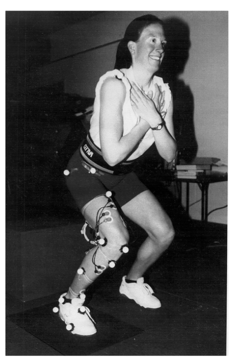

FIGURE 6
JUMPING JACK MODULE FOCUSES ON VERTICAL JUMPING.

$$\dot{y}(0) = \int a dt = \int \frac{F}{m} dt - \int g dt$$

They then calculate jump height using a projectile equation. The second and third JJ challenges deal with computer graphics modeling and simulation of vertical jumping.

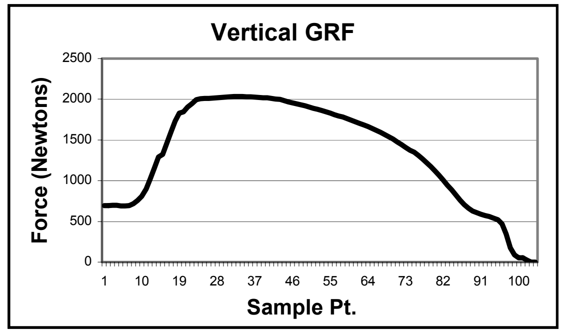

FIGURE 7
THE VERTICAL GROUND REACTION FORCE (GRF) FOR A SQUAT JUMP.

IV. The Knee Challenge

The final challenge involves studying the knee joint. The challenge is posed by the question "Can Voluntary Contraction of the Quadriceps Muscle Group Tear the Anterior Cruciate Ligament (ACL) During an Isometric Knee Extension Exercise." The students use an Excel spreadsheet that contains kinematics data of the knee during a simulated flexion experiment. Using a free body diagram, they derive the forces at the knee and then calculate the force in the ACL as a function of the flexion angle. They plot the forces in the ACL and then determine if the ACL force ever exceeds the given maximum ACL force of 2000 N.

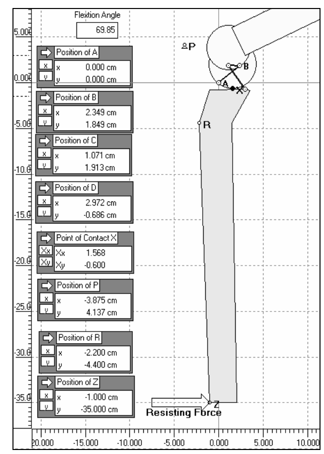

FIGURE 8
THE KNEE DIAGRAM USED TO SOLVE THE ACL PROBLEM.

RESULTS OF CLASSROOM TESTING

The classroom testing of the challenges were outlined earlier in Table 1. The following are results of the various testing and survey methods employed in the course.

I. Pre-Course and Post-Course Test Results

On the first class day, the students took a comprehensive pre-course test consisting of thirty multiple-choice questions that covered all topics covered in the course. The same thirty-question test was given on the last class day as a post-course test. Table II shows the numerical results depicting the average pre-course and post-course scores. It can be seen that, on the average, there was an increase of 7.72 points in the post-course test, when measured against the pre-course test. This equates to the students answering approximately eight more questions correctly, out of thirty, at the end of the course.

TABLE II
PRE-POST COURSE TEST SCORES (N=18)

Pre-Course Average (Std. Dev.)	Post-Course Average (Std. Dev.)	Gain (Post-Pre)
15.17 (3.47)	22.89 (2.81)	7.72
Effect Size = 2.46		

In order to determine if the pre-post conditions are significantly different, an Effect Size (E.S.) statistic [6] is calculated using the formula:

$$E.S. = \frac{AVE_{Post} - AVE_{Pre}}{pooled\ \ Std.Dev.},$$

Where AVE_{Post} is the average post score, AVE_{Pre} is the average pre score, and *pooled Std. Dev.* is the average of the pre standard deviation and the post standard deviation. An E.S. of 1.3 is considered significant at the 90% level, an E.S of 1.6 is considered significant at the 95% level, and an E.S. of 2.5 is considered significant at the 99% level, assuming a normal distribution of scores. For example, the E.S. of 2.46 in Table II indicates that the post-course scores were clearly statistically better than the pre-course scores at close to a 99% certainty level.

II. Module Pre-Test and Post-Test Results

As indicated earlier, four topical areas were addressed by the eight challenges. Thus there were four sets of module pre-tests and post-tests. The pre-post tests were the same for each module. A grading rubric was created for each test, and the maximum score was normalized to five points for each test. Table III shows the distribution of pre-test and post-test score averages for all four topical areas, along with the Effect Size (E.S.) statistic. It can be seen that the gain from pre to post-tests scores was positive for all four cases, ranging from 0.55 to 1.06, on a scale of 5.00 maximum points.

An observation worth noting is the widely-varying range in the E.S. statistic, from a non-significant value of 0.70 for the Knee module, to a highly significant value of 2.75 for the Jumping Jack module. This suggests that the challenges' levels of difficulty, at least as represented by pre-post tests, varied somewhat. Based on the E.S. score, one would suggest that the Knee module is more straightforward than, for example, the Jumping Jack module. This might suggest a re-ordering of presentation of the modules in the course. Perhaps a more pedagogically acceptable order would be: Knee, Iron Cross, Virtual Biomechanics Lab, and Jumping Jack.

III. Pre-Affect and Post-Affect Survey Results

A student's learning during an educational experience cannot be totally measured by a test score or graded work. The development of appropriate attitudes towards learning can be a significant factor in an educational experience. Our group has developed an affect survey to measure these subjective learning factors.

TABLE III
SUMMARY OF PRE-POST TESTS FOR THE FOUR TOPICAL MODULES

Module Topic	Pre-Test Ave. (Std. Dev.)	Post-Test Ave (Std. Dev.)	Gain (Post-Pre)	Effect Size
Iron Cross	3.28 (0.63)	4.11 (0.54)	0.83	1.41
Virtual Biomechanics Lab	2.55 (0.46)	3.26 (0.34)	0.70	1.78
Jumping Jack	2.51 (0.39)	3.57 (0.38)	1.06	2.75
Knee	3.30 (0.99)	3.85 (0.58)	0.55	0.70

TABLE IV
LEARNING FACTORS USED IN THE AFFECT SURVEY

1. I gain factual knowledge (terminology, classifications, methods, trends).
2. I learn conceptual principles, generalizations, and/or theories.
3. I get a chance to talk to other students and explain my ideas to them.
4. I am encouraged to frequently evaluate and assess my own work.
5. I learn to apply course materials to improve my own thinking, problem solving, and decision making skills
6. I develop specific skills, competencies, and points of view needed by professionals in the field.
7. I acquire interpersonal skills in working with others in the class.

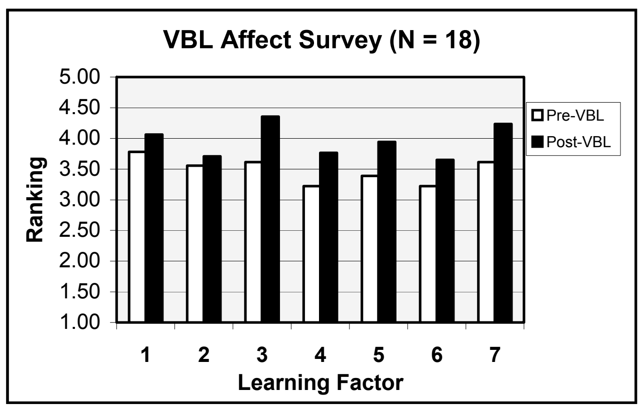

FIGURE 9
Results of Pre-Post Affect Survey for the VBL Modules.

Table IV lists seven affect learning factors that students typically would acquire in a positive educational experience. These affect factors include experiences in talking and working with other students in the class, gaining factual knowledge and competencies, and improving critical thinking. This affect survey was administered to the students in conjunction with the pre- and post-test tests for all four modules. The students were asked to rank their quality of learning in these seven affect factors using a 5-point scale of 1-None, 2-Below Average, 3-Average, 4-Good, or 5-Exceptional. An example result of this pre-post affect survey for VBL is shown in the bar chart of Figure 9.

TABLE V
AVERAGE POST-PRE GAIN IN AFFECT SURVEYS.

Learning Factor	Iron Cross Post-Pre Gain	VBL Post-Pre Gain	Jumping Jack Post-Pre Gain	Knee Post-Pre Gain	Average Post-Pre Gain
1	0.00	0.28	0.06	0.40	0.185
2	0.06	0.15	0.47	0.51	0.297
3	1.61	0.74	0.29	0.41	0.763
4	0.83	0.54	0.53	0.33	0.558
5	0.28	0.55	0.24	0.17	0.310
6	-0.28	0.42	0.18	0.32	0.160
7	1.78	0.62	0.41	0.35	0.790

Table V shows the results of all affect surveys as a function of each learning factor. As can be seen, almost all learning factors had a positive gain in all the modules. Indeed, out of 28 possible cases, there was only one learning factor that had a negative gain (learning factor six in the Iron Cross). This is true despite the fact the students ended completing this same pre-post affect survey eight times during the course. Thus it can be concluded that each VaNTH module had its own positive affect experience within itself, as well as the course as a whole. Based on magnitude of the gains, learning factors 3, 4, and 7 had the most impact on the students. Thus it appears that working in teams and assessing work through interpersonal relations are important aspects to this challenge-based approach to education.

IV. Outcomes Surveys Results

Student outcomes are defined by the Accreditation Board for Engineering and Technology (ABET) [7] as the knowledge, skills, abilities, and attitudes that engineering undergraduates should be able to demonstrate at the time of graduation. Table VI lists the ten program outcomes (PO's) for the Mechanical Engineering Department at the University of Texas at Austin. These ten program outcomes apply to all courses in the ME department, and not just the Biomechanics course.

In an effort to see how the course was achieving these departmental-wide outcomes, the students were asked to describe their improvement in each outcome as a result of learning activities provided in the course. This PO survey was conducted three times during the course: Pre, Mid, and Post. The ranking scale was: 1-No skill/ability, 2-A little skill/ability, 3-Some skill/ability, 4-Significant skill/ability, and 5-Very significant skill/ability. The results of these three surveys are shown in the comparative bar chart of Figure 10. It can be seen that the students felt that some of the outcomes were achieved. In particular, outcome numbers 1, 2, 5, 6, and 7 showed a steady rise in ranking from the pre-, through the mid-, and then to the post- conditions. On the other hand, some outcomes (3, 4, 8, 9, and 10) showed little gains.

TABLE VI
THE ME STUDENT PROGRAM OUTCOMES.

1. Knowledge of and ability to apply engineering and science fundamentals to real problems.
2. Ability to solve open-ended problems.
3. Ability to design mechanical components, systems and processes.
4. Ability to setup, conduct and interpret experiments and to present the results in a professional manner.
5. Ability to use modern computer tools in mechanical engineering.
6. Ability to communicate in written, oral and graphical forms.
7. Ability to work in teams and apply interpersonal skills in engineering contexts.
8. Ability and desire to lay a foundation for continued learning beyond the baccalaureate degree.
9. Awareness of professional issues in engineering practice, including ethical responsibility, safety, the creative enterprise, and loyalty and commitment to the profession.
10. Awareness of contemporary issues in engineering practice, including economic, social, political, and environmental issues and global impact.

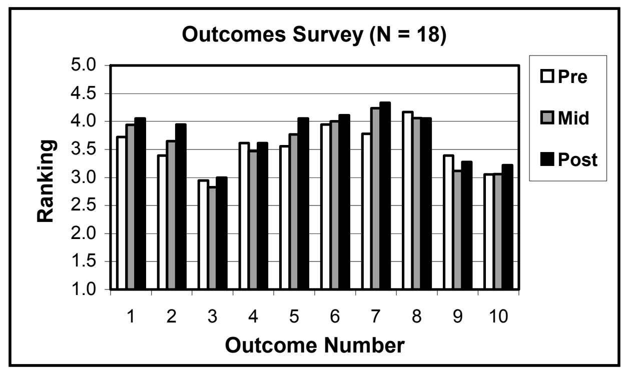

FIGURE 10
RESULTS OF THE PRE-, MID- AND POST-OUTCOMES SURVEYS

V. Biomechanics Topics Matrix

A final survey was conducted at the end of the course. The students were asked to complete a "Biomechanics Topics" matrix. The survey form (Figure 11) had a listing in the left-hand column of all pertinent topics that should be taught in an undergraduate Biomechanics course. This list was derived from a extensive taxonomy effort conducted by the VaNTH Biomechanics domain leaders. The students were asked to check the appropriate cells for each challenge that they felt addressed that particular topic. The results are shown in Figure 11, with the total number of mentions (counts) reported by all the students (N=18) in each cell. Those cells with 12 or more counts are shaded dark, those with 6 to 11 counts are shaded light, and those with less than 6 counts are not shaded. The total counts for each topic are summed in the final column. It can be seen that almost every topic had at least one shaded cell, with a few exceptions. The most notable topics omitted in the course were calculations for the moment of inertia and radius of gyration. Nonetheless, the results of this Biomechanics matrix exercise are gratifying and prove that the topics can be taught using this challenge-based approach.

Biomechanics Topics	Iron Cross	VBL I	VBL II	VBL III	Jumping Jack I	Jumping Jump II	Jumping Jack III	Knee I	Total Counts
Skeletal System	11	8	4	4	3	3	3	16	52
Muscular System	18	10	10	16	11	14	13	15	107
Mechanical Properties of Muscle	12	1	2	8	8	10	10	10	61
Stress and Strain in Muscle	13	1	1	3	2	2	4	11	37
Classification of Human Movements	10	16	13	12	9	9	10	11	90
Joint Biomechanics	11	4	2	1	4	3	4	16	45
Dimensions, Units, Conversions	13	12	11	12	12	12	11	11	94
Anthropometrics	15	13	6	4	4	4	4	2	52
Center of Gravity Calculation	2	17	11	8	9	7	5	0	59
Moment Arm Calculation	18	3	3	2	6	7	6	10	55
Moment of Inertia Calculation	3	2	1	1	5	8	2	1	23
Radius of Gyration Calculation	1	1	0	0	1	4	1	0	8
Free Body Diagrams	17	8	11	4	8	10	8	18	84
Static Equilibrium Problem	18	2	2	2	1	2	0	14	41
Linear Kinematics	3	13	11	5	13	12	10	3	70
Angular Kinematics	4	4	4	2	6	12	8	6	46
Finite Difference Calculation	0	6	11	8	5	5	3	0	38
Dynamics of Link Segments	2	7	4	3	7	9	12	7	51
Reaction Forces	12	7	15	12	11	8	6	14	85
Torque Summation	15	1	1	1	3	11	7	15	54
Impulse-Momentum Problem	0	0	0	0	16	9	8	0	33
First-Order Systems	3	3	2	2	8	8	5	4	35
Second-Order Systems	0	0	0	1	5	10	10	1	27
Projectile Dynamics	0	0	0	0	13	14	10	0	37
Experimental Techniques	5	17	17	16	13	11	11	4	94
Experimental Equipment	4	17	17	16	13	9	10	3	89
Electro-physiology and Neural Control	0	4	4	12	2	2	4	1	29
Signal Processing of EMG	0	5	6	17	3	3	3	1	38
Computer Graphics Modeling and Simulation	2	8	10	10	5	11	13	9	68
Total Counts	212	190	179	182	206	229	201	203	

FIGURE 11
THE BIOMECHANICS TOPICS MATRIX

SUMMARY AND CONCLUSIONS

This paper presented the classroom implementation of the challenge-based VaNTH Biomechanics learning modules. A variety of tests and surveys were implemented in this educational research effort. While preliminary results indicate the course had a very positive influence on the students' learning, one must caution that the class sample size (N=18) is small and a larger sample size would make the case stronger.

The results for the pre-course versus post-course tests showed that the students increased their knowledge and skills in the field of Biomechanics. On the average, the class was able to answer 8 more questions correctly (out of 30 multiple choice questions) after the course than before the course, and the effect size statistic (2.46) clearly shows significance.

The pre-test and post-test methodology worked well. The results are convincing that the students learned the material. Out of 72 possibilities (4 modules x 18 students), there were only six instances were a student showed a decrease in the post-test scores. Also, the gain from pre- to post-test showed at least a 0.55 point improvement or higher in all cases. Furthermore, three of the four effect sizes for the pre-post test results were above 1.3 (90% confidence level).

The pre- and post-affect surveys are also valuable instruments to measure the subjective aspects of student learning. It is interesting to note that there was only one negative gain in affect out of all possibilities. This demonstrates that the modules had a positive influence on the students' learning experiences throughout the course.

Outcome testing is one way to determine where a particular course fits into the overall curriculum or degree plan. Based on the results of this outcomes survey, it appears that the VaNTH Biomechanics modules contribute to the following ME outcomes: 1 (basic science and engineering knowledge), 2 (problem solving), 5 (modern computer skills), 6 (communication), and 7 (teamwork). No doubt that by working in teams, by using the Legacy Cycle, and by discussing the "Test Your Mettle" exercises, the students realized a higher level of satisfaction and a feeling of accomplishment in the course.

The results of the Biomechanics Topics matrix are pleasing to the authors. It supports the contention that a semester-long, complete Biomechanics course could be taught using these eight challenges as the primary method of educational delivery. Almost all of the important Biomechanics topics were covered in one or more of the challenges. Thus challenge-based instruction can deliver the same body of knowledge and understanding as a traditional engineering course, while motivating students to engage in interesting problems that use these fundamental topics.

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