Visuo-haptic Simulations to Improve Students' Understanding of Friction Concepts

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***Abstract*— Statics is a backbone course for several engineering disciplines and also a pre-requisite for dynamics and mechanics of materials. Researchers have identified a lack of understanding of statics as a significant source of difficulties in terms of both conceptual understanding, representation of free body diagrams (FBD) and problem-solving ability. Our approach to improve the learning of the concept of friction focuses on students' understanding of acting forces and specific components of such forces of a system. The presented quasi-experimental study investigates how the use of visuo-haptic simulations can improve students understanding and use of FBD. Specifically, we compared two visuo-haptic simulations; one that explicitly visually depicts FBD of multiple objects interacting with different surfaces, while the other only provides haptic feedback while students engage in the same forms of interaction. Our results suggest that using the visuo-haptic simulator with FBD leads to better learning results. These findings support the hypothesis that appropriately sequenced visuo-haptic simulators with well-designed visual cues can help students to better understand and use FBD.**

Keywords*— *Haptic devices, Visuohaptic simulator, Friction forces, Free-body Diagrams, Visual cues

I. Introduction and Problem Statement

Statics is a backbone course for many engineering disciplines and a pre-requisite for dynamics and mechanics of materials. Researchers have identified a lack of understanding of statics as a significant source of difficulties in terms of both conceptual understanding, representation of free body diagrams (FBD) and problem solving ability [1]. The same authors identified a set of eleven common errors that students make. These errors include the students' inability to identify acting forces, specific components (e.g., bodies) of a system, and resulting behaviors from interacting parts. In a follow-up work Steif and Dantzler [2] used a Delphi panel of experts to distil statics content into eleven critical concepts covering the nature of force (magnitude and direction), moment, and equilibrium in structures. The early results were reinforced in subsequent studies [3, 4] and they identified that location and directionality of force, force balance, and equilibrium statements as the most enduring misconceptions among students.

Our attempts to improve the learning of FBD focuses on students' understanding of acting forces and specific components of such forces of a system. Specifically, one critical skill students need to develop is their ability to "translate the forces and couples which could be exerted at a connection into the variables, constants, and vectors that represent them" [2]. Three common errors are associated with developing this understanding [2]: (a) leaving a force off of the free body diagram when it should be acting; (b) drawing a force as acting on the body in the FBD, even though that is an internal force exerted by a body which is also included in the FBD; and (c) drawing a force as acting on the body of the FBD, even though that force does not act directly on the body. To address these common errors, we developed visuo-haptic simulation-based learning experiences as cognitive mediators for conceptual understanding of friction concepts. We used an in-house developed visuo-haptic simulator (see Fig. 3). It is a computer-based system that is connected to a hardware haptic device that allows to feel haptic feedback from the simulation. The user manipulates 3D point probe by using the device. The motion is

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translated into the simulator that calculates the corresponding feedback. The feedback is sent to the haptic device that generates forces at the frequency 1kHz. We hypothesize that the proper combination of visual and tactile information can lead to students' improvement of conceptual learning of friction concepts as opposed to learning experiences that provide minimal visual information. Specifically, we compared two visuo-haptic simulations; one that explicitly visually depicted FBD of multiple objects interacting with different surfaces, while the other only provided haptic feedback while students engaged in the same forms of interaction.

II. THEORETHICAL FRAMEWORK

Embodied cognition is the theoretical grounding for our study. Embodied cognition emphasizes the formative role of bodily movement and the interaction of the environment play in the development of cognitive processes [5]. The general theory argues that cognitive processes develop when learning emerges from real-time, goal-directed interactions between organisms and their environment [6]. The types and nature of the interactions influence the formation of cognitive capacities. One important assumption of this early theory is that an individual's sensorimotor capacities enable learners to successfully interact with the environment. A second assumption is that there is a common goal of developing cognitive explanations that capture the manner in which mind, body, and world mutually interact and influence one another to promote an organism's adaptive success. As noted by Wilson [5], "The emerging viewpoint of embodied cognition holds that cognitive processes are deeply rooted in the body's interactions with the world". He also claimed that people advocating embodied theory believe that it is not the mind that processes abstract ideas, "but the body that requires the mind to make it function" ([5] p. 625). Our work contributes to the body of knowledge based on the theory of embodied cognition [6] by identifying the role of touch as a cognitive mediator for abstract concept learning as evidenced by a student's conceptual learning.

III. RELATED WORK

Visuo-haptic simulators have been developed to enhance learning of different topics and levels of physics learning [7]. For classical mechanics concepts, simulators have been designed for example to improve understanding the operation of simple machines [8], gears [9], or the nature of friction forces [10-12], among other studies. In the case of electromagnetism, visuo-haptic environments have been implemented for understanding electrical interactions between molecules [13] and the nature of electrostatic forces produced by different electrical charge distributions [14, 15].

Various studies have been conducted to assess the impact of the use of haptic technology on students' perceptions and learning [10-12, 14, 15]. All these works report that students are in general motivated when practicing with the simulators, but only [10] reports statistically significant students' learning gains. Some visuo-haptic experiments for studying the nature of friction forces have added the force vectors in the visualization in order to provide visual cues to students in addition to the force feedback. For instance, Anonymous et al. [11] included the applied force and the friction force vectors on a block located on a flat surface. In a similar way, Hamza-Lup & Bird [10] and Anonymous et al. [12] designed visualizations including these same forces on a block placed on an incline. Nevertheless, the effect on student learning by including the FBD in the environment has not fully yet been assessed and this is one of the main contributions of the present study.

IV. METHODS

Our quasi-experimental study investigates how the use of visuo-haptic simulations can improve students understanding and use of FBD. Specifically, we investigate the characteristics of visuo-haptic simulations that can result in students' effective representation and use of FBD. Our experiments compare two visuo-haptic simulations; one that explicitly visually depicts FBD of multiple objects together with the haptic feedback while they interact with different surfaces, while the other experiment only provides haptic feedback while students engage in the same forms of interaction. It has been hypothesized that visual information can overpower tactile information [16]. However, we argue that with the right sequence, the combination of visual and tactile information can result in conceptual learning [17, 18]. The overview of our method is shown in Fig. 1.

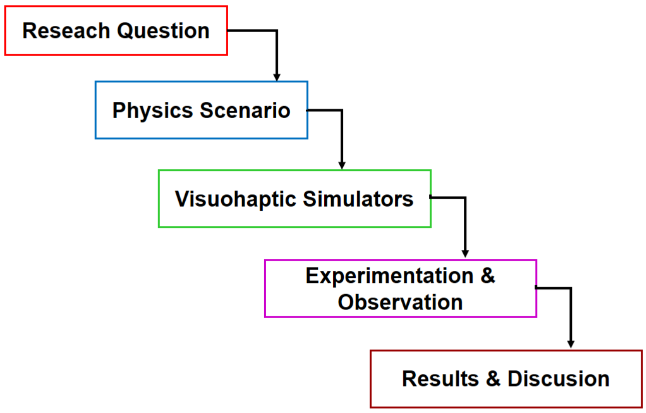

Fig. 1 Overview of our experiment design.

A. *Research Question:*

The research question of this study is:

What are the differences in students' conceptual understanding of friction concepts between students who were exposed to a FBD visuo-haptic scenario and students exposed to a non-FBD visuo-haptic scenario?

For this research question focus was set to study the students' ability to:

a) perceive the difference in magnitude between the static and the kinetic friction forces.
b) perceive the difference in magnitude of friction forces for surfaces with different roughness.
c) perceive the dependence of the magnitude of friction forces according to the object mass.
d) perceive the dependence of the magnitude of friction forces according to the contact area between the object and the horizontal surface.

e) calculate the static and kinetic friction forces exerted on a given object located on a flat table.

B. Physics Scenario

A common problem that students show in the introductory *Physics courses* is the correct understanding of the nature of friction forces between bodies. Therefore, a scenario was designed in which cubes of several masses and sizes can be displaced on flat surfaces with different roughness. The purpose of the experiment was to explore the dependency of friction forces with: a) the roughness of the contact surface between cube and surface, b) the mass of the cube, and c) the area of the contact surface between cube and table.

Three surfaces with different friction coefficients could be chosen: cardboard (low friction), fabric (intermediate friction) and sandpaper (high friction). Three cubes with different properties were also used (Table 1). Cubes 1 and 2 have the same size and are larger than Cube 1, while Cubes 2 and 3 have the same mass but twice the mass of Cube 1.

TABLE 1 CUBE PROPERTIES

Cube	Size (u^3)	Mass (u)
1	1.5 x 1.5 x 1.5	1
2	1.5 x 1.5 x 1.5	2
3	1 x 1 x 1	2

The FBD of the block includes: the applied force F_{app}, the cube's weight W, the normal force N, and the friction force F_f (Fig. 2).

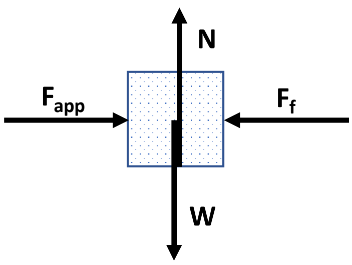

Fig. 2 Forces shown in the FBD scenario

The behavior of the friction force is shown in Fig. 3. In particular, if the value of F_{app} is smaller than the maximum static friction force ($F_S = \mu_S N$) the cube remains at rest and the friction force equals the applied force by the user ($F_f = F_{app}$; the line with slope 1 in Fig. 3).

In order for the cube to slide, the friction force required is the maximum friction force ($F_f = F_S$; the maximum in Fig. 3). Finally, when F_{app} is further increased and the cube moves with constant velocity, the friction force decreases and matches the kinetic friction force $F_K = \mu_K N$, that is, $F_f = F_K$ (the horizontal line in Fig. 3)

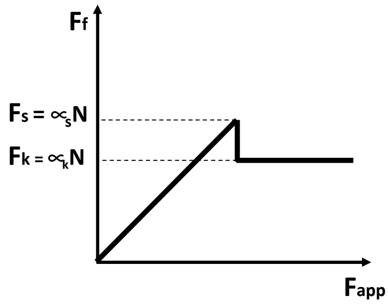

Fig. 3 Comparison of F_f and F_{app}

C. Visuohaptic simulators

Two visuo-haptic simulators were developed and used to explore friction forces when trying to displace a cube on a flat surface. We have developed the simulator in C++ by using modern OpenGL to visualize the 3D scene and to provide visual cues such as shadows and cross-hair cursor. We used Chai3D API to synchronize our simulator with the haptic device. We used Novint Falcon haptic device that provides up to 10N haptic feedback within an area of 10 x 10 x10 cm. A student working with the FBD simulator is shown in Fig. 4.

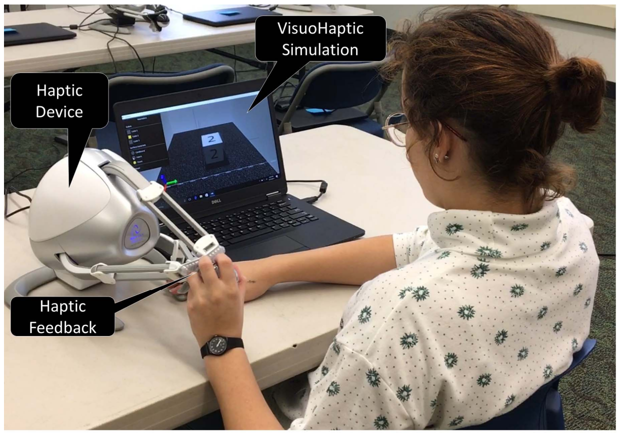

Fig. 4 A student interacting with the visuo-haptic simulation

In the first simulator (the FBD visuo-haptic simulation) the FBD is explicitly included when the user interacts with the cubes (Fig. 5), while in the second simulator (the Non-FBD visuo-haptic simulation) the FBD is not shown: students only perceive the force feedback given by the system (Fig. 6).

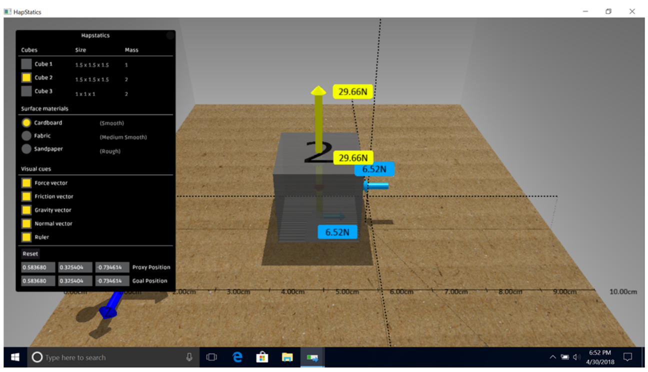

Fig 5 Free body diagrams and the visuo-haptic simulation

In both scenarios the magnitude of the forces is properly calibrated to change dynamically in order to satisfy the conditions for the friction force behavior discussed above. In the FBD scenario the arrows representing these forces and their corresponding magnitudes are shown. On the other hand, the dynamical behavior of the second scenario (Non-FBD scenario) was identical to the first one, except that the cube's FBD was not shown.

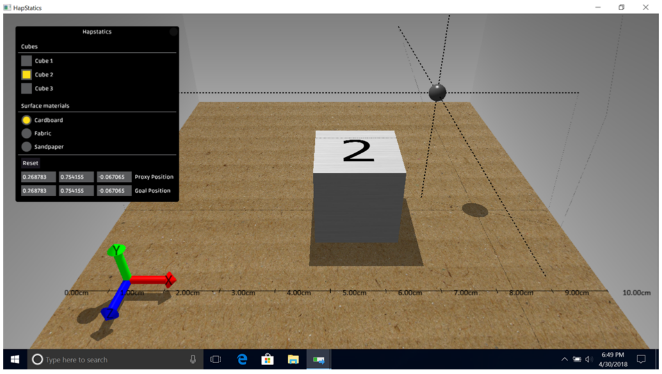

Fig. 6 Non-free body diagrams visuo-haptic simulation

D. Participants and Procedures

The participants of this study were freshmen engineering students enrolled in an introductory Physics course at Tecnologico de Monterrey in Mexico City Campus, during the January-May 2018 term. The sample was integrated by the two sections given by two of the authors of this work, out of the six sections of the course. Half of the students of each section were randomly selected to use the simulator with visual cues (hereafter "Group A") while the other half used the simulator without them (hereafter "Group B"). The respective populations were $N_A = 22$ and $N_B = 25$. Both groups followed the sequenced approach proposed by [17, 18] by having students first focus in one modality (i.e., haptic modality). However, differences between the groups were that Group A used the visuo-haptic simulation explicitly including the FBD of a cube on a rough surface, while Group B used the same simulator but not showing the FBD (Fig. 7). Students of both groups had already attended lectures on drawing FBD for objects exposed to friction forces.

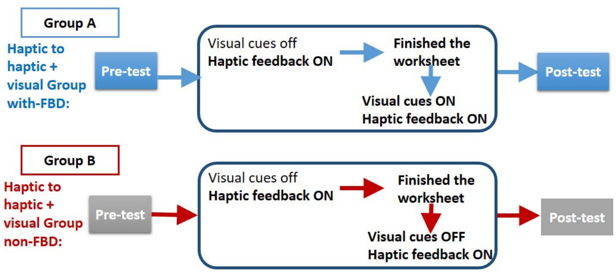

Fig. 7 Experimentation & observation processes for Groups A and B respectively

Groups A and B were asked to answer a pre-test of 5 questions before practicing with their corresponding simulator, that is, the FBD scenario and the Non-FBD scenario, respectively. Then students were given a guide to practice with the visuo-haptic simulator in an inquiry-based activity and were engaged to explore the magnitude of friction forces exerted on cubes of different masses and sizes, as shown in Table 1. The assigned time for this activity was one hour. At the end of the activity students answered a post-test very similar to the pre-test, in order to assess whether the use of the simulator had (or not) an impact on their answers.

E. Data Collection and Data Analysis Methods

The pre- and post-test item description are in Table 2.

All pre and post-tests were graded by one of the authors with a previously defined rubric. The grading scale ranged 0-100 points. Then average pre and post-test grades were calculated for each group. Additionally, a comparison between the answers from each question for groups A and B was also performed.

TABLE 2. PRE/POST-TEST ITEM DESCRIPTION

Question/ keyword	Item description
Q1 Static vs. Kinetic	To compare the magnitude of the maximum static friction force needed to start moving the cube vs. the kinetic friction force needed to keep it moving
Q2 Friction coefficient	To compare the magnitude of the friction force as function of friction coefficient between the surfaces
Q3 Cube mass	To compare the magnitude of the friction force as function of the mass of the cube upon which it acts
Q4 Cube contact area	To compare the magnitude of the friction force as function of the contact area between the surface and the cube
Q5 Static and kinetic friction force magnitudes	To compute the maximum static frictional force and kinetic frictional force for a given cube mass and frictional static and kinetic coefficients

V. RESULTS AND DISCUSSION

A. Overall Performance by Treatment.

The average pre- and post-test grades for groups A and B are shown in Table 3.

TABLE 3. PRE-TEST AND POST-TEST AVERAGES FOR GROUPS A AND B.

Group	<Pre>	<Post>
A	86.6	93.1
B	89.0	85.9

Table 3 shows that Group A achieved the average post-test grade 6.5 points higher than the average pre-test grade, while for Group B the average post-test grade was 3.1 points lower than the average pre-test grade. In order to investigate whether these differences were statistically significant, two-tail t-tests were performed to compare the post-test average grade and the pre-test average grade for each group. The null hypothesis assumed that the average post-test grade and the average pre-test grade for Group A, or for Group B, were equal:

$$H_0: < Post > = < Pre >$$

The significance level selected for this study in order to reject the null hypothesis was $p < 0.05$. It was found that the null hypothesis was rejected for Group A with a p-value = 0.02555, while for Group B the p-value = 0.2704 was too high to reject H_0. Therefore, there was statistical evidence to assert that Group A students, who were exposed to the FBD, had a higher average post-test grade than their pre-test grade, but there was no statistical evidence for a change in the post-test average grade, compared with the pre-test average grade, for Group B students. Additionally, a two-tail t-test was performed comparing the differences of post-test minus pre-test mean gains between Group A and Group B. A p-value = 0.028 was found, also suggesting that the students in Group A obtained statistically significant larger gains than Group B.

These results imply, on the one hand, that the incorporation of the explicit FBD in the visuohaptic simulator helped students to better understand the relation between friction forces and the other physical parameters: surface roughness, cube mass and cube size. On the other hand, the Non-FBD scenario did not help students to improve their previous knowledge on the topic.

TABLE. 4. PRE-TEST AND POST-TEST ITEM DISTRIBUTION

Pre-Test item (average + stdev)					
	Q1	Q2	Q3	Q4	Q5
A	91 (± 21)	95 (± 21)	95 (± 21)	86 (± 35)	76 (± 31)
B	92 (± 29)	96 (± 21)	96 (± 21)	80 (± 43)	83 (± 31)
Post-Test item (average + stdev)					
	Q1	Q2	Q3	Q4	Q5
A	100 (± 0)	95 (± 21)	95 (± 21)	86 (± 35)	91 (± 20)
B	92 (± 28)	92 (± 28)	100 (± 0)	56 (± 51)	88 (± 26)

B. Analysis of items responses.

In order to study the answers for each question in more detail, all test items were normalized in a [0 – 100] point scale. The corresponding average grades for each question and for each group, A and B, are presented in Table 4.

The comparison between the pre- and the post-test for Groups A and B is also shown graphically in Figures 8 and 9, respectively.

Table 4 and Fig. 8 show that the use of visual information during the haptic session (FBD) helped students to attain an increment in questions Q1 and Q5 (which both relate to the understanding of the static and kinetic friction) but gave no gain for questions Q2 (relation between the coefficient μ and F_f), Q3 (relation between mass and F_f), and Q4 (relation between Area and F_f). The null gain for Q2, Q3 and Q4 may be explained by the fact that students already had previous knowledge on the corresponding topics, and therefore their answers did not change even after using the FBD visuohaptic simulator.

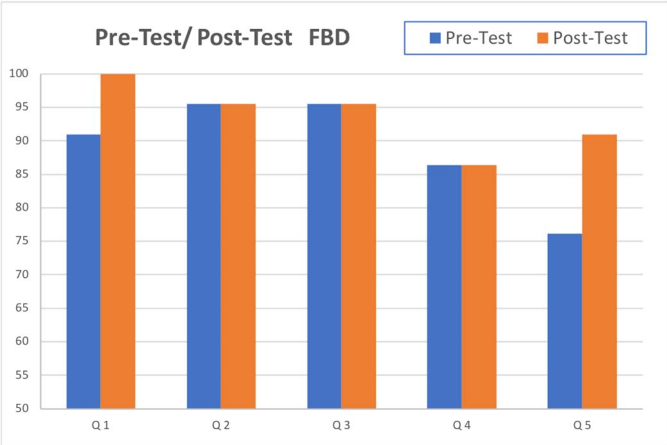

Fig. 8 Pre-test & post-test grades for Group A

As can be seen from Table 4 and Fig. 9, in the case of the Non-FBD experimental group, not having visual aids got a severe negative effect of 24 points on Q4 regarding the area dependence for the friction force (Table 4 and Fig. 9), and a slight decrease on Q2. However, there were also some gains for the Non-FBD group for questions Q3 and Q5. These divergent results tend to cancel out and, even though the post-test average grade is slightly lower than the average pre-test grade for Group B, this difference is not statistically significant.

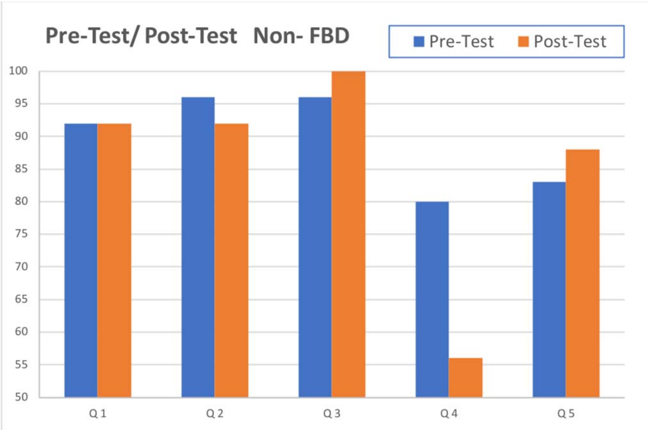

Fig. 9 Pre-test & post-test grades for Group B

A t-test study was carried out to investigate whether the differences for each question for post and pre-test grades were significant, for both Groups A and B. There were not statistical differences for questions Q1, Q2 and Q3 for both groups (p-values > 0.05). In the case of Q4 for Group A there was not a difference. In the case of Q4 for Group B it was found that even though <Pre> is 24 points larger than <Post> the corresponding p value is 0.056, therefore still not statistically significant. Finally, for question Q5 it was found that <Pre> is smaller than <Post> for both groups A and B with p = 0.039 and 0.096, respectively, therefore the difference is statistically significant in the first case but not in the other one. Overall, all these findings suggest that both simulators increased the success rate for the calculation of friction forces (Q5), but Group B students got confused with the non-dependence of friction forces with contact surface area (Q4).

A possible explanation for this later result is that, despite the fact the force feedback was the same for both FBD and non-FBD scenarios, in the second scenario students unconsciously associated the friction force they felt with the surface contact area they saw, even when the feedback force had the same strength for different contact areas. This effect did not happen with the FBD scenario, though, in which students could see that the length of the friction force vectors visually increased or decreased according to their strengths. This point deserves further investigation.

VI. CONCLUSIONS AND FUTURE WORK

This paper presented a comparison between two visuo-haptic scenarios aimed to study friction forces on a cube pushed on a horizontal rough surface were presented: one contained explicitly the Free-Body Diagram (FBD) of the cube while the second did not show it.

Following a sequenced approach [17, 18], students using the visuo-haptic simulator with the FBD performed statistically better in a post-test after manipulating the simulator than before using it. On the contrary, students using the simulator without the cube's FBD did not show a statistically significant difference between pre and post-test. Furthermore, our findings from our gains analysis resulted in statistical significant differences between both treatment groups (p-value = 0.028). We can therefore conclude that providing the FBD as part of the learning experience gave students a learning advantage.

In particular, the recognition of the increase of the friction force with roughness and the calculation of static and kinetic forces was benefited for the FBD scenario. On the other hand, the frequency of students that incorrectly concluded that the friction force depended on the area of the cube's contact surface increased after using the Non-FBD scenario. This finding has to be investigated with more detail.

These results suggest that the inclusion of properly sequenced visual cues in the design of visuo-haptic simulators is highly recommended in order to prevent student confusion and misconceptions. Moreover, they can help students to better recognize and therefore interpret the physical conditions of a given scenario.

Future work includes the design of other scenarios showing the corresponding FBD, for example, the corresponding of a block on an incline, in order to assess the impact of the addition of the FBD on student learning in more detail. On the other hand, it will be also important to perform studies to measure long-term retention two or three weeks after using the visuo-haptic simulators and investigate whether the use of these scenarios helps students to better internalize physics concepts.

ACKNOWLEDGMENTS

This work was supported in part by Novus Grant, TecLabs, Tecnologico de Monterrey, Mexico; and in part by the U.S. National Science Foundation under grant No. EEC 1606396. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the Tecnologico de Monterrey.

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