

DETC2015-46060

HAPTIC MODULES TO AUGMENT UNDERGRADUATE MECHANICS EDUCATION

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ABSTRACT

This article reports the evaluation results of the software modules we are developing to augment teaching and learning in standard required undergraduate engineering mechanics courses. Using these modules, students can change parameters, predict answers, compare outcomes, interact with animations, and “feel” the results using a force feedback joystick. The overall system aims to increase teaching and learning effectiveness by rendering the concepts compelling, fun, and engaging. Three software modules in Dynamics were evaluated by a sample of the target population, 40 undergraduate engineering students who were enrolled in a sophomore-level Dynamics course. Students showed significant preference in that the modules would increase both their interest in the dynamics subject ($p < .001$) and their engagement in the Dynamics course ($p < .05$). Evaluation results also showed significant difference in preference in that the modules would improve students’ conceptual understanding of the Dynamics subjects ($p < .001$) and problem-solving skills ($p < .001$). Tactile learners believed that the modules would improve their conceptual understanding of Dynamics subjects more than the visual learners ($p < .05$). 97.5% of the students were willing to use the software again in the future. 92.5% of the students believed that the incorporation of this software to the instruction of Dynamics would be beneficial to their learning.

KEYWORDS

Haptics, undergraduate engineering, engineering mechanics courses, virtual reality, force feedback, user evaluation, Dynamics

1. INTRODUCTION

Haptics is related to the sense of touch and forces in humans. Haptic interfaces provide force and touch feedback from virtual models on the computer to human users. Existing papers relating haptics and education are largely from the medical training field. The Interventional Cardiology Training Simulator [1] linked technical simulation with specific medical education content. A virtual reality based simulator prototype for the diagnosis of prostate cancer was developed [2]. The Immersion Corporation (www.immersion.com) developed haptic interfaces for injection training and sinus surgery simulation; these interfaces are expensive and special-purpose. The GROPE Project [3] developed over 30 years a 6D haptic/VR simulation of molecular docking. Howell et al. [4] describe a virtual haptic back model for improving the learning of palpatory diagnosis by medical students. A research group at the Ohio Supercomputing Center applied haptics in virtual environments to improve tractor safety by training young rural drivers [5]. Their results show haptics increases training effectiveness, but access to their unique training system is limited. Haptics was applied to make virtual environments accessible to blind persons [6,7]. The effectiveness of virtual reality in the learning process has been demonstrated by many authors [8].

Jones et al. [9] explored viruses with middle and high school students with haptic feedback from the very expensive PHANToM haptic interface. Williams et al. [10,11] developed haptics-augmented software activities and tutorials for improving the teaching and learning of K-12 science. This work included alpha and beta software testing with students. Immersion Corporation [12] investigated the potential benefits of incorporating their commercial haptic mouse into software

intended for college and high school physics curricula. Bussell [13] posed the question “Can haptic technology be applied to educational software and Web sites to enhance learning and software usability?” and presented a review article. The thesis of Dede et al. [14] was that “learning difficult, abstract material can be strongly enhanced by multi-sensory immersion”. Okamura et al. [15] developed their own single axis force-feedback ‘haptic paddle’ which students build to support linear systems in engineering education. Minogue and Jones [16] present a baseline review article concerning the role of touch in cognition and learning. Richard et al. [17] present a multi-modal virtual environment with a range of haptic feedback, for students to explore the energy levels in the electron bound state in the Bohr atom model. Grow et al. [18] review their work in educational haptics at all levels to encourage young students to consider STEM careers. Brandt and Colton [19] investigate the suitability of the LEGO MindStorms kit for college and pre-college students to build haptic interfaces to learn programming and engineering concepts.

This paper presents the overall structure of our system along with the evaluation results for three of the haptic modules for undergraduate dynamics course: “Crate on the Ramp” (Particle Dynamics), “Race Car on the Track” (Particle Dynamics), and “Sliding Box” (Rigid-Body Dynamics).

2. SYSTEM DESCRIPTION

2.1 Haptic Interface

The system is flexible to be used with any DirectX-compatible force feedback joystick that is readily available. We successfully tested the modules using Logitech Wingman Force 3D, Force™ 3D Pro (both shown in Figure 1), and the Microsoft Sidewinder joysticks. Joysticks without force feedback can also be used with the system, but this would limit the capabilities of the modules to only animation.



Figure 1. Logitech Wingman (left) and Force™ 3D Pro (right) Joysticks. The software can be used with any off-the-shelf DirectX-compatible force feedback joystick.

2.2 Process Flow

The overall process chart is shown in Figure 2. Users must enter their user name and password in order to access the system. In the case of first time users, a new user account can be created using the sign-in menu. Once the students sign in to the system, first time users are required to view an introductory Flash tutorial before they can start their practice. This tutorial is also accessible by all users anytime during their practice via the drop-down menu at the top section of the screen. Returning users can directly sign in using their existing user name/password combination. The users can select any available module for practice and construct a new problem by changing the variables. The flexibility of changing the problem variables

allows students to experiment, visualize and “feel” the corresponding changes on the forces acting on an object and its motion (when applicable) For instance, a crate on the ramp may remain at rest, move up or down the ramp depending on several physical properties (mass, static friction coefficient etc.) and the amount of applied force. Once the variables are chosen, the problem is activated. At this point, the variables cannot be changed until the user manually stops or cancels the current simulation. The simulation starts by pressing the designated (trigger) button on the joystick. A significant contribution of this system is the augmentation of haptics by enabling the students to select and feel any force that is acting on the object of interest by using the joystick. The forces reflected to the users are normalized so that the maximum force value corresponds to the maximum force that the joystick can exert to user’s hand.

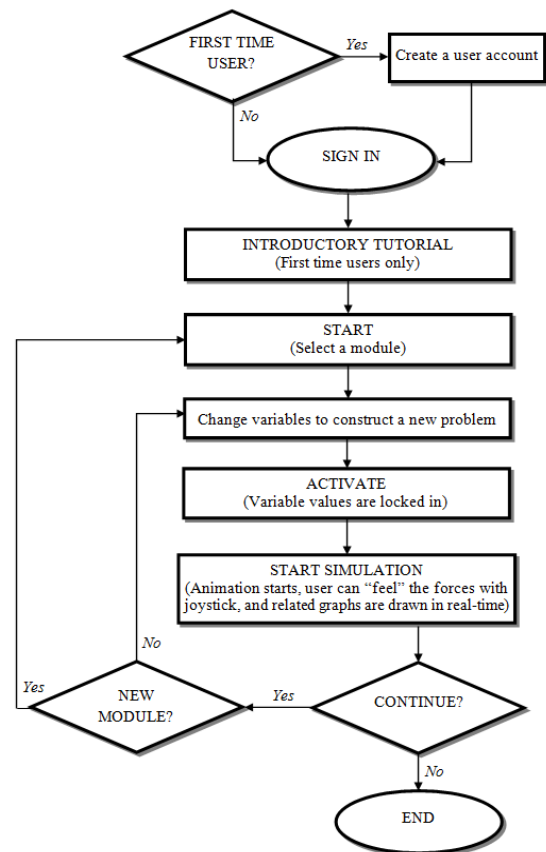


Figure 2. Process flowchart

2.3 User Interface and Virtual Environment

The virtual environment for each module was designed using the same functional elements in order to ease the transition from one module to the other. The sign-in menu for the modules is a dialog box and serves as the entrance to the system. Using the sign-in menu users can: 1) Create a user name and a password before they start their practice, 2) Retrieve their user name/password. Users are required to sign in to be able to access the available modules. A unique user name is necessary to store individual user data in the database to keep track of users’ progress with practice.

The screen layout (Figure 3) is the same for all modules and consists of several elements. The simulation view is located

in the middle of the screen and is the largest element for easy viewing of the simulated objects. “Course View” that is on the left side of the screen allows students to select a particular module to practice or to switch another one at any time. On the right side of the screen, “Variables View” includes the variables specific to the active module. “Results and Messages View” at the bottom of the screen displays any messages, errors (e.g., if the user enters a value that is out of the acceptable range) and summary of the variables that were locked in after activating a problem. “Graphs View” appears when a problem’s variables are adjusted and activated. It replaces the Course View on the screen until the simulation is stopped by the user.

3. MODULES DESCRIPTION

This section presents an overview of our development and implementation of the haptics-augmented “Crate on the Ramp”, “Race Car on the Track”, and “Sliding Box” modules for undergraduate engineering dynamics (Figure 4). More detailed descriptions of the modules including their mathematical models can be found in [20]. The same process and computer implementation will be followed for all ensuing haptic modules to be developed.

3.1 Crate on the Ramp (Particle Dynamics)

3.1.1 Problem Description

A point mass m is on a ramp inclined by angle θ , with an applied force F inclined by angle ϕ relative to the ramp, as

shown in Figure 4. With the point mass assumption, there can be no box rotation by definition. The static coefficient of friction between the point mass and ramp is μ_s , and the kinetic (dynamic) coefficient of friction between the point mass and ramp is μ_k .

3.1.2 Implementation

User sets:

- Mass of the crate
- Ramp angle
- Force angle
- Static friction coefficient
- Dynamic (kinetic) friction coefficient
- Externally-applied force (magnitude)

Computer sets: $g = 9.81 \text{ m/s}^2$.

Visualization:

Free-body diagram with forces to scale, plus kinematics plots for acceleration, velocity, and position of the crate.

User Feels:

The joystick displays the following vector forces on the interactive FBD (one at a time) to the user’s hand:

- Externally-applied force
- Normal force
- Friction force
- Weight

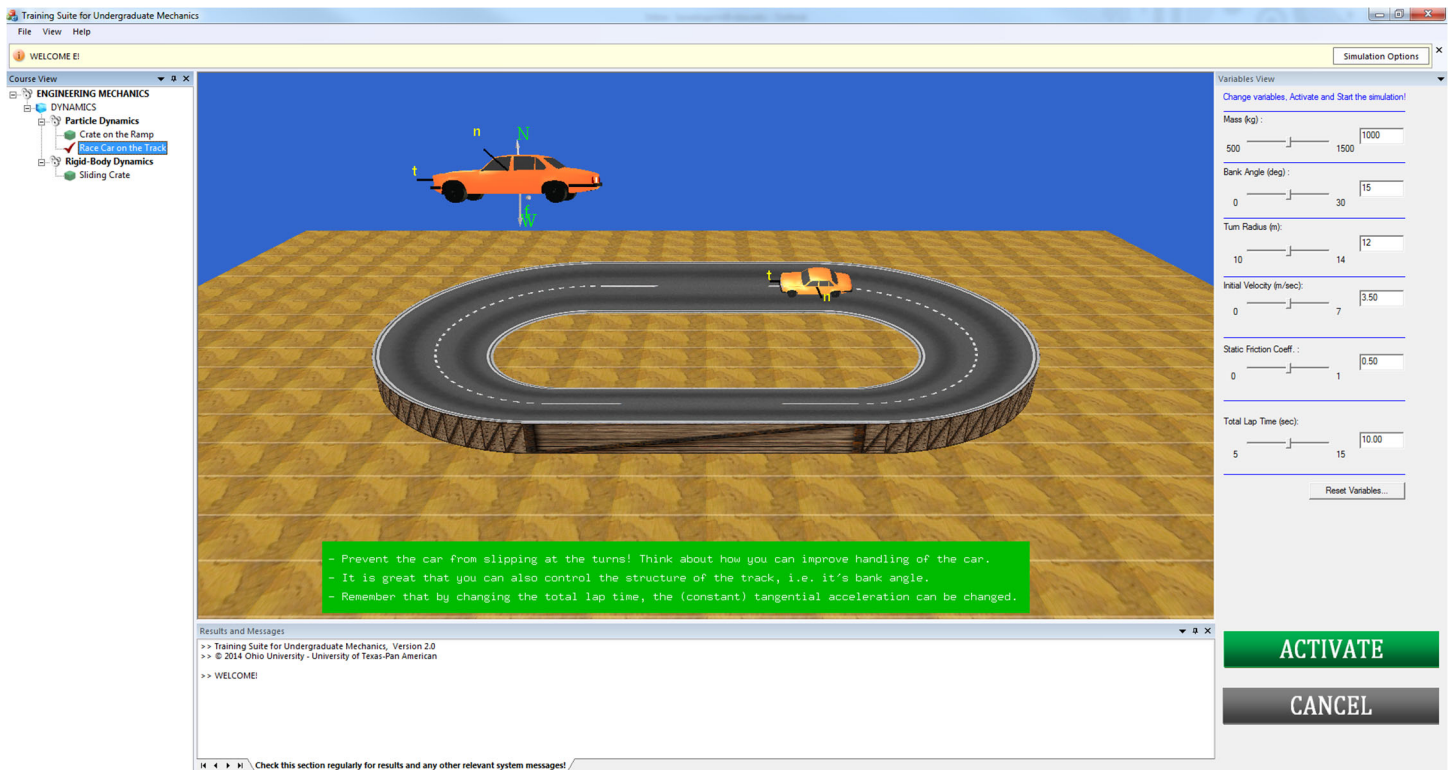


Figure 3. Screen Shot (Race car on the Track module shown)

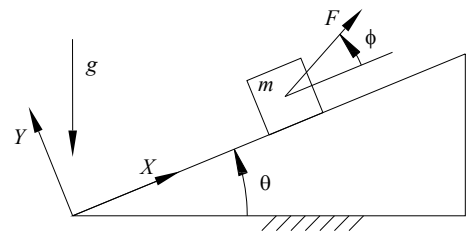
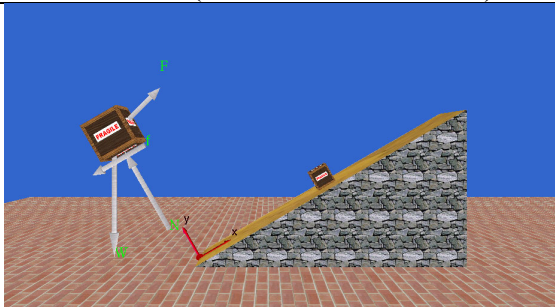
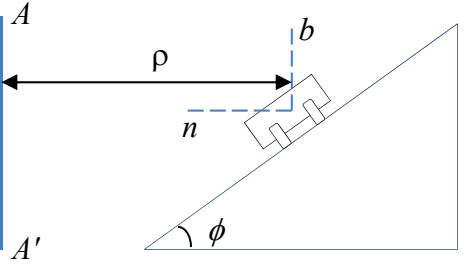
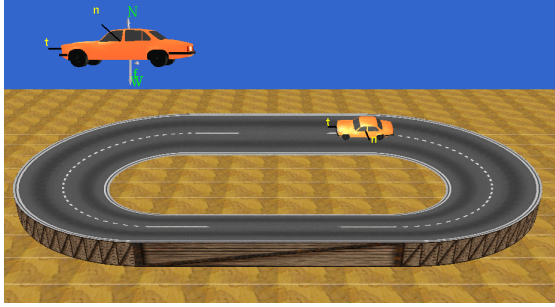
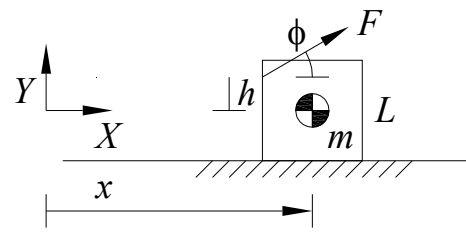
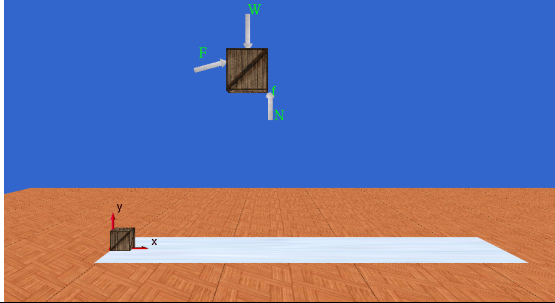
Module		Schematic	Screenshot (User interface not shown)
Particle Dynamics	Crate on the Ramp		
	Race Car on the Track		
Rigid-Body Dynamics	Sliding Box		

Figure 4. Current Haptic Modules for Training in Undergraduate Mechanics

3.2 Race Car on the Track Module

3.2.1 Problem Description

A point mass (the race car) of mass m moves with *constant* tangential acceleration on a track that is composed of two curved (half-circles) and two straight portions, as shown in Figure 4. The coefficient of static friction between the vehicle (tires) and the track surface is μ_s . The turn radius ρ is the perpendicular distance between the vehicle and the axis passing through the center of the half-circles during the turns (AA' on the following diagram). The structure of the track can be changed by using the bank angle variable, ϕ . Total lap time is also specified by the user which changes the constant tangential acceleration of the vehicle.

3.2.2 Implementation

User sets:

- Mass of the race car
- Bank angle of the track
- Turn radius (i.e., radius of curvature at the turns)
- Initial velocity at the start line
- Static friction coefficient (checked to prevent slipping before start)
- Total lap time (for only one full lap)

Computer sets: $g = 9.81 \text{ m/s}^2$.

Visualization:

Free-body diagram with forces to scale, plus kinematics plots for the normal and tangential acceleration, and the velocity.

User Feels:

The joystick displays the following vector forces on the interactive FBD (one at a time) to the user's hand:

- Normal force
- Friction force
- Weight

3.3 Sliding Box (Rigid-Body Dynamics)

3.3.1 Problem Description

A rigid-body box of mass m is pushed along a flat motion surface by a force F , angled at ϕ , as shown in Figure 4. The static and dynamic (kinetic) coefficients of friction between the box and motion surface are μ_s and μ_k , respectively. The planar size of the box is a square of side L , the center of mass (CG) of the box is in the geometric center of the square, and force F is applied a distance h above the center of mass.

3.3.2 Implementation

User sets:

- Mass of the box
- Vertical distance of the applied force from the center of gravity
- Dynamic (kinetic) friction coefficient
- Static friction coefficient
- Externally-applied force (magnitude & angle with the x-axis)

Computer sets: $g = 9.81 \text{ m/s}^2$, side length of the box (a cube with $L = 1 \text{ m}$).

Visualization: Box motion to the right, plus kinematics plots for the acceleration, velocity, and position of the box.

User Feels:

The joystick displays the following vector forces on the interactive FBD (one at a time) to the user's hand:

- Externally-applied force
- Normal force
- Friction force
- Weight

4. METHODS

4.1 Participants

The students were from the target population of this software, students who were actively enrolled in the MECE 2304 Dynamics course at the University of Texas-Pan American. 40 undergraduate students (33 male and 7 female) participated in the evaluation. Course credit was offered to the students for their voluntary participation to either this software activity or, as an alternative, for reviewing an article of their choice from a refereed publication or popular science magazine relevant to the concepts taught in the dynamics course. The students majored in four different disciplines: 33 students were in mechanical engineering, 6 were in civil engineering, one in manufacturing engineering, and one in biology. None of the students declared any learning disabilities, or any other abnormalities that would affect the outcome of the evaluations.

4.2 Experimental Setup

The evaluations were run on three identical 3.1 GHz dual Pentium PCs with 16 GB RAM and a 1GB AMD 7470 video adapter. The Logitech Wingman Force 3D force feedback joystick displayed the relative magnitude of the forces to the students. The graphical interface was written using Microsoft Visual C++ and the OpenGL® graphic library. The force effects were implemented by using the Microsoft DirectX SDK.

As described in the User Interface and Virtual Environment section previously, the screen layout of the software had common user interface elements for each module that displayed the available modules, adjustable variables for the particular module selected, results and messages to the user (output window), and a pane that appears when a simulation is running and draws the kinematic graphs (position/velocity/acceleration vs. time) in real-time. The 3D view of the modules were displayed in the middle of the screen and covered most of the active window space.

4.3 Procedure

The evaluation for each student consisted of a 30-min session in front of a computer and was completed in one sitting. Students were given a brief introduction of which joystick buttons would be used with the software in order to prevent any potential confusion during the evaluations—only three out of the existing nine elements (buttons, slider etc.) were programmed to be used by the software. The students had five minutes to explore each module before the computer informed them that their time with a particular module had expired. The students were free to randomly choose the order in which they explored the modules. If a module(s) was explored for five minutes that module was not available to be selected again and the user was asked to change to another available module until all modules were explored by the student.

All modules, when double-clicked from the course view, displayed the assumption of particle or rigid body, a description of the variables that can be set, and a reminder about the relevant buttons on the joystick. For each module, on-screen clues (such as “Oops, your car has started to slip!”, “Do you think decreasing the applied force or decreasing friction would help the crate move up the ramp?” etc.) were added based on our anticipation of stages that may require extra information to increase engagement.

After going through all three modules, the session was automatically ended and the students were asked to fill out an anonymous evaluation survey on paper. These exit surveys included questions about students' subjective evaluation and feedback on the usage and overall purpose of the software. The questions were composed of multiple-choice questions (in the form of “Yes/Maybe/No” or “Yes/Somewhat/No”), rating questions using Likert-type scales, and one ordinal scale question to discern the most favored modules by the students. It was emphasized to the students that the survey results were anonymous and the instructor of the course were not present during the filling of the surveys.

4.4 Data Analysis

Student responses to the questionnaire were analyzed with Chi Square goodness of fit tests for multiple choice questions. The variables associated with Likert-scales were analyzed using Independent Samples t-test. The correlational analyses were also performed to find out any associations between the overall interest of the students in the dynamics as a subject and the software's purpose of improving both conceptual understanding of the subject and the problem-solving skills.

5. RESULTS

Gender

There was no significant gender difference in terms of the students' overall interest in Dynamics as a subject, overall level of engagement in the Dynamics course that they were enrolled at the time of the evaluation, and their belief that the software improves their conceptual understanding of dynamics topics or problem-solving skills.

Learning Style

The survey asked students to categorize themselves into one of the following learning styles: tactile (kinesthetic) style (learning by object manipulation, positioning, body movements etc.) and visualizing style (learning by picture, shape, sculpture, paintings etc.). 16 students categorized their learning style as tactile, 15 students responded as visual style. A significant Independent Samples t-test revealed that the tactile learners ($M=8.75$) believed that the software would improve their conceptual understanding of Dynamics subjects more than the visual learners ($M=7.67$), $t(29)=1.083$, $p<.05$.

Overall Interest in Dynamics as a Subject (Figures 6a & 6b)

A Chi Square goodness of fit test indicates that there is a significant difference in the proportion of students who thinks that the software increases their overall interest in Dynamics, $X^2(2)=22.85$, $p<.001$.

Engagement in the Currently-enrolled Dynamics Course (Figures 6c & 6d)

A significant proportion of students believes that the software increased their level of engagement in the Dynamics course, $X^2(2)=33.65$, $p<.001$. The difference between mechanical engineering majors and other majors in terms of their overall interest in Dynamics was marginally significant. Mechanical engineering majors were significantly more engaged in the Dynamics course ($M= 8.65$) as compared to other majors ($M=7.50$), $t(38)=2.008$, $p=.05$.

Effect on Conceptual Understanding of Dynamics Subjects (Figures 6e & 6f)

A Chi Square goodness of fit test indicated that a significant difference in the proportion of students who believe that further practice with the software will help them in the development of conceptual understanding of Dynamics subject, $X^2(2)=48.65$, $p<.001$.

Effect on Problem-Solving Skills in Dynamics (Figures 6g & 6h)

A Chi square goodness of fit test revealed that a significant difference in the proportion of students who believe that further practice with the software helps them develop problem-solving skills in Dynamics, $X^2(2)=25.55$, $p<.001$.

Future Use of the Software (Figure 7a)

A significant proportion of students would like to use the software again, $X^2(2)=57.95$, $p<.001$.

Concurrent Usage of the Software with the Dynamics Course (Figures 7b)

A significant Chi Square goodness of fit test revealed that there is a significant preference among students towards using the software as a supplement to the dynamics course, $X^2(2)=35.45$, $p<.001$. A significant proportion of students believes that the software increased their level of engagement in the Dynamics course, $X^2(2)=33.65$, $p<.001$.

Overall Quality of the Modules

Each student put the modules into an order for overall quality in terms of attractiveness, engagement, problem handled, helpfulness etc. (Figure 5). We calculated an “overall quality

score” by simply assigning weights to the modules depending on their corresponding order. Most favorite module for each subject was assigned a score of 3, second best a score of 2, and the remaining module a score of 1. The results showed that the Race Car on the Track module was the highest rated of all modules (score of 103). The Crate on the Ramp module took the second place in overall quality and the Sliding Box module took the third place. Although the calculated scores of the latter two modules were very close, students rated the modules on particle dynamics slightly higher than the only module on rigid-body dynamics.

User Interface and Layout

97.5% of the students (72.5% said “Yes”; 25% said “Somewhat”) stated that the user interface was easy to understand. 100% of the students (77.5% said “Yes”; 22.5% said “Somewhat”) stated that they understood the on-screen instructions.

Correlation Analyses

Correlational analysis were investigated using Pearson product-moment correlation coefficient. Preliminary analysis were performed to ensure no violation of assumptions of normality, linearity and homoscedasticity. The analysis revealed moderate to strong correlations. There is a moderate positive correlation between overall interest of the students in the dynamics subject and their engagement in the dynamics course they were enrolled at the time, $r(40)=.43$, $p<.05$ with high levels of overall interest in the subject associated with high level of engagement in the course. Likewise, there is a moderate positive correlation between the overall interest of the students in the dynamics subject and their belief that the software improves their problem-solving skills, $r(40)=.36$, $p<.05$ with high levels of overall interest associated with increased belief that the software improves problem-solving skills. There was a strong positive correlation between the students’ belief that the software improves conceptual understanding of Dynamics subjects and their belief that the software improves their problem-solving skills, $r(40)= .62$, $p<.001$ with high levels of overall interest associated with increased belief that the software improves problem-solving skills.

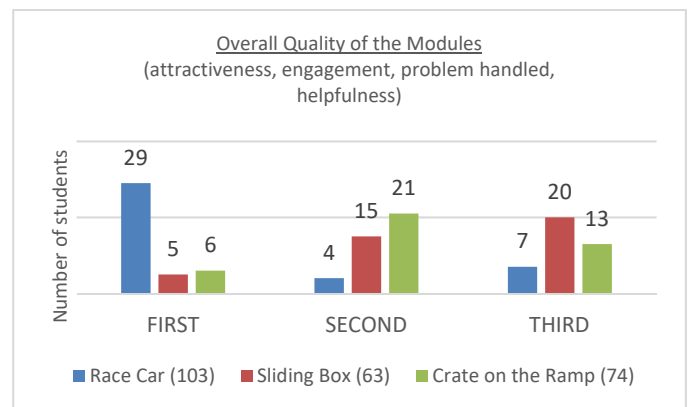
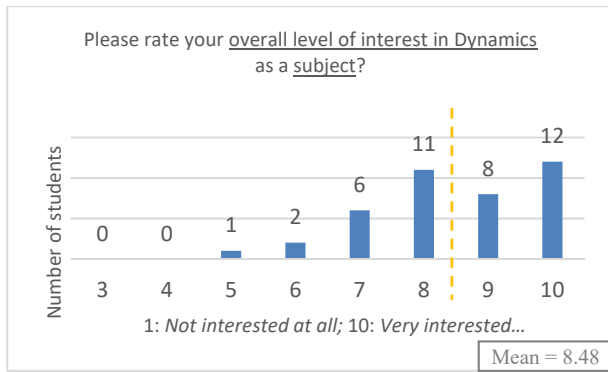
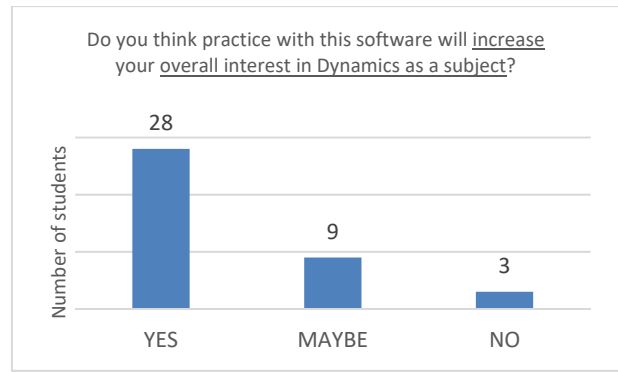


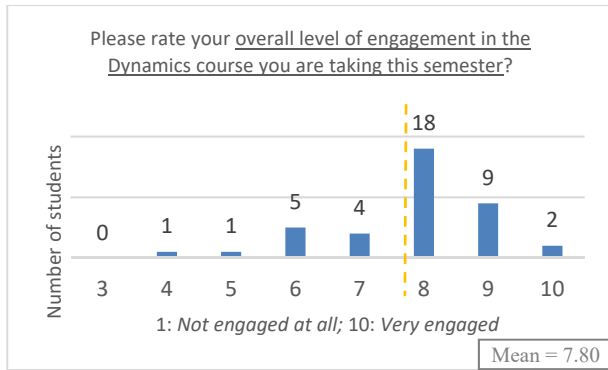
Figure 5 Overall quality of the evaluated modules; the calculated overall scores are also shown. (Most favorable: 3, Least Favorable: 1)



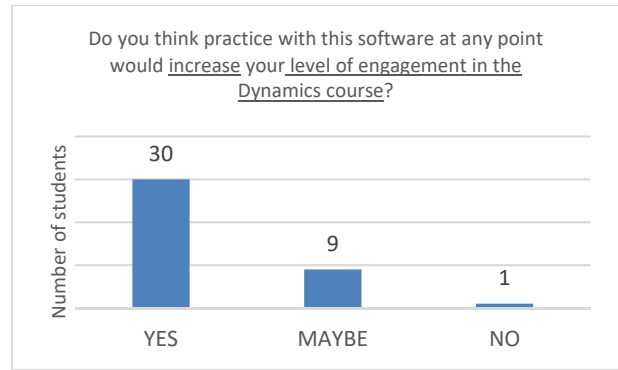
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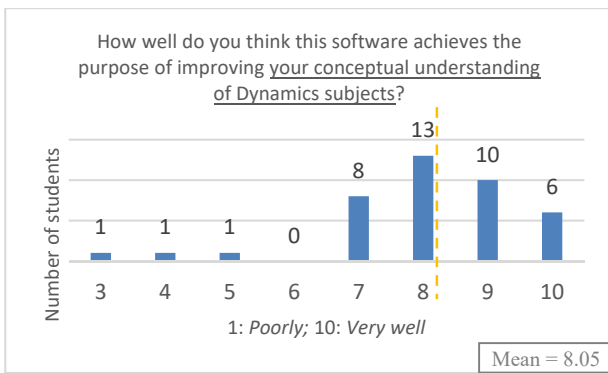
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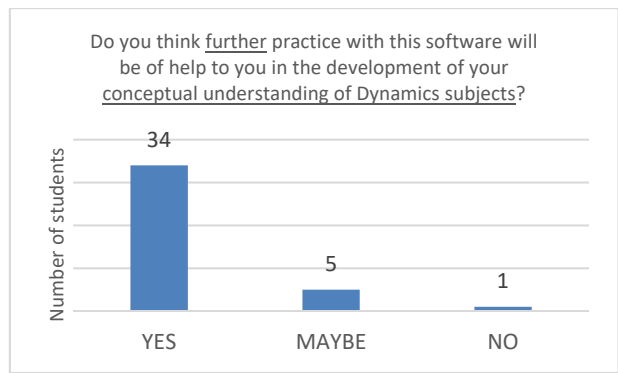
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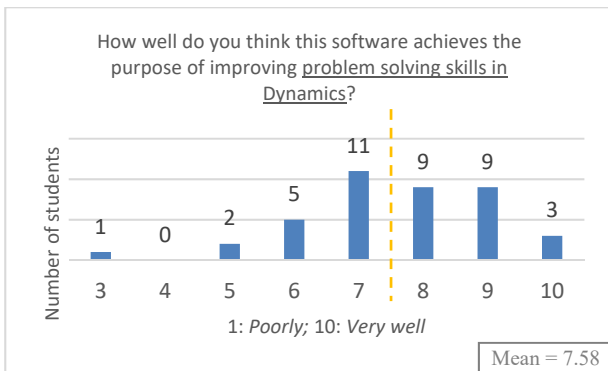
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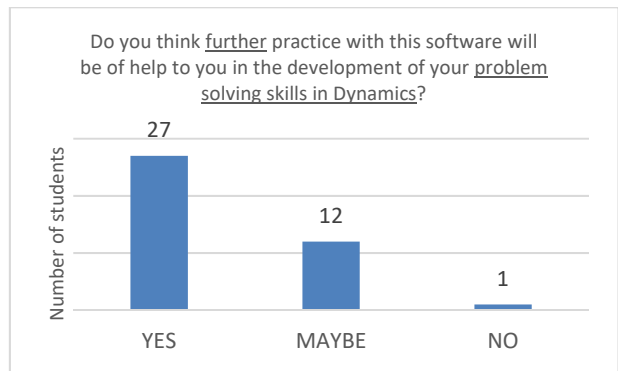
(e)



(f)



(g)



(h)

Figure 6 Post-assessment results from the exit surveys (n=40); the means are shown with a dashed line (when applicable).

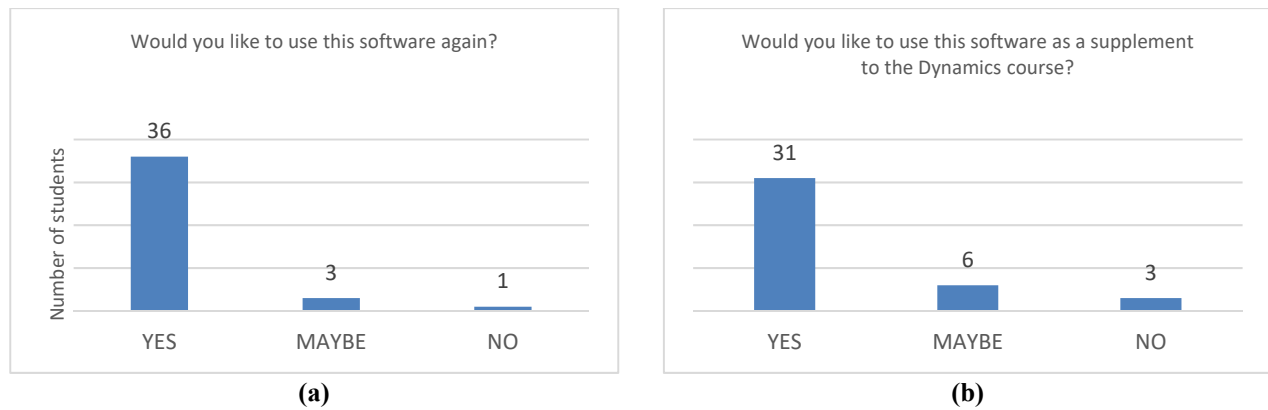


Figure 7 Post-assessment results from the exit surveys (continued)

6. DISCUSSION

The incorporation of the sense of touch into simulations adds one more modality to the multimodal learning tools that conventionally made use of visual and/or auditory feedback. There has been a significant amount of research on multimodality in learning and its effects on the learning process. Our software is an example of a multimodal tool that utilizes both the visual and haptic modalities—auditory feedback is currently not available. When it comes to multimodality in learning, the potential advantages and disadvantages can be discussed by considering two theories: Dual-Coding Theory (DCT) [21] and the Cognitive Load Theory (CLT) [22]. DCT suggests that cognition involves the activity of two subsystems, verbal and nonverbal (dealing with nonlinguistic objects and events). These subsystems are composed of modality-specific representations that are evoked by words, visual, auditory and *haptic* properties of objects. CLT suggests that the working memory has a limited storage—whereas the long-term memory is effectively unlimited—and in order to increase the effectiveness of learning, we need to decrease cognitive load or increase working memory. Considering that each modality has its own working memory (similar to a multi-core processor), the addition of another modality—the haptic modality in our case—should result in a decreased cognitive load [23]. In brief, it is believed that the more modalities involved during the learning process, the less the cognitive load will become, which in turn will increase the effectiveness of learning. Alternatively, the addition of another modality can cause cognitive overload which in turn delays or negatively affects the learning process.

The use of haptic-augmented activities to improve science instruction has been of interest since scientific concepts are often perceived as difficult to grasp. Due to this attribute, it has been suggested that haptic feedback should be incorporated because touching may make the abstract more concrete [24]. The use of multi-sensory modalities in learning is believed to be involved in the developmental process of shifting from concrete to abstract conceptualization [25]. Therefore, “hands-on” experiences provided by haptic feedback could be helpful for students in learning complex, abstract material, such as scientific concepts [26]. The results from our evaluations suggest that the students who categorized themselves as tactile learners, as compared to visual learners, believed that the modules would help develop their conceptual understanding of the dynamics subjects. Even though the addition of haptics is

not a controlled variable in our evaluations, one can speculate that the positive effects of haptics in conceptualization may be intensified for tactile learners. It should be also noted that there are also studies that have failed to provide consistent empirical support for integrating haptic feedback in improving students’ learning of cognitive tasks [27]. Apparently, more basic research is necessary to shed light on the individual effect of incorporating haptics on the learning process and, therefore, teaching tools such as our haptic modules.

The current evaluation of the haptic modules is not intended to investigate the effect of our software on the mechanisms of learning. However, the evaluation results revealed significant differences suggesting that the students believe that our software will affect their learning process in a dominantly positive manner. For instance, based on student opinions, the software would increase both their interest in the dynamics subject and their engagement in the classroom. Their written comments (not given here for brevity) provide evidence that they appreciated viewing the objects move as opposed to using paper and pencil to solve problems. Addition of the force feedback joystick also drew their attention, some of them asking to use the software more than the allotted time. The results were also encouraging in the sense that students thought this software would improve their conceptual understanding of the relevant topics and problem-solving skills. Expectedly, students thought their conceptual understanding would be improved more than their problem-solving skills as the software currently does not ask users to attempt to solve a similar problem before attempting the modules. However, addition of this feature is in our plans for future versions and a few students in the evaluation also commented on the potential contribution of having this feature on their problem-solving skills. The majority of students (90%) were willing to use the software again in the future, and, more importantly, most of them (77.5%) believed that it could be beneficial to them if this software was incorporated to the instruction of Dynamics as a supplement—the percentages are much higher when the students with a “Maybe” answer are also included as being at least open to these ideas. The user interface and the instructions were also rated as straightforward and clear.

At the end of the evaluations, Race Car on the Track module was clearly the favorite of most students. The main difference between this module and the remaining two is that this module brings out the competitive side of the students by

adjusting the variables so that the car finishes an entire lap without slipping at the corners. The second most favorite module was the Crate on the Ramp module that also included a goal-oriented feature. The crate had three possibilities according to the variables selected by the student: stand still in the middle of the ramp, move up or move down. In the Sliding Box module, however, the crate always slides in one direction as the main focus in this module is how the free-body diagram changes with other variables and to improve understanding of when a box is about to tip. This is an important deduction as it relates to increased engagement and interest in any software.

All students used the software with the force feedback enabled throughout their evaluation session. Therefore, we didn't collect the data that could be used to compare student opinions on the effect of the haptic modality. Our main purpose was to evaluate the existing software using the target population, i.e. students of Dynamics. This comparison, however, is planned to be performed in the future to investigate students' reaction towards having the haptic feedback. Furthermore, the written comments from some students expressed that the force feedback joystick was a novel and good idea, and it increased their engagement with and interest towards the software.

Some of the students requested better graphics and auditory feedback, when, for example, the vehicle starts slipping off of the track. It was observed that the game-like elements would make this software more attractive.

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Overall, during the evaluations, students were observed to be highly engaged in the instruction and expressed strong interest in the software program. Their subjective feedback was also representative of their willingness to try and adopt such a software with haptics included.

6. CONCLUSION

We presented the evaluation of our existing haptic-augmented training modules that were designed to increase teaching and learning effectiveness of undergraduate mechanics courses. Currently, three haptic modules in Dynamics were evaluated: "Crate on the Ramp", "Sliding Box", and "Race Car on the Track". The results of the evaluations are encouraging in the sense that the students expressed strong interest in using the software as a supplement to the Dynamics course by also emphasizing that the current software may increase their overall interest in the Dynamics as a subject and their level of engagement in the course that they were actively enrolled at the time of the evaluation. We are constantly working to add new modules to the system and improve the existing ones. The evaluation results will also be used to improve the current modules in terms of, for instance, developing a more detailed computer-based tutorial and an efficient method of giving students customized feedback with their performance.

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