

Simulation-based Learning Modules for Undergraduate Engineering DynamicsErnur Karadoğan¹, and Figen Karadoğan²¹ School of Engineering & Technology, Central Michigan University, Mount Pleasant, MI 48858.² Psychology Department, Central Michigan University, Mount Pleasant, MI 48858.Corresponding Author: Ernur Karadoğan (e-mail: ernur.karadogan@cmich.edu).

Abstract. In this paper, we describe software modules that provide both visual and haptic feedback to the student, and evaluate their effectiveness. The system integrates software modules with a haptic interface that can augment teaching and learning in a required undergraduate engineering Dynamics course. Students can change parameters, predict answers, compare outcomes, interact with animations, and “feel” the results using a haptic interface. Three software modules were evaluated in two separate studies. The first study focused on subjective ratings based on student opinions. The second study assessed the effect of the modules on students’ conceptual understanding for force and motion using a pre-test/post-test design. The results revealed that the practice with the modules significantly improved the conceptual understanding of the targeted concepts. Additionally, students showed a significant preference by stating that the modules would increase their interest in Dynamics as a subject and their engagement in the Dynamics course.

Keywords: educational simulations; haptics; dynamics; undergraduate engineering education

1 INTRODUCTION

The conventional lecture format in core engineering mechanics courses such as statics and dynamics, which form the backbone of several other upper-level engineering courses, can potentially place significant strain on students as these courses require them to visualize abstract concepts and develop critical problem solving skills. Additionally, engineering mechanics courses tend to be susceptible to misconceptions that may stay with the students for a long time [1]. Any effort made to clear these misconceptions requires significant work on the instructor’s part with the aim of increasing the students’ conceptual understanding. In that context, fostering conceptual change, which can be defined as restructuring the conceptual understanding, gains importance [2]. This conceptual change

can be better implemented when lectures are augmented with tools that are repeatable, flexible (in a sense that is harder to accomplish with physical experimentation labs), and economically feasible.

A simulation is a representation of a real world system in a controlled artificial environment such as in virtual environments. Simulation-based learning occurs when these simulations are employed in an educational setting. Simulation-based learning takes advantage of technological advancements in both software and hardware in order to increase learning effectiveness. The process of going through a simulation may lead to higher conceptual understanding of the subject matter [3]. It can also be beneficial in providing the background-knowledge and in helping learners make hypotheses, conduct experiments, interpret data, and regulate the learning process [4]. Using simulations as a learning tool has additional advantages as they are considered to be flexible (various scenarios can be introduced by modifying the software or its components), repeatable (the same scenario can be created for each learner with the same fidelity providing the same outputs for certain given inputs), and free of time and peer pressure as the learner can spend as much time as needed without direct supervision [5]. In addition, the simulations can be repurposed and become effective assessment tools.

The potential benefits of simulation-based learning makes this an attractive method of learning for STEM fields [6-11]. Especially in undergraduate engineering, the need for supplementary instruction is evident because the material to be learned may be abstract and counterintuitive, both of which make the learners extremely prone to misconceptions that may plague them throughout their professional lives. It is a great challenge of any instructor to clear, or predict and prevent the misconceptions of learners. Therefore, once proven effective, any supplement in this regard including computer-based simulations should be a welcome addition to the toolset of an instructor.

Some examples in this domain include the efforts in educational haptics at all levels to encourage young students to consider STEM careers [12], utilization of haptics to explore molecular science with a haptic virtual biomolecular model [13], a virtual control laboratory for college engineering students [9], a virtual reality tool for chemical reaction engineering (Vicher) [10], investigation of the effect of haptics on undergraduate students' comprehension of buoyant forces [14], and another virtual reality tool for CAD education for training drivers [15]. A comprehensive review of the usage

of interactive visualization and haptics in nanoscience and nanotechnology education can be found in [16].

Addition of haptics (sense of touch) to computer applications in education has become increasingly common due to its potential benefits by allowing students to feel forces or contour of objects to gain a better understanding of the concepts. Williams et al. [17, 18] developed software using haptics for teaching and learning of science concepts. Immersion Corporation studied the effects of incorporating a haptics mouse to teach physics in college curriculum [19]. Okamura et al. [20] developed a proprietary haptic device that was intended to be used with simulations in engineering education.

Given the potential benefits of simulation-based learning, our purpose is to describe and evaluate a simulation-based learning tool that was created by incorporating the haptics technology in order to overcome some of the inherent challenges of learning and teaching of undergraduate mechanics courses. The modules were mainly designed to supplement out-of-classroom practice for students. Additionally, the guided exercises developed for these software modules can be used as homework problems that students can complete for a better understanding of the targeted topics as detailed in the following sections. The modules incorporate a modular design such that the portfolio of targeted topics and corresponding guided exercises may be added for future use. Specifically, the Dynamics course was our initial target due to it being a significant potential source of crucial misconceptions when force and motion are considered [1], which adversely affect students' understanding and performance in later courses and, potentially, in their careers [21]. These modules have been designed by utilizing important outcomes in the aforementioned research studies from several research domains including simulation-based and problem-based learning. The current set of modules were evaluated by means of two separate studies with participation of undergraduate engineering students. The first study solicited subjective feedback from the students for all existing haptic modules ("Crate on the Ramp", "Race Car on the Track", and "Sliding Box"). A second study was performed with a different subset of engineering students in order to evaluate two of the haptic modules ("Crate on the Ramp",

“Race Car on the Track”) in terms of their effectiveness in increasing conceptual understanding of students in targeted Dynamics topics.

2 SYSTEM DESCRIPTION

The designed software modules function as part of a system that is composed of a desktop (or laptop) computer, and a haptic interface that enables the interaction between the software and the user by providing force feedback. The following sections explain the main elements of the system.

2.1 *Haptic Interface*

The current choice of haptic device is a force feedback joystick, mainly due its cost effectiveness. The overall system is flexible, and can be used with any DirectX-compatible force feedback joystick as shown in Fig. 1. We have successfully tested the modules using Logitech Wingman Force 3D, Force™ 3D Pro, and the Microsoft Sidewinder joysticks. Due to the limited force feedback capabilities, the forces reflected to the users are normalized so that the maximum force value corresponds to the maximum force that any joystick can exert to user’s hand.

Fig. 1. Logitech Wingman (left), Logitech Force™ 3D Pro (middle), and Microsoft Sidewinder (right). The software can be used with any off-the-shelf DirectX-compatible joystick.

2.2 *Process Flow*

The process flow is summarized in Fig. 2. Users start interacting with the modules by first creating an account in order to access the system as a unique user name is required to store individual user data to keep track of their progress with practice. Once they sign in to the system, first time users are required to view an introductory Adobe® Flash® tutorial before they can start their practice. There are currently three modules as a part of the system: “Crate on the Ramp”, “Race Car on the Track”, and “Sliding Box”—more detailed information on the modules are given in the following section. The users can select any available module for practice and construct a new problem by changing the variables particular to each module. The flexibility of changing the problem variables allows students

to experiment, visualize and, through the joystick, feel the corresponding changes on the forces acting on an object and its motion (when applicable) 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 such as an externally applied force, the normal force, and the friction force acting on a block on the ramp.

Fig. 2. Process flowchart.

2.3 *User Interface and Virtual Environment*

The virtual environment for each module was designed using C++ and OpenGL graphics library in Visual C++ IDE. When applicable, the same functional elements were included in all modules in order to ease the transition of user from one module to another. The screen layout is the same for all modules and consists of several elements (Fig. 3). The simulation view is located in the middle of the screen and is the largest element for easy viewing of the simulated objects; in this region, the animations are displayed to the user. The “Course View”—a tree structure—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, the “Variables View” includes the variables specific to the active module. The “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. The “Graphs View” (Fig. 4) appears when a problem’s variables are adjusted and activated. It replaces the Course View on the screen until the simulation is terminated by the user.

Fig. 3 Sample screenshot (Race car on the track module).

Fig. 4 Graphs view appears during animation as shown on the left side of the screen (Sliding Box module).

3 SOFTWARE MODULES

The system currently includes three haptic-augmented modules for Dynamics: “Crate on the Ramp”, “Race Car on the Track”, and “Sliding Box”. Among these three modules, only the Sliding Box module uses the rigid-body assumption; in the remaining two modules, objects are treated as particles. The difference between these two assumptions is that a particle (or point mass) cannot rotate and, therefore, it is a simplification of the rigid-body motion. The screenshots of the modules along with the descriptions of their software implementations are given in Fig. 5. The following sections describe the details of each model including their mathematical model and user implementation.

Fig. 5 Haptic Modules (Elements of the user interface are not shown).

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 Fig. 6. 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 .

Fig. 6. Crate on the Ramp Schematic (Particle Dynamics).

3.1.2 Mathematical Model

For this problem, there are three possibilities: box accelerates down or up the ramp, or no motion of the box occurs. The mathematical model used to discern the type of motion for a selected externally applied force is found by following the procedure below.

Impending Motion Up the Ramp

The free-body diagram (FBD) for the point mass box in this case is shown in Fig. 7.

Fig. 7. Crate on the Ramp FBD, Motion Impending up.

From the free-body diagram, we apply Newton's Second Law, $\sum \mathbf{F} = m\mathbf{a}$ to find $F_{\min,up}$ that is the minimum applied force to maintain static equilibrium, i.e. just before acceleration is possible up the ramp.

Impending Motion down the Ramp

The free-body diagram (FBD) for the point mass box in this case is shown in Fig 8.

Fig. 8. Crate on the Ramp FBD, Impending Motion Down.

From the free-body diagram, we can apply Newton's Second Law, $\sum \mathbf{F} = m\mathbf{a}$ to find the $F_{\min,down}$ that is the minimum applied force to maintain static equilibrium, i.e. just before acceleration is possible down the ramp.

We can now consider three cases of the particle's (box) motion by using the minimum forces $F_{\min,up}$ and $F_{\min,down}$ for impending motion up and down the ramp, respectively.

Case I. Box Accelerates up the Ramp when $F > F_{\min,up}$

We can solve for the acceleration a up the ramp given the applied force F as:

$$a = \frac{F(\cos \phi + \mu_k \sin \phi) - mg(\sin \theta + \mu_k \cos \theta)}{m} \quad (1)$$

That is, the box will accelerate up the ramp with a in this Case I.

Case II. Box in Static Equilibrium on the Ramp when $F_{\min,down} \leq F \leq F_{\min,up}$

No motion of the box occurs.

Case III. Box Accelerates down the Ramp when $F < F_{\min,down}$

We can solve for the acceleration a down the ramp given the applied force F as:

$$a = \frac{F(-\cos \phi + \mu_k \sin \phi) + mg(\sin \theta - \mu_k \cos \theta)}{m} \quad (21)$$

The box will accelerate down the ramp with a in this Case III.

3.1.3 Implementation

User sets: $m, \mu_s, \mu_k, \theta, F$, and ϕ $5 \leq m \leq 10(\text{kg}), 0 \leq \mu_k \leq 0.5, \mu_k < \mu_s \leq 1$
 $0 \leq \theta \leq 60^\circ, 0 \leq \phi \leq 30^\circ$

Based on these values, the computer can calculate the minimum force $F_{\min, \phi}$ and suggest the user to enter a larger value for F .

Computer sets: $g = 9.81 \text{ m/s}^2$, (down, not in the $-Y$ direction unless $\theta = 0$).

Visualize: Free-body diagram with forces to scale, plus kinematics plots for a, v, x .

User Feels: Forces F, N, F_f , or W (user's choice). The joystick displays the vector forces (one at a time) to the user's hand.

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 (Fig. 5 and 9). 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 built of the track can be changed by using the bank angle variable, ϕ . Total lap time is also specified by the user and affects the constant tangential acceleration of the vehicle.

Fig. 9. Race Car on the Track Schematic (normal and binormal axes are shown; Particle Dynamics).

3.2.2 Mathematical Model

The free-body diagram for the vehicle is shown in Fig. 10. W and N represent the weight ($W = mg$) and the normal force between the track and the vehicle. F_{f_1} and F_{f_2} are the components of the friction force between the vehicle and the track in the lateral and longitudinal direction of the vehicle, respectively. Note that F_{f_2} (the traction force) is not zero as the vehicle experiences constant tangential acceleration depending on the initial velocity at the start line, radius of turn, and the total lap time, all set by the user.

Fig. 10. Race Car on the Track FBD (normal, tangential, and binormal axes are shown).

Kinematics:

The constant tangential component of acceleration can be found using initial speed v_0 at the start line, radius of turn—used to find the total track length s ($s_0 = 0$), and the total lap time t_{total} :

$$a_t = \frac{2\{(s - s_0) - v_0 t_{total}\}}{t_{total}^2} \quad (3)$$

The normal component of acceleration a_n at any given time t can be found using the instantaneous speed v . Note that at the straight portions this component is zero due to infinite radius of curvature.

$$a_n = \frac{v^2}{\rho} \text{ where } v = v_0 + a_t t \quad (4)$$

Kinetics:

We can apply Newton's Second Law, $\sum \mathbf{F} = m\mathbf{a}$, to find that the car starts to slip at the instant the following inequality is invalid, which ends the simulation:

$$\sqrt{F_{f_1}^2 + F_{f_2}^2} \leq \mu_s N \quad (5)$$

Where F_{f_1} , F_{f_2} , and N are calculated by using μ_s (the coefficient of static friction between the tires and the tracks) in the following equations of motion in the n-b and n-t planes.

The dynamic equations of motion in the n-b plane:

$$\begin{aligned}
 -W \cos \phi + N &= ma_n \sin \phi \\
 F_{f_1} + W \sin \phi &= ma_n \cos \phi
 \end{aligned}
 \tag{6}$$

And, the dynamic equations of motion in the n-t plane:

$$F_{f_2} = ma_t \tag{7}$$

3.2.3 Implementation

User sets: $m, \mu_s, \rho, v_0, t_{total}$, and ϕ $500 \leq m \leq 1500(kg), 0 < \mu_s \leq 1, 10 \leq \rho \leq 14(m)$
 $0 \leq v_0 \leq 7(m/s), 5 \leq t_{total} \leq 15(s), 0 \leq \phi \leq 30^\circ$

Computer sets: $g = 9.81 \text{ m/s}^2$, (in the $-n$ direction).

Visualize: Free-body diagram with forces to scale, plus kinematics plots for a_n, a_t, v .

User Feels: Forces F, N, F_{f_1} , or W (user chooses). The joystick displays the vector forces (one at a time) to the user's hand.

3.3 Sliding Crate (Rigid-Body Dynamics)

3.3.1 Problem Description

A rigid-body crate of mass m is pushed along a flat motion surface by a force F , angled at ϕ , as shown in the diagram below. 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 as shown in Fig. 11.

Fig. 11. Sliding Crate Schematic (Rigid-body Dynamics).

3.3.2 Mathematical Model

The free-body diagram for the rigid-body box is shown in Fig. 12. The equations are derived based on the conditions for tipping as this module removes the particle assumption and treats the box as a rigid-body in plane motion.

Fig. 12. Free-Body Diagram for the Sliding Crate.

Static Case

We can apply Newton's Second Law, $\sum \mathbf{F} = m\mathbf{a}$ to calculate the applied force F for impending motion as:

$$F_{imp} = \frac{\mu_s mg}{\cos \phi + \mu_s \sin \phi} \quad (8)$$

where the weight is $W = mg$.

Now let us consider the case of impending tipping (rotation) of the box, prior to the impending translation motion. In this case the friction force is unknown, while the distance where the normal force N acts is on the corner of the box, $s = L/2$. The impending tipping force can be found as:

$$F_{tip} = \frac{mgL}{2 \left[L \sin \phi + \left(h + \frac{L}{2} \right) \cos \phi \right]} \quad (9)$$

Now, we must have $F_{imp} < F_{tip}$ if the box is to accelerate to the right without tipping over around the lower-right corner of the box. Thus, the following inequality must be satisfied to obtain translation without tipping:

$$\phi < \tan^{-1} \left[\frac{L - 2\mu_s \left(h + \frac{L}{2} \right)}{\mu_s L} \right] = \tan^{-1} \left[\frac{1}{\mu_s} - \frac{2h}{L} - 1 \right] \quad (10)$$

Dynamic Case

We can calculate the minimum applied force for dynamic motion (taking $a_x = 0$) as:

$$F_{\min} = \frac{\mu_k mg}{\cos \phi + \mu_k \sin \phi} \quad (11)$$

In this case, for no tipping, the maximum applied dynamic force is found as:

$$F_{\max} = \frac{mg(1 - \mu_k)}{(2 - \mu_k) \sin \phi + 2 \frac{h}{L} \cos \phi} \quad (12)$$

3.3.3 Implementation

User sets: h, μ_k, ϕ $0 \leq h \leq L/2(m), 0 \leq \mu_k \leq 0.4, \mu_k < \mu_s \leq 1$

Based on these values (plus $m, g,$ and L set by the computer below), the computer can calculate the bounds on applied force F as discussed above and suggest the user enter an appropriate value for F :

$F_{\min} \leq F \leq F_{\max}$ to ensure dynamic motion to the right without tipping.

Computer sets: $g = 9.81 \text{ m/s}^2$, (in the $-Y$ direction), $L = 1 \text{ m}$.

Visualize: Box motion to the right, plus kinematics plots for a, v, x .

User Feels: Forces $F, N, F_f,$ or W (user chooses). The joystick displays the vector forces (one at a time) to the user's hand.

4 METHODS

The modules have been evaluated in two separate studies. The first study solicited subjective feedback from a subset of the target population (i.e., engineering Dynamics students) for face validation. The second study quantified the effectiveness of the selected modules by means of a pre- and post-test design.

For both studies, the students were selected from the target population who would potentially be using this software; i.e. students who were actively enrolled in a sophomore-level undergraduate Dynamics course. Extra 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 course.

All 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.

All students were given a brief introduction by the proctors, who were student research assistants, describing 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. 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. Specific differences in methodology between the two studies are detailed in their corresponding sections.

4.1 Study I

In the first study, three available modules (“Crate on the Ramp”, “Race Car on the Track”, and “Sliding Box”) have been evaluated by the participants for face validation. Their subjective ratings have been solicited in order to identify strengths and weaknesses of the software, hardware, and the instructional design.

4.1.1 Participants

Forty undergraduate students (33 male and 7 female) participated in this evaluation. 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.

4.1.2 Procedure

This study consisted of one 30-min session (including the pre- and post-test) in front of the computer and was completed in one sitting. The students had five minutes to explore each of the three modules 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 was explored for five minutes, that module was not available to be selected again and the user was asked to change to another available one until each student explored all modules. 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.

4.1.3 Results

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.

There is a significant difference in the proportion of students who believe that the software increases their overall interest in Dynamics, $\chi^2(2)=22.85$, $p<.001$ (Fig. 13a and 13b), and that the software increased their level of engagement in the Dynamics course, $\chi^2(2)=33.65$, $p<.001$. (Fig. 13c and 13d). There is 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 as a subject, $\chi^2(2)=48.65$, $p<.001$ (Fig. 13e and 13f), and that further practice with the software would help them develop problem-solving skills in Dynamics, $\chi^2(2)=25.55$, $p<.001$ (Fig. 13g and 13h). A significant proportion of students would like to use the software again, $\chi^2(2)=57.95$,

$p < .001$. There is a significant preference among students towards using the software as a supplement to the Dynamics course, $\chi^2(2) = 35.45$, $p < .001$. A significant proportion of students believe that the software increased their level of engagement in the Dynamics course, $\chi^2(2) = 33.65$, $p < .001$.

Additionally, each student was asked to order the modules for overall quality in terms of attractiveness, engagement, and helpfulness of the problem handled (Fig. 14). We calculated an “overall quality score” by simply assigning weights to the modules depending on their corresponding order. The most favorite module for each subject was assigned a score of 3, the 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 third place. 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.

Lastly, the students were given the opportunity to state their opinions on the software by responding to an open-ended question regarding their current experience. Some of these responses were:

“I like that you can both feel and see the forces being applied.”

“It requires you to use critical thinking to solve the problem for each situation. I like the force feedback it provides for every force. It’s a lot easier to understand than being on the plain paper.”

“The tactile feedback is a really cool idea and was especially useful for the curvilinear motion of the car. I would focus more simulations of curvilinear motion so that students can better feel the direction changes.”

“One could feel the forces that are being applied. You got more of a sense at what actually is happening as opposed to doing a problem in the book. This software gave me more of an interest.”

4.2 *Study II*

Based on the feedback received from the first study, we have determined that the “Sliding Box” module needed more improvement in order to enhance its graphics before it can be evaluated any further. Therefore, we evaluated two of the modules (“Race Car on the Track” and “Crate on the Ramp”) in the second study in order to evaluate the effect of the modules on the conceptual understanding of the targeted concepts using a pre- and post-test design.

4.2.1 *Participants*

Eleven undergraduate students (9 male and 2 female) participated in this evaluation. The students all majored in mechanical engineering. None of the students participated in both Study I and II.

Fig. 13 Post-assessment results from the exit surveys (n=40); the means are shown with a dashed line (when applicable).

Fig. 14 Overall quality of the evaluated modules as ranked from first to third by the students. calculated overall scores are also shown in parenthesis next to the module names (Most favorable: 3, Least Favorable: 1)

4.2.2 *Procedure*

This study evaluated two of the modules that were rated highest in overall quality in Study I, i.e. “Race Car on the Track” and “Crate on the Ramp” modules (see Results, for the average overall quality scores rated by students in Study I). We have decided to improve the “Sliding Box” module based on the student feedback from Study I before further evaluation.

The procedure for the second study simulated the conditions under which these modules are most likely to be utilized in an actual learning environment such as a supplemental instruction tool that the

learners can use to practice without any time pressure and complete given exercises to master a topic of interest. For that reason, this study had no time limits and incorporated exercises to achieve the learning objective of each module. This study was also completed in one sitting. We ensured that the students were aware of the no-time-limit condition for any of the activities including the pre- and post-test. Before the initial introduction of the system, students were given the pre-test. Once the pre-test was completed, they received the “guided exercises” for each module and were instructed to complete them while experiencing the modules. The guided exercises asked students to answer questions that were straight-forward and could be answered by only after running the corresponding simulations, i.e. the questions were very specific to the current module and selected values of variables. Finally, students were given the same questions as the post-test and asked to fill in an online anonymous survey that concluded the experimentation.

4.2.3 *Guided Exercises*

Assignments that guide learners are important in order to establish relationships between variables and facilitate learning [22, 23]. Based on these findings, the modules were augmented by predetermined scenarios that help students learn the concepts within the objectives (Appendix A) of a particular software module and still have the opportunity to freely change the environment (in the form of changing variables in a problem) and explore the outcome of virtually limitless number of self-created scenarios.

The guided exercise questions were designed for the two modules evaluated in Study II. During Study I, in which students freely explored the modules for five minutes each, it was observed that the modules attracted students’ attention considerably, but the teaching and learning aspect needed to be enhanced to focus student's attention on the learning objectives of a particular module. Therefore, we developed the guided exercises to help students focus on the specific learning objective(s) of each module. These exercises started by instructing students to set variables in a given module to a pre-determined scenario (see Appendix B for a sample representation of guided exercises). Then, they answered multiple-choice questions pertinent to each module’s objective(s) in order to encourage students towards mindful practice and, therefore, to increase their conceptual understanding of the

underlying physical principles (such as kinematic relationships and Newton's Laws of Motion). The questions were designed to involve students in the observing and critical thinking process rather than presenting students with tricky questions to test their misconceptions—contrary to the pre- and post-test questions as described below. It should also be noted that, before and after going through these exercises, students had an opportunity to change all variables and curiously explore the consequences of these changes in the problem.

4.2.4 *Pre- and Post-test*

The pre- and post-test included the same 11 questions that were 1) selected from three well-established conceptual tests, and 2) aligned with the teaching objectives of modules. These questions were selected from three sources: Mechanics Baseline Test (MBT) [24], Force Concept Inventory (FCI) [25], and Dynamics Concept Inventory (DCI) [26]. These well-tested inventories are tailored towards identifying misconceptions by means of extremely effective distractors. They are designed to test students' conceptual understanding of the topics related to kinematics and dynamics of particles and rigid bodies. Naturally, we selected the questions that were relevant to particle dynamics as both modules in Study II employed that fundamental assumption. Students did not receive feedback on the tests in order to protect the promised confidentiality of the aforementioned resources.

4.2.5 *Results*

The number of correct responses in pre- and post-test for all participating students is given in Fig. 15. There was a significant difference in the number of correct responses between pre- and post-test scores, $t(10) = -3.07$, $p = .012$, $d = .92$. The effect of practicing with the software was very large, indicating that the number of correct answers in the post-test was .92 SD more than in the pre-test (and before experiencing the modules and guided exercises).

In addition to the data collected to objectively assess the gain of knowledge, student opinions were also solicited using an exit survey in order to understand their perception and to evaluate the modules from a learner's point of view. The survey results are summarized in Fig 16.

When the students were asked if they would recommend this software to other students who are taking a Dynamics course and struggling with it, the average response rating was 6.4 out of a 7.0 point Likert-type scale. When they were asked to rate the extent to which further practice with this software will help them learn the Dynamics course topics/concepts, the average response rating was 5.9 out of a 7.0 point Likert-type scale.

The exit survey also included questions regarding the guided exercises. The results showed that these exercises helped students better understand the key concepts in Dynamics (45% Agree and 55% Strongly Agree); they have helped students learn how to apply studied concepts in future questions (45% Agree and 45% Strongly Agree); they were relevant to the Dynamics course students were taking at the time (27% Agree and 73% Strongly Agree); and the instructions of the exercises were clearly defined (27% Agree and 73% Strongly Agree).

90% of the students stated that the use of the force feedback joystick helped them better understand topics/concepts in the guided exercises (40% Agree, 50% Strongly Agree, 10% Neutral).

Finally, 90% of the students said that their interest was held during the training session (50% Agree, 40% Strongly Agree, and 10% Neutral). 100% of the students stated that the software was easy to use (36% Agree and 64% Strongly Agree) and user-friendly (36% Agree and 64% Strongly Agree).

5 DISCUSSION

In this study, we were able to quantify the effect of the evaluated software modules objectively on the conceptual understanding of the targeted concepts. The pre- and post-test questions used in the evaluations required students to have/gain a solid understanding of the relevant concept(s) as they were designed to exploit common misconceptions held by the general engineering student body. The results showed that the students' conceptual understanding improved after going through the modules and the guided exercises. As stated previously, these questions were carefully prepared to map to a particular module's objectives. The feedback received from the students stated that the exercises helped them during their training on the modules. From now on, we plan to merge these exercises with the software portion of the current and future modules to accompany them as lab exercises.

As can be seen in Fig. 15, most of the students increased their number of correct answers by one, which may initially be perceived as a relatively small improvement. The difference, however, is statistically significant (Cohen's $d = 0.92$) and stems from the consistent increase in the percentage of correct answers from 41.3% in the pre-test to 47.9% in the post-test after practice with the modules. We also note that the increase from pre- to post-test translates to an average of 21.6% individual improvement in the number of correct answers across all students. In the context of conceptual understanding in science, this improvement should not be considered a small one. For instance, it is known that understanding science concepts require both immediate and long-term cognitive mechanisms that affect the learner's accurate conceptual understanding [27]. The restructuring of conceptual understanding (also described in the research literature as conceptual change) is also challenging to obtain by means of a brief interaction with a simulation. However, as our evaluation results indicate, simulations can contribute to the additive process of acquiring knowledge and restructuring the existing conceptual understanding. Additionally, it should be noted that the pre- and post-test questions were selected from well-tested inventories that are specifically tailored towards identifying misconceptions (with extremely effective distractors)—some of these misconceptions are so persistent that they may not be removed even after an entire semester of instruction. For instance, Gray et al. [28] reported that Dynamics students were able to correctly answer 30.6-34.9% of the questions in the Dynamics Concept Inventory (DCI, which is one of the sources used for the composition of the pre- and post-test in our evaluation) at the beginning of the semester, and 32.1-63.9% of the questions at the end of the same semester (upper range of 63.9% was performed at a very selective small private university).

Fig. 15 Number of correct answers in the pre- and post-test for all students ($n = 11$; Max. score = 11).

Fig. 16 Student response to the exit survey ($n = 11$; 1: Not at all – 7: Very much).

It is worth noting that these haptic software modules in a sense are a collection of virtual experiments in which learners can change variables and see/feel their immediate effects on the particular problem. They have been designed to accommodate potential individual differences in learning and to benefit from the decrease in cognitive load while teaching. Although, in some cases, the virtual and physical experimentation were shown to be equally effective in increasing the conceptual understanding of undergraduate students [29], the modules have not been designed as an alternative to physical experimentation. The value of physical experimentation as a tool to teach how science is carried out and data is interpreted should still be emphasized as generally virtual models are simplified (or converted to ideal models) and the acquired data are clean from any imperfections that is present in real world [30].

As mentioned previously, we incorporated the guided exercises for the second study in order to focus the students on the specific objectives of a particular module. These exercises required students to go through the solution of a problem step-by-step where the solution is displayed directly by our software as compared to a solved example on paper or in a textbook. This method creates the “worked-example effect” that has been observed using both well-defined problems as encountered in the STEM disciplines [31], and ill-defined problems in art and design [32]. Worked-example effect can be described as the positive learning effect of a subject when novice learners are presented with worked-examples instead of problems to solve on their own. The studies reveal that, in their current form, the modules and our methodology of practicing with the modules enhances the conceptual understanding of students in Dynamics.

As can be seen from the students’ comments at the end of the first study, the 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 having to adjust the problem variables in such a way that their car finishes an entire lap without slipping at the turns. 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 to show how the free-body diagram changes with other variables and to improve understanding of when a box is about to tip. Therefore, it was observed that the game-like elements make this software more attractive.

6 CONCLUSION

We presented the three existing haptic-augmented training modules that were designed to increase learning effectiveness for students in an undergraduate mechanics course. Student evaluations were also presented with two separate studies that allowed us to analyze both subjective perception of the students toward the modules and their improvement in conceptual understanding. The results of the evaluations are encouraging in the sense that the students expressed strong interest in using the haptic 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. Students were observed by proctors to be highly engaged during the sessions 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. The analysis of the pre- and post-test results showed that the student's conceptual understanding on the targeted topics improved significantly after going through two of the modules.

Finally, the objective and subjective data obtained from the students favor simulation-based learning with haptics incorporated for a multimodal learning experience. Based on our experience, unlimited time and the exercises accompanying the modules aided students in performing mindful practice rather than random exploration of the software. We recommend, as in any product, evaluating and improving any supplemental instruction tool with especially the targeted user group and at the intended time in the curriculum.

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APPENDIX A: MODULE OBJECTIVES*Crate on the Ramp (Rectilinear Motion)*

After completing this module, students will:

- Understand the kinematic relationships between position, velocity, and acceleration using motion graphs.
- Understand the kinematic relationships between position, velocity, and acceleration using the interpretation of derivation (slope of a curve) and integration (area under a curve).
- Be able to compose and recognize the forces on a Free-Body Diagram for particles
- Be able to apply Newton's Second Law of motion to particles

Race Car on the Track (Curvilinear Motion)

After completing this module, students will:

- Understand the kinematic relationships between velocity and normal acceleration by means of motion graphs
- Understand the kinematic relationships between velocity and tangential acceleration by means of motion graphs
- Be able to apply Newton's Second Law of motion to particles

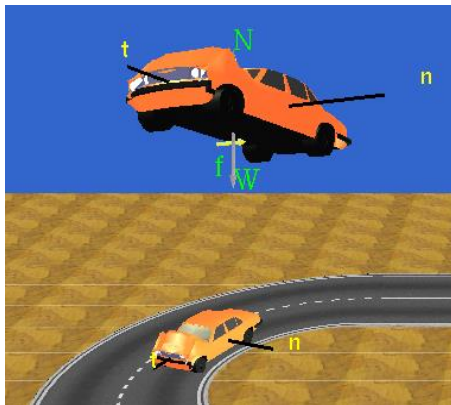
APPENDIX B: SAMPLE GUIDED EXERCISE QUESTIONS**Case I**

1. In the “**Course View**” left hand side of the screen, double-click on the “**Race Car on the Track**” module (You may need to first click “**CANCEL**” if another simulation is currently activated).
2. As shown below, click on the “**Reset Variables**” button on the “**Variables View**” to set all values to their default values (right hand side of the screen).
3. Use the corresponding sliders to change the following variables on the “**Variables View**”.

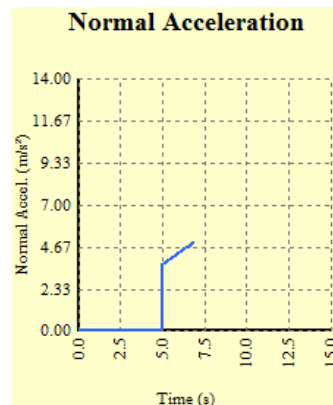
Variable Name	Value
Bank Angle (deg)	0.0 deg
Turn Radius (m)	10.0 m
Total Lap Time (sec)	15.00 sec

4. Click on the “**ACTIVATE**” button to lock in your changes. You should see the “**Graphs View**” appear on the left hand side of the screen.
5. Push the *Trigger* button (shown below) on the joystick to start the animation. You can observe the **Velocity**, **Normal Component of Acceleration**, and **Tangential Component of Acceleration** of the block in real-time using the “**Graphs View**” (left hand side of the screen).
6. Now, based on what you observe in the simulation, answer the questions to the best of your ability on the next page. You can refer to the simulation anytime you need.

For the next exercise question, use the following figures that show the Car on the track, its free-body diagram, and the Normal Acceleration:



Car on the track and the free-body diagram (shown as after the slip)



Normal acceleration graph (until slip)

1. The direction of the **Normal Acceleration** is always towards the center of rotation and along the positive “n” axis (see the free-body diagram above for the normal “n” direction). Considering the Newton’s Second Law ($\Sigma \mathbf{F} = m\mathbf{a}$), what can be said about the existence of a (net) force in the “n” direction”?
 - a. According to the Newton’s second Law, existence of acceleration does NOT require a force in the same direction
 - b. According to the Newton’s second Law, existence of acceleration in the “n” direction requires a force in the same direction (i.e., the friction force on the free-body diagram)
 - c. Acceleration and force are NOT related at all
 - d. None of the above
2. Hypothetically, if the **speed** (i.e., magnitude of velocity) of the vehicle were constant and nonzero during its turn, what could be said about the **Normal Component of its Acceleration**, which is defined as $\frac{v^2}{\rho}$ (v : speed; ρ : radius of curvature)?
 - a. It is equal to zero as the velocity curve would have zero slope during the turn
 - b. It is NOT equal to zero as the speed is NOT equal to zero
 - c. None of the above



Fig. 1. Logitech Wingman (left), Logitech Force™ 3D Pro (middle), and Microsoft Sidewinder (right). The software can be used with any off-the-shelf DirectX-compatible joystick.

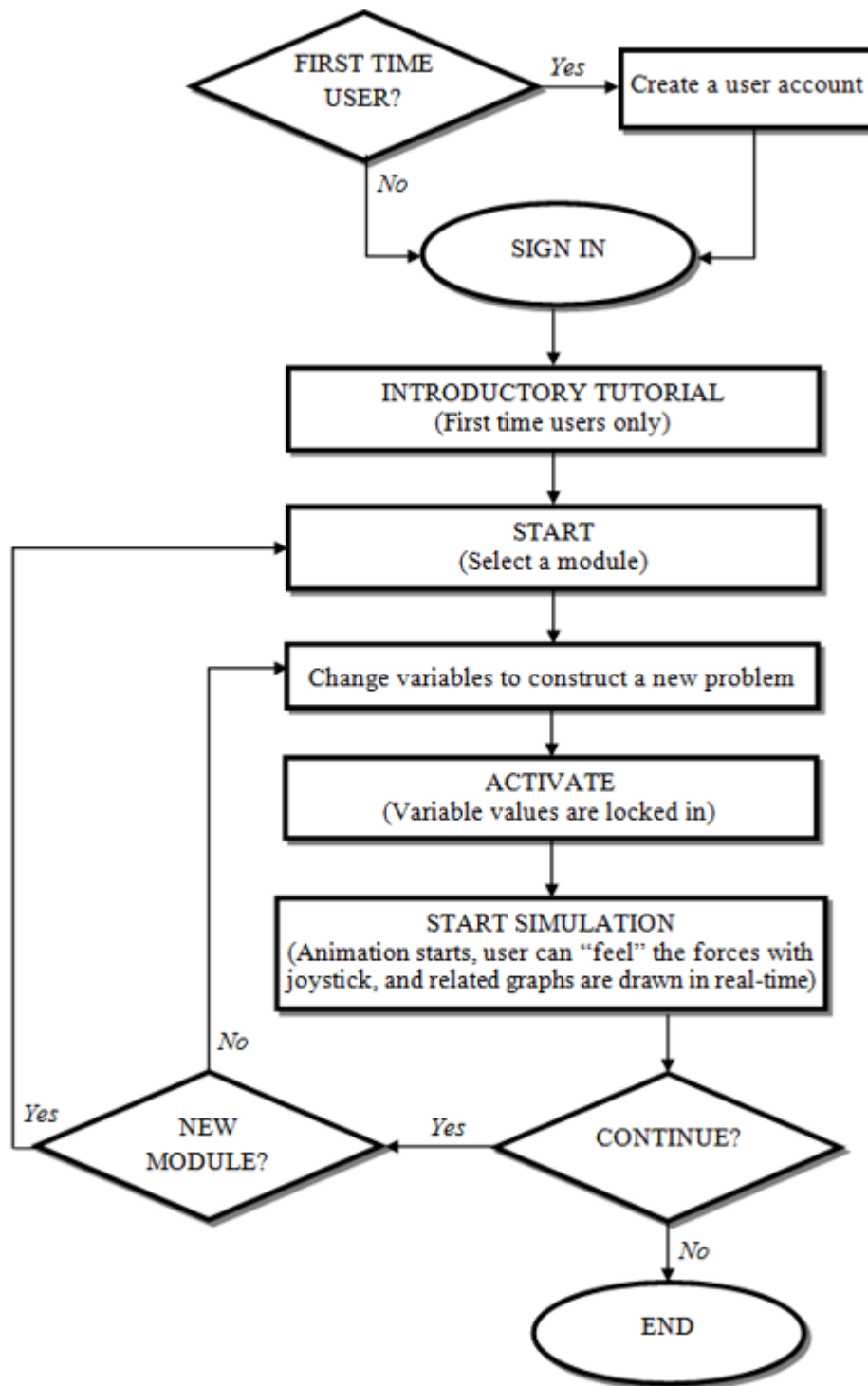


Fig. 2. Process flowchart.

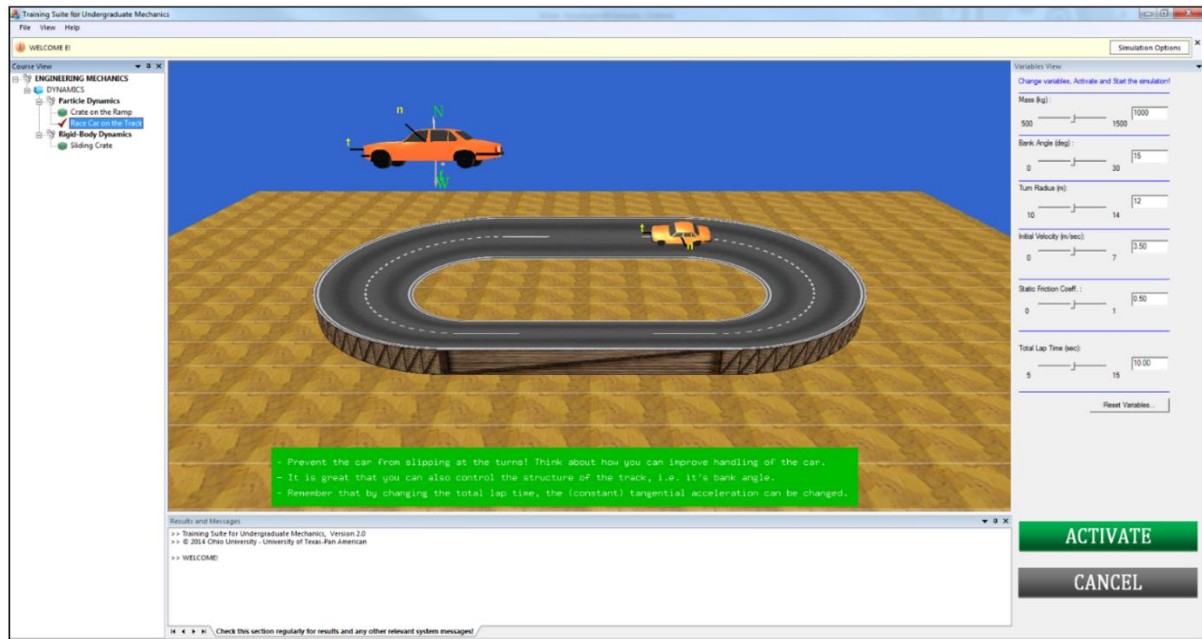


Fig. 3 Sample screenshot (Race car on the track module).

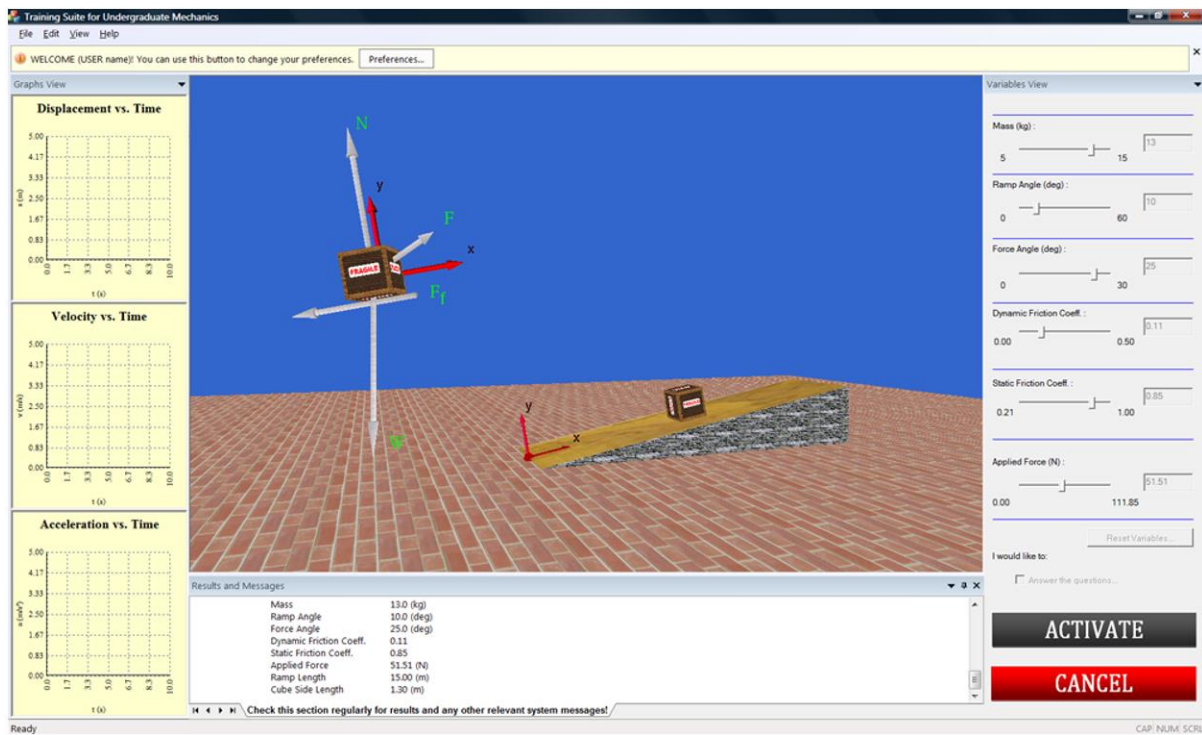


Fig. 4 Graphs view appears during animation as shown on the left side of the screen (Sliding Box module).

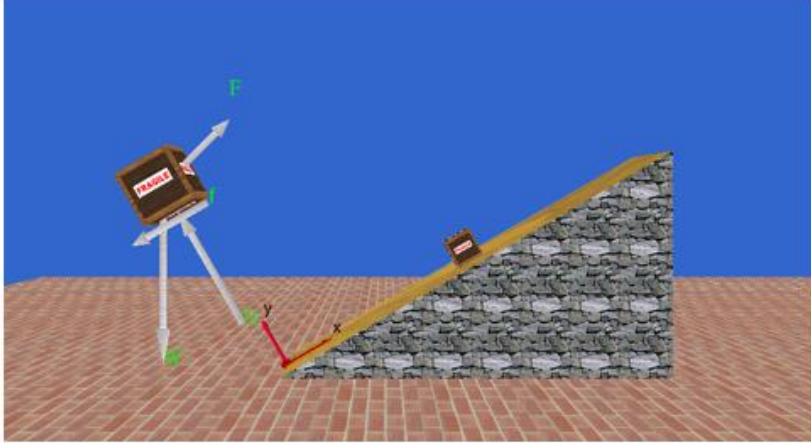
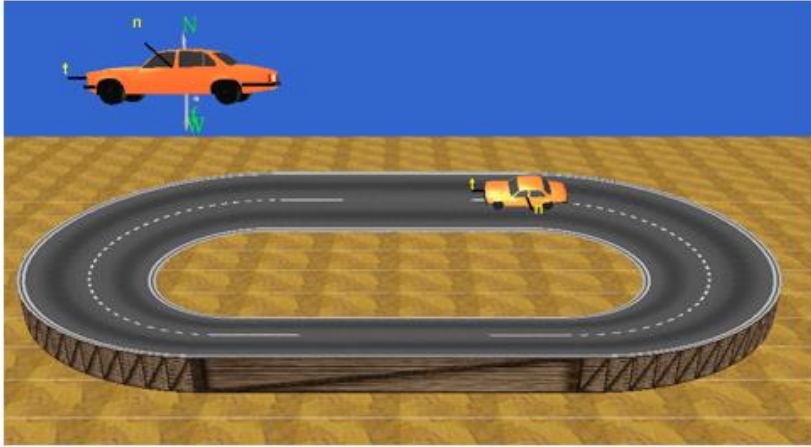
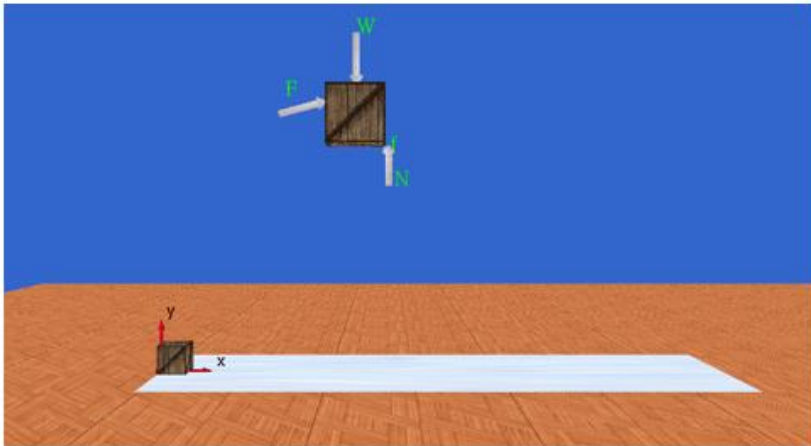
Module	Screenshot (User interface not shown)	Adjustable Variables
Particle Dynamics		<ul style="list-style-type: none"> • Mass of the crate • Ramp angle • Force angle • Static friction coefficient • Dynamic (kinetic) friction coefficient • Externally-applied force (magnitude)
		<ul style="list-style-type: none"> • 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)
Rigid-Body Dynamics		<ul style="list-style-type: none"> • Mass of the Crate • Vertical distance of the applied force from the C.G. • Force Angle • Dynamic (kinetic) friction coefficient • Static friction coefficient • Externally-applied force (magnitude)

Fig. 5 Haptic Modules (Elements of the user interface are not shown).

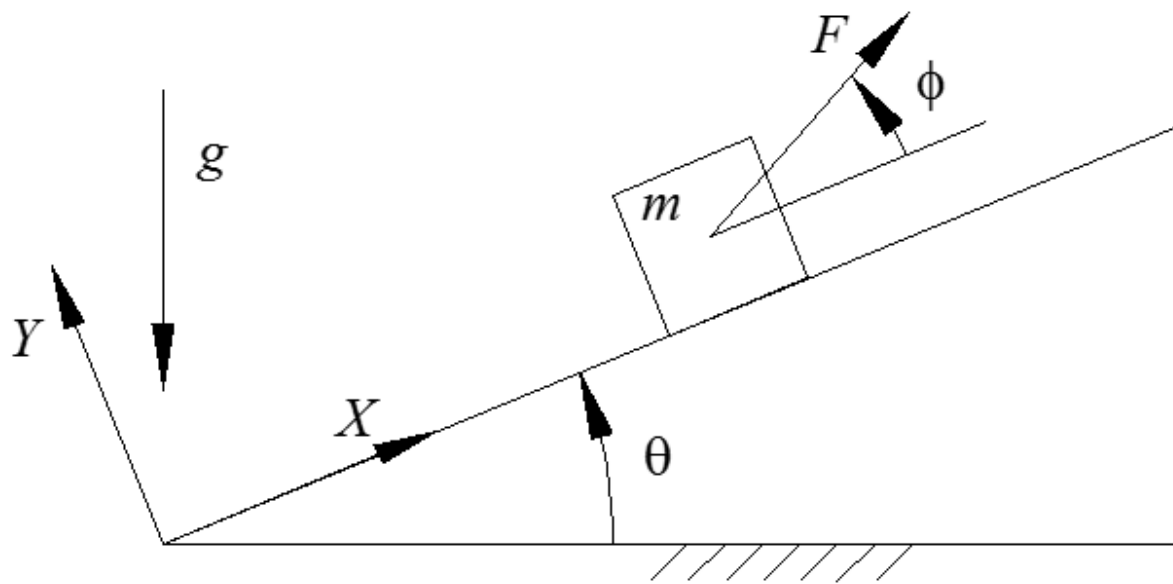


Fig. 6. Crate on the Ramp Schematic (Particle Dynamics).

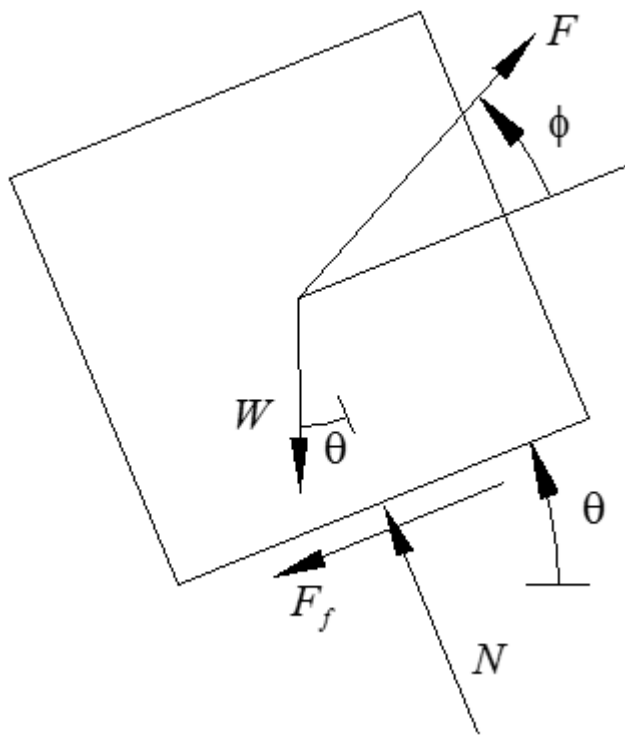


Fig. 7. Crate on the Ramp FBD, Motion Impending up.

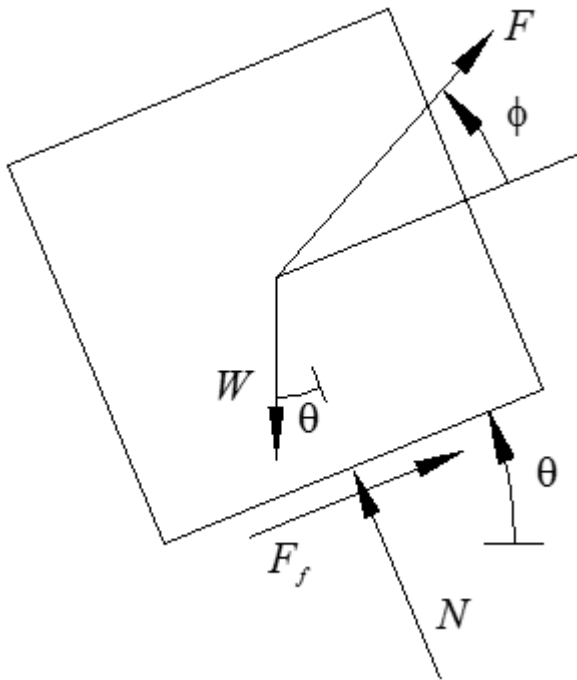


Fig. 8. Crate on the Ramp FBD, Impending Motion down.

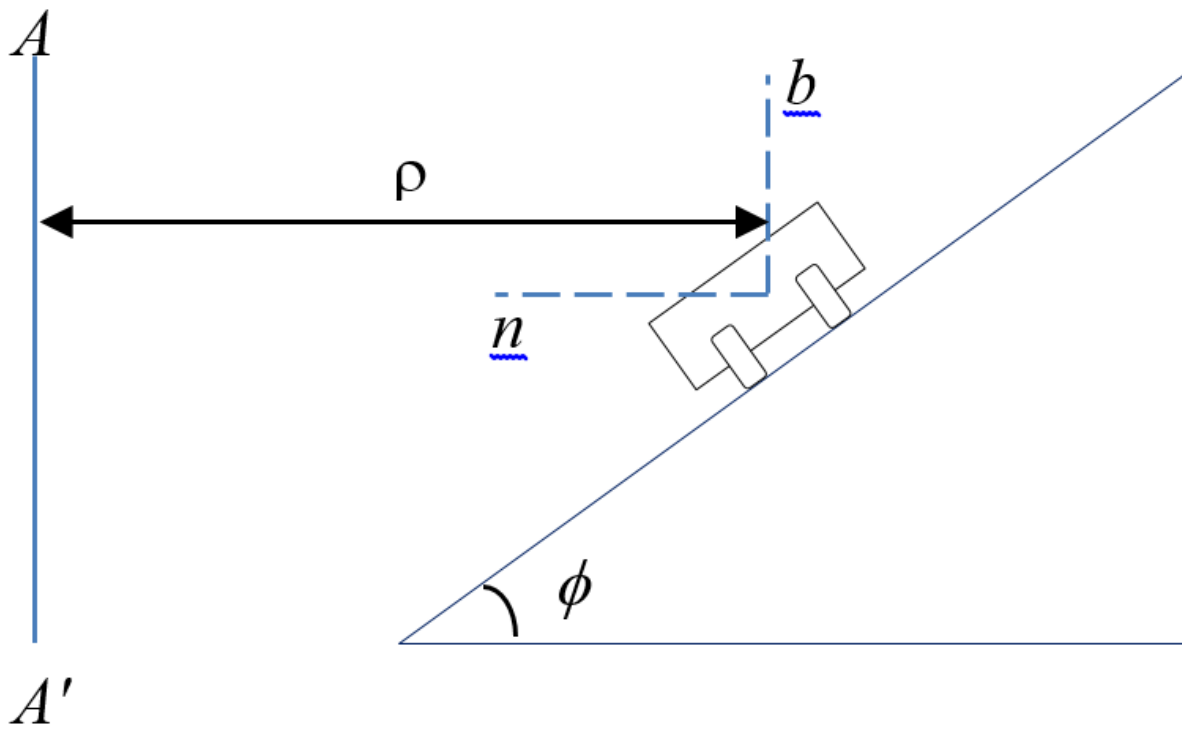


Fig. 9. Race Car on the Track Schematic (normal and binormal axes are shown; Particle Dynamics).

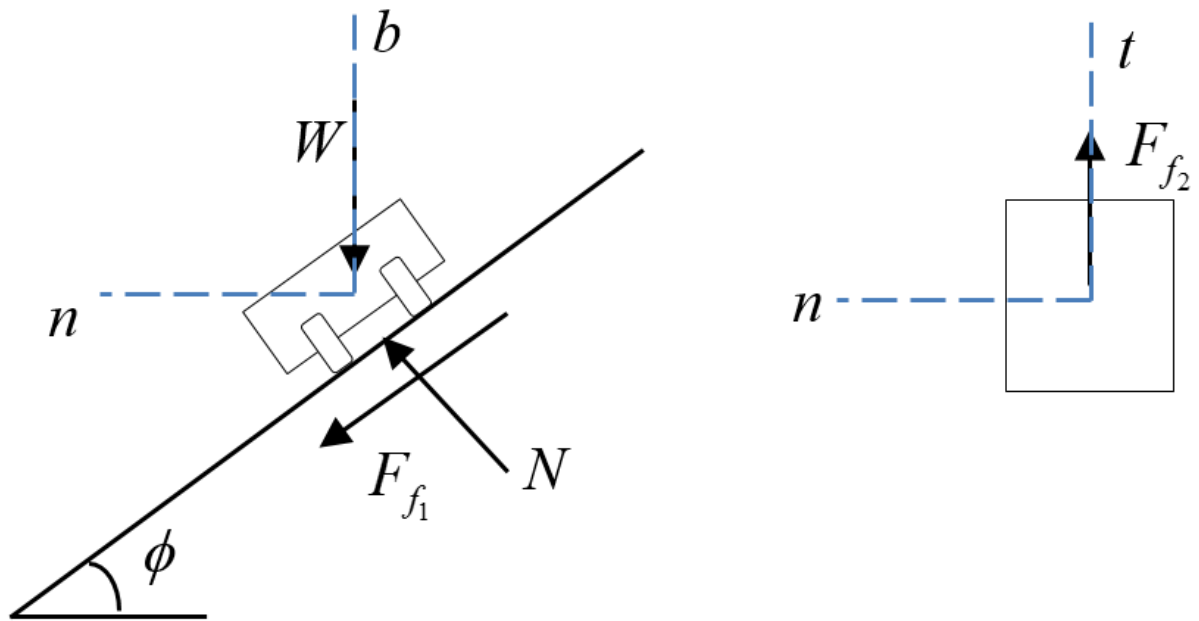


Fig. 10. Race Car on the Track FBD (normal, tangential, and binormal axes are shown).

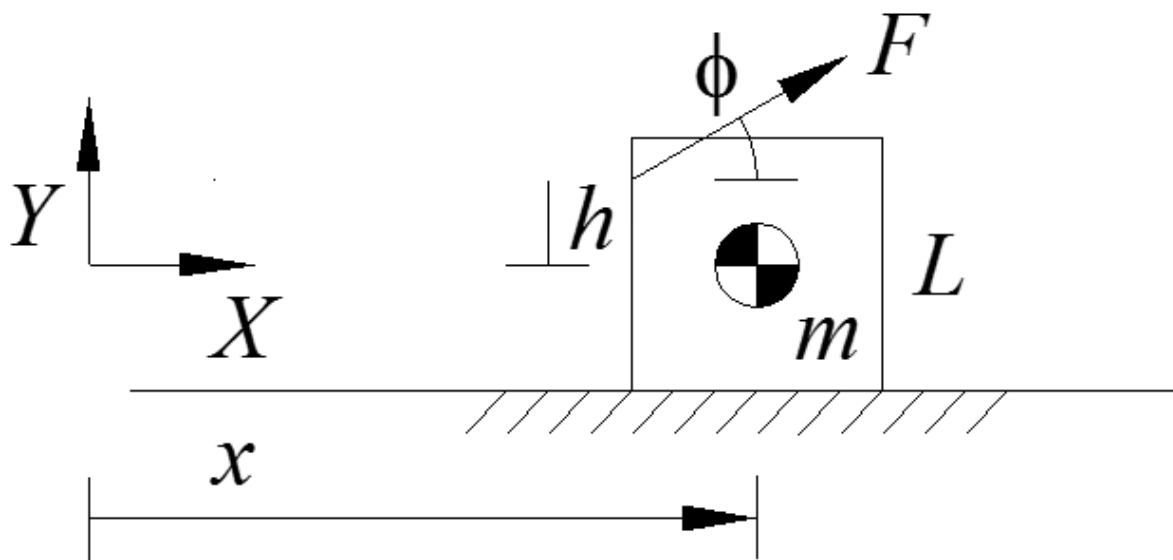


Fig. 11. Sliding Crate Schematic (Rigid-body Dynamics).

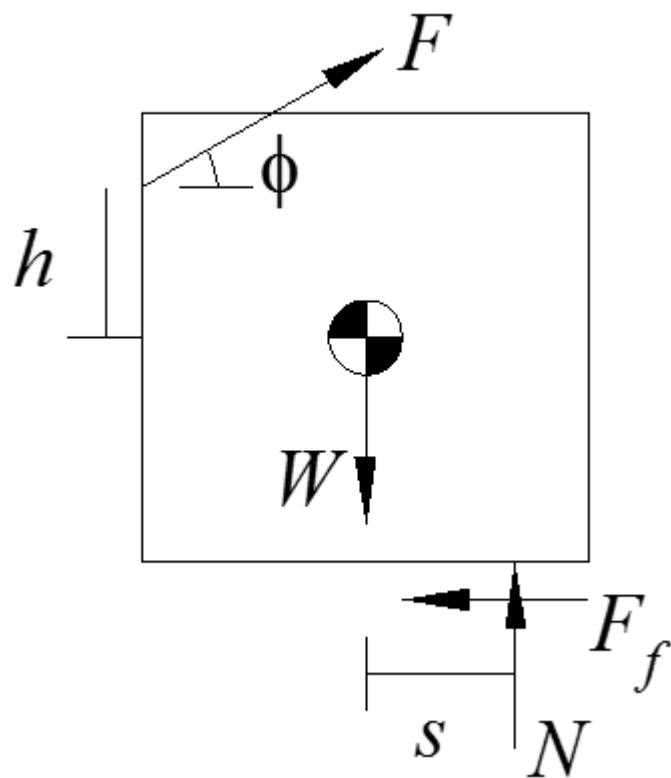


Fig. 12. Free-Body Diagram for the Sliding Crate.

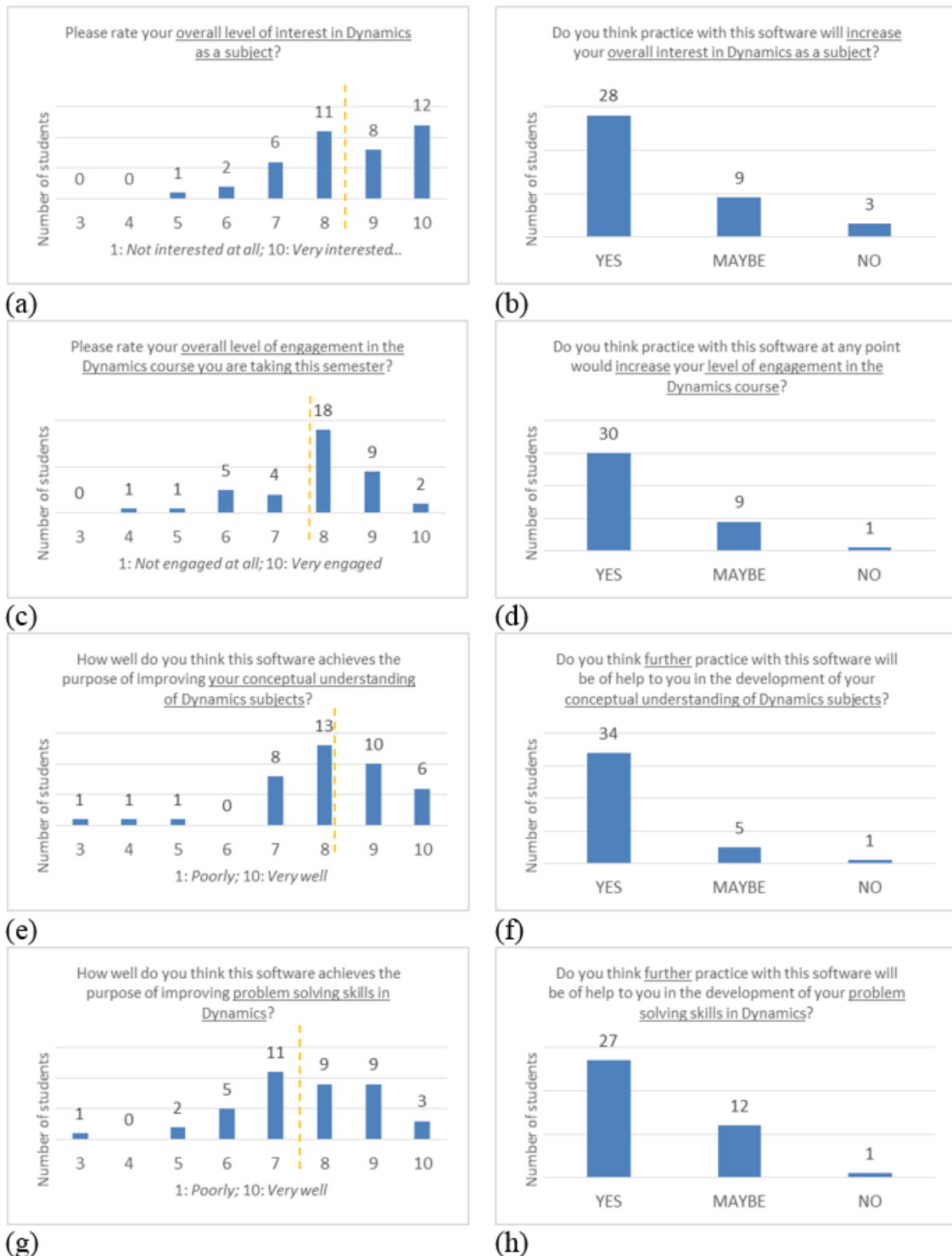


Fig. 13 Post-assessment results from the exit surveys (n=40); the means are shown with a dashed line (when applicable).

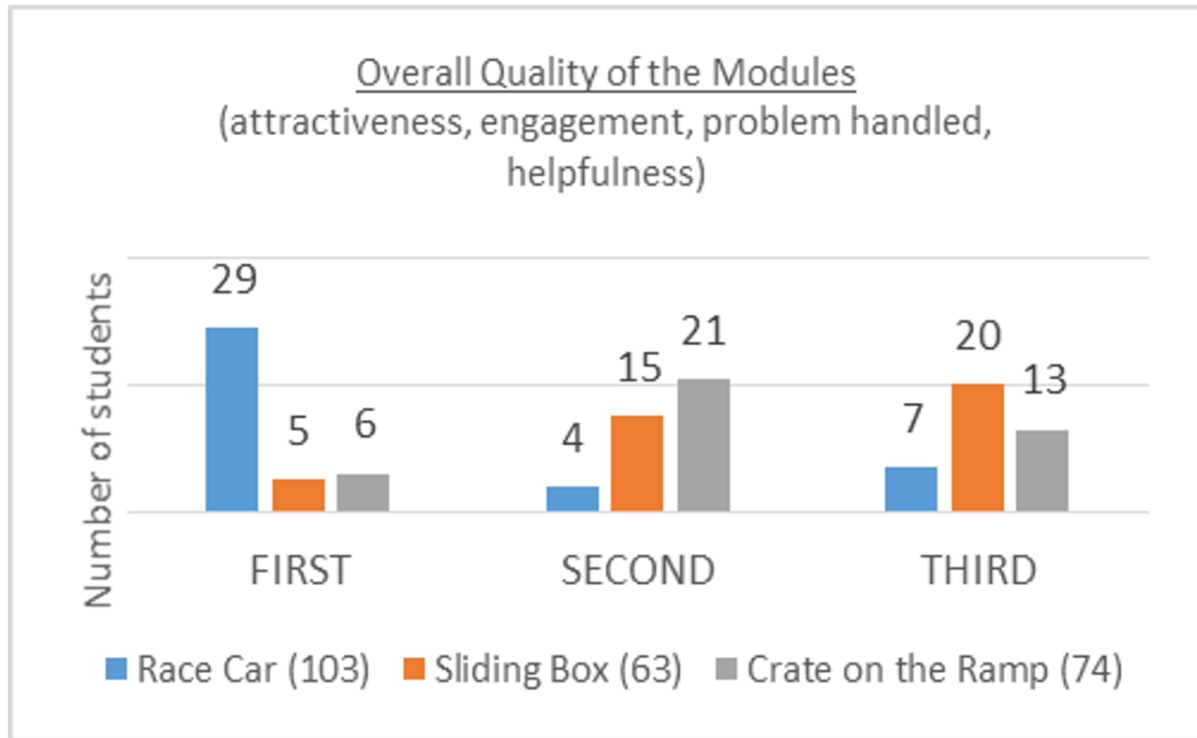


Fig. 14 Overall quality of the evaluated modules as ranked from first to third by the students.

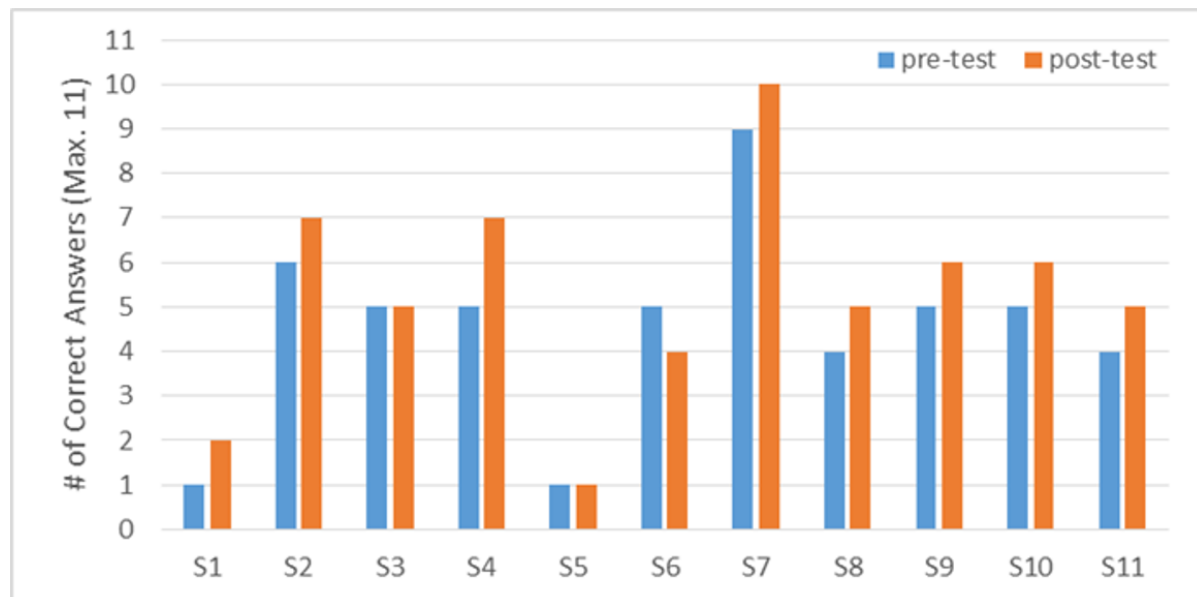


Fig. 15 Number of correct answers in the pre- and post-test for all students (n = 11; Max. score = 11).

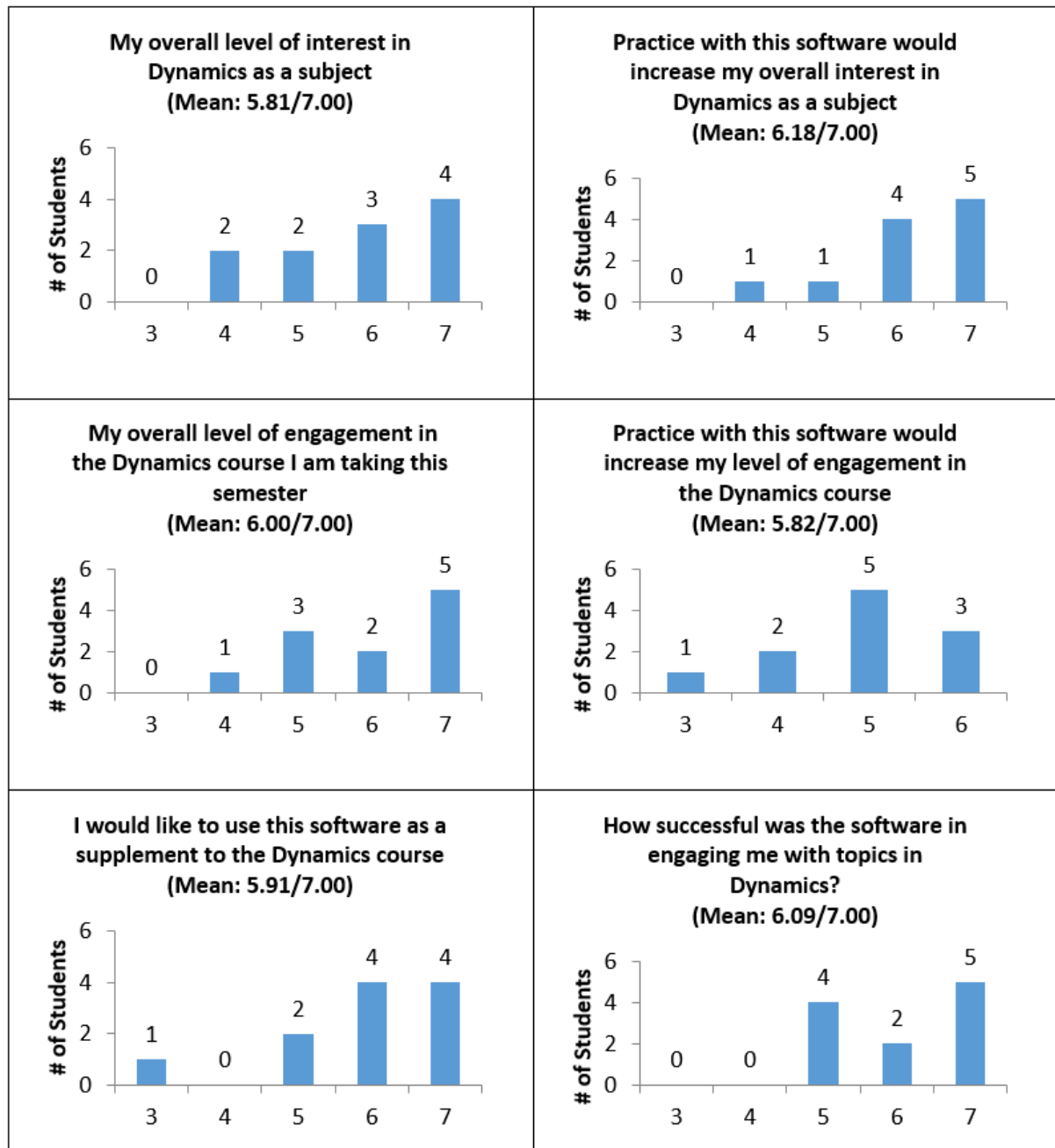


Fig. 16 Student response to the exit survey (n = 11; 1: Not at all – 7: Very much).