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A STUDY OF THE IMPACT OF 3D HAPTIC-AUGMENTED LEARNING TOOLS ON DYNAMICS COURSE

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ABSTRACT

This paper presents our recent investigation on the impact of 3D haptic-augmented learning tools on Dynamics, which is a basic course in most of the engineering education program. Dynamics is considered to be one of the most difficult and non-intuitive courses that engineering students encounter during their undergraduate study because the course combines basic Newtonian physics and various mathematical concepts such as vector algebra, geometry, trigonometry, and calculus and these were applied to dynamical systems. Recent advances in Virtual Reality and robotics enable the human tactual system to be stimulated in a controlled manner through 3-dimensional (3D) force feedback devices, a.k.a. haptic interfaces. In this study, 3D haptic-augmented learning tools are created and used to complement the course materials in Dynamics course. Experiments are conducted with a group of Mechanical Engineering students in the Dynamics class. The assessment result shows that the innovative learning tools: 1) allow the students to interact with virtual objects with force feedback and better understand the abstract concepts by investigating the dynamics responses; 2) stimulate the students' learning interests in understanding the fundamental physics theories.

1. INTRODUCTION

Research indicates that students often have difficulty in understanding science and engineering concepts and instructors, likewise, have difficulty in conveying these concepts without effective teaching tools [Richard 2002]. *Dynamics* is considered to be one of the most difficult and non-intuitive courses that engineering students encounter during their undergraduate study because the course combines basic Newtonian physics and various mathematical concepts such as vector algebra, geometry, trigonometry, and calculus and these were applied to dynamical systems [Cornwell 2004]. *Dynamics* is an important engineering course for three reasons. First, it is essential to have a strong grasp of the concepts covered in the course when pursuing a degree in engineering. Second, it is a required course for many engineering departments and is the first engineering course that covers both difficult and abstract concepts. Third, for many capable students this course can become a roadblock to a career in engineering [Low 2004].

Figure 1 Virtual Environment with Haptic Interface at Lamar [Zhu 2006]

Computer-mediated instructional technologies, typically in Virtual Environments, hold great promise for use in educational settings in that they can increase students' access to knowledge and act as vehicles that may promote learning [Minogue 2006]. Traditional Virtual Environments only provides visual and/or audio feedback. Recent advances in Virtual Reality and robotics enable the human tactual system to be stimulated in a controlled manner through 3-dimensional (3D) *force feedback* devices, *a.k.a.* ***haptic interfaces*** [Biggs 2002, SensAble Web].

Figure 1 shows a lab setup of haptic interface used in our research [Zhu 2006]. With the addition of haptic (sense of touch) feedback, Virtual Environment / Virtual Reality technology has much greater potential to profoundly change the nature of inquiry in Science, Technology, Engineering and Mathematics (STEM) education. In addition, the cost of 3D haptic interface with authentic force feedback continues to drop, which facilitates its wide adoption as the affordable next-generation human-computer interface.

Haptic interfaces offer greater opportunity to present abstract concepts dynamically to the sense of touch combined with visual feedback in the Virtual Environment. Generally, haptic interface devices serve as special purpose hardware for information input and output with computers. Our sense of touch is an active, informative and useful perceptual system and it is the only human sense that enables us to modify and manipulate the world around us [Klatzky 2002]. It was suggested that something touched is more real than something seen [Taylor 1973]. However, there is limited effort to exercise these concepts in an Engineering classroom based on a real 3D haptic interface for the undergraduate students, and the sense of touch has been an understudied and underutilized sensory modality in the design of these computer-mediated instruction tools [Dede 1994, Williams 2001, 2003].

The *function* of this project is to integrate haptic-augmented Virtual Environment technology into the course of '*Dynamics*' for the undergraduate engineering students. 3D haptic-augmented learning tools have been created and used to complement the course materials in Dynamics course. Experiments are conducted with a group of Mechanical Engineering students in the Dynamics class in Spring 2008 semester at Lamar University. The assessment result shows that the innovative learning tools: 1) allow the students to interact with virtual objects with force feedback and better understand the abstract concepts by investigating the dynamics responses; 2) stimulate the students' learning interests in understanding the fundamental physics theories.

The rest of the paper is organized as follows. Section 2 describes the research objectives. Section 3 narrates the research methodology. In Section 4, the data are summarized and preliminary study results are analyzed. The paper is concluded in Section 5.

2. RESEARCH OBJECTIVES

Virtual Reality / Augmented Reality (VR/AR) has been advocated as the great tool for education [ECU Web]. In the recent years, with the advance of desktop haptic interface technology and computer technology, haptic feedback research for education and training is rising up significantly. The research objective of this project is to perform research and prototyping work to create innovative learning materials and tools for *Dynamics* course using a 3D haptic-augmented virtual environment. We investigated the efficacy of such materials in supplementing the fundamental engineering courses.

On the cognitive behavior, the goal is to improve understanding of concepts and applications in the '*Dynamics*' course by demonstrating exemplary problems in the haptic-augmented virtual environments, complemented with additional exercises. The outcomes for this cognitive goal are:

- Students will be better able to solve conceptual problems in *Dynamics*.
- Students will be better able to solve out-of-context problems.

On the affective behavior, the goal is to improve the students' interest and self-confidence in the course and their attitudes about the course, curriculum and engineering as a profession. The outcomes for this affective goal are:

- Students will have more interest and positive attitudes towards engineering courses with the positive experience from the '*Dynamics*' course.
- Students will be confident in learning engineering courses and be more likely to describe engineering as an exciting career.

The research team is composed of the University Assessment Specialist, an Industrial Engineering faculty and a graduate student for material development, and three Mechanical Engineering faculties related to the fundamental engineering instruction. The undergraduate students involved in this research come from Mechanical Engineering, Civil Engineering and Industrial Engineering at Lamar University.

3. RESEARCH METHODOLOGY

To meet our research objectives, we have identified five key concepts in the Dynamics course. We have developed haptic-augmented learning materials based on these five key concepts. Student subject experiments were conducted with a one-on-one teaching lab format. Two groups of students were randomly selected. One was for graphics-only instruction with the developed material. The other one is taught the concepts with both haptics and graphics materials. The two groups are compared in order to find out whether learning has occurred and whether haptics material helps improve learning. Detailed research plans and tasks are described as follows.

3.1 Investigate the '*Dynamics*' course teaching methodology and choose exemplary dynamics problems to explore the effectiveness of the haptic and visual feedback in a Virtual Environment

As a preliminary result of our investigation, we have identified the following exemplary *Dynamics* problems (**Table 1**).

Table 1 Concepts and Exemplary Problems

No	Concept	Problem
1	Sliding and Rolling Motion	Motion of a block and a wheel on a plane
2	Impulse and Impact	An impact between a bowling ball and a bowling pin, or between two balls
3	Centrifugal and Centripetal Forces	A merry-go-round ride, or Particle waltz
4	Coriolis Acceleration	A slider on a rotating arm
5	Kinetics of Rigid Bodies	A piston-crank mechanism of an internal combustion engine

***Problem 1*:** Sliding and Rolling Motion

This example is chosen to convey the concept of friction ($F_f = \mu N$, where F_f = friction force, μ = friction coefficient, and N = normal force). Many students found friction a difficult concept as they could not see friction force with their eyes but could realize its existence through the resistance to motion.

***Problem 2*:** Impulse and Impact

This example is selected to reinforce two difficult concepts: impulse and impact. Impulse ($\int \mathbf{F}dt$) is the action of a force acting a very short time interval on a rigid body or a particle that results in the change in momentum (m***V**) of the object it acts on. An impact is a collision between two bodies which occur in a very small interval of time and during which the two bodies exert relatively large forces on each other. One way for students to learn and understand these two concepts is to test the effects by themselves through the use of an interface of haptics.

***Problem 3*:** Centrifugal and centripetal forces

This example is chosen to compare and contrast centrifugal and centripetal accelerations and forces. These forces are commonly encountered in practice but the concepts need to be reinforced as the students find the two concepts difficult to comprehend. The magnitude and direction of these forces will be demonstrated through haptics. The example problem chosen is the particle-waltz.

***Problem 4*:** Coriolis acceleration and force

This example is chosen to demonstrate a very difficult concept in engineering dynamics: *Coriolis* acceleration. This concept is difficult to comprehend even for the junior and senior students as the effect of Coriolis acceleration is counter-intuitive. In this example, the motion of a slider on a rotating arm is used to show the action of the Coriolis acceleration and resultant force experienced by the slider. By using haptic interface, the user will be able to vary problem parameters and experience the Coriolis effects through the force feedback.

***Problem 5*:** Kinetics of Rigid Body

This example uses the transmission of force through a series of rigid bodies. The example is modeled after the operation of a cylinder inside an internal combustion engine. The force acting on the moving piston inside the cylinder is transmitted to the rotating crank shaft by a slider-crank mechanism. This is an important topic for the students as they need to understand both kinematic and kinetic aspects of the problem such as transforming the linear force to a moment.

3.2 Derive algorithms and design software for the exemplary problems to help students understand the abstract concepts by touching and manipulating virtual objects with haptic interface in a virtual environment

Corresponding to the key concepts identified in the previous section, we have developed algorithms and software as the new learning materials. We used Open Dynamics Engine (ODE) as the dynamics engine to support the computation in our graphics and haptics applications. OpenGL is adopted as the graphics engine. OpenHaptics is adopted as the haptics engine [SensAble Web].

Open Dynamics Engine (ODE) is an open source, high performance library for simulating articulated rigid body dynamics [ODE Web]. It is useful for simulating vehicles, objects in virtual reality environments and virtual creatures. With the geometric and non-geometric properties assigned to them, these virtual objects behave similar to the physical objects in the real world [ODE Web]. Students will be able to interpret these properties by touching and manipulating the virtual objects, and relate these properties to the physical objects they meet in their daily life. The following are the detailed description of the developed materials. After this we describe the general procedure of student experiments, including the use of the software materials.

3.2.1 The developed haptic-augmented learning materials for the Dynamics course

***Problem 1*:** Sliding and Rolling Motion

There are two cases. The two cases look similar but work differently for the block and the ball. One can feel the friction force with a haptic device.

1) A block moving with an initial speed on the surface from left to right: because of the friction on the surface, the block gradually slows down, until it comes to a full stop. The block slides on the surface all the time.

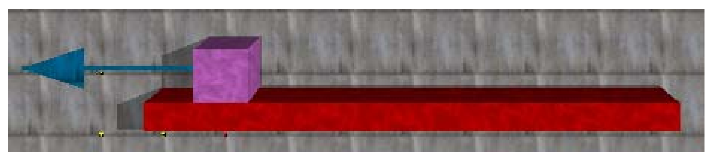


Figure 2 A Sliding Block on a Flat Plane

2) A ball (sphere) with an initial speed on the surface from left to right: because of the friction on the surface, the kinetic energy of linear motion is gradually converted into the kinetic energy of the rotational motion. This means that at the beginning of the motion, the ball is both sliding and rolling. At a certain moment, the ball is no longer sliding as the contact point between the ball and the surface has a zero velocity, which means there is no friction at the contact point. Thus the ball will keep moving at a constant speed. And this motion is pure rolling, without sliding.

Figure 3 A Rolling and Sliding Ball on a Flat Plane

***Problem 2*:** Impulse and Impact

There are two demos for this problem. By manipulating the ball with a haptic device, one can try different impact results.

1) Two (billiard) balls collide with each other: direct impact or oblique impact. By pressing and holding the blue button of the haptic probe, one can drag one ball and try to hit the other

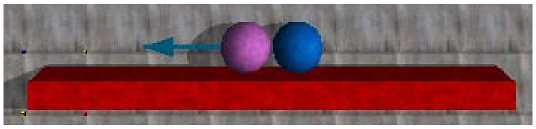


Figure 4 Two Balls in Collision

1) One (bowling) ball hits a (bowling) pin. By pressing and holding the blue button of the haptic probe, one can drag the ball and try to hit the bowling pin.

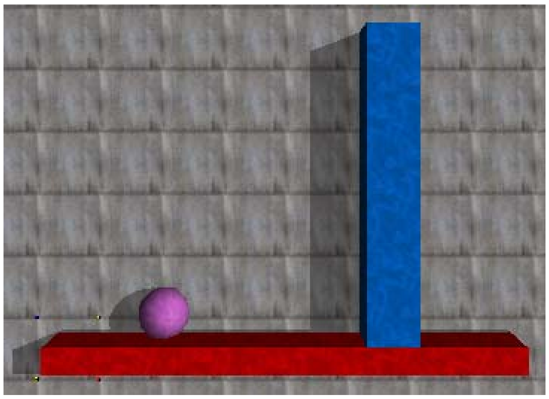


Figure 5 Rolling ball and the Bowling Pin

***Problem 3*:** Centrifugal and centripetal forces

This demo shows particle-waltz example. Two particles are used to represent two persons. They are dancing like in a waltz. One particle is leading the other. The other particle follows the motion of the first particle, as if the two are connected with a rubber band. The force arrow shows the magnitude and the direction of the centripetal force. One can feel the centripetal force when dragging the ball with a haptic device.

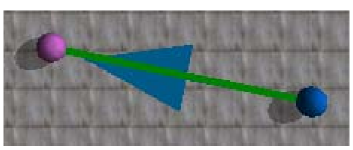


Figure 6 Particle Waltz Example

***Problem 4*:** Coriolis acceleration and force

This demo shows Coriolis acceleration and its corresponding Coriolis force. It shows a rotating bar, which rotates at a constant speed. On the rotating bar, a slider block is moving at sine wave motion (autonomously). With a haptic device, one can feel the Coriolis force when following the motion of the slider.

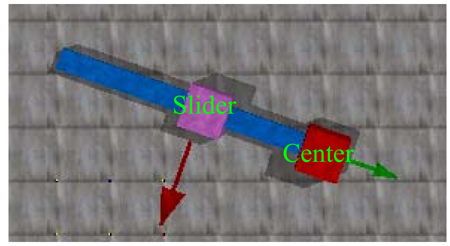


Figure 7 Coriolis Force and Acceleration Example

***Problem 5*:** Kinetics of Rigid Body

This demo shows the slider-crank mechanism of an internal combustion engine. Generally speaking, there are three types of planar motion: 1) linear translation; 2) rotation; 3) combined translation and rotation in a plane. In a slider-crank mechanism, the slider is moving at linear translational motion; the link BC is at rotational motion; the link AB is at combined translational and rotational motion. In this case, the slider is actually the piston of a car engine and it drives the crank and wheel (not drawn in this figure). One can drag the slider to move the mechanism with a haptic device.

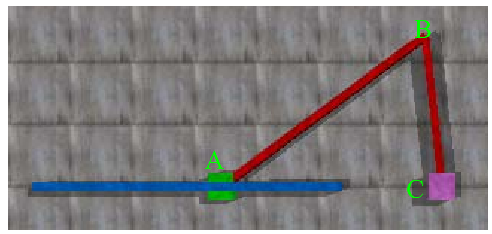


Figure 8 Slider-crank Mechanism Simulation

3.2.2 General procedure of the student experiments

The innovative course materials have been used in teaching for the first time in the Spring 2008 semester. Before the new course material is used in the lab teaching, pilot study was conducted with a small group of students to test the usability.

In order to document the quality and impact of the integration of the haptic interface system into the *Dynamics* education and to aid in the new learning materials and tools' improvement, we have designed an evaluation plan that provides information concerning program activities and support for decision making. Our evaluation plan and data collection is briefly described as follows. We conducted a pre-/posttest experiment with the undergraduate engineering students in the *Dynamics* course. The students were divided into a haptics training group and a control group to be taught with graphics animation only. At pre-test, all participants were presented with a battery of spatial reasoning and problem-solving ability tests. Then, each participant was randomly assigned to one of two groups: a) *Graphics group*: Participates in the pre- and post-test, but is taught *Dynamics* with graphics animation only; b) *Haptics group*: Participates in the pre- and post-test, but is taught *Dynamics* concepts combined with haptic-augmented animation. The effectiveness of the exemplary learning materials and tools will be measured through analysis of survey and interview data (indirect measure) and student learning outcomes (direct measure).

A battery of assessment was used to generate both quantitative and qualitative data from both the affective and cognitive domains of student learning. The brief descriptions of assessment tools are as follows [Minogue 2004]:

- *Student Information Sheet and Computer Use Survey*: This gathers demographic information and information about students' use of computers outside of school. The information will be used to assess if the individual differences in the influences of new instruction method exist.
- *Purdue Visualization of Rotations (ROT) Test*: This timed test assesses students' spatial ability, namely their ability to perform mental rotation tasks of 3D objects [Bodner 1997]. It will be used as covariant of student performance on the pre/post-assessments.
- *Pre-assessments and post-assessments*: This is a written-response instrument that combines objective and open-ended questions designed to elicit student's knowledge in the dynamics concepts presented in the instructional program. It will be scored by the educators. Pilot testing will first be conducted to support its content validity.
- *Interview*: The interview protocol includes questions designed to gain insight into what aspects of the instructional program students find salient in regard to the validity of haptic/visual feedback.
- *Assessment of Instructional Module* (AIM): The AIM is a self-report survey based on a similar instrument to [Jones 2003], which is designed to gather information about the affective impact of the haptic-augmented Virtual Environment on the student's experience.

Before the one-on-one lab instruction, we spent one lecture session on informing the students the lab contents and conducting the pre-assessment and data collection. After that, we scheduled the one-on-one lab instruction session with each student. Altogether 40 students took the pre-assessment. But due to the scheduling conflict, only 27 students were able to complete the lab sessions. The 27 students who completed all the study were paid for their participation. The whole procedure is shown in the Table 2.

Table 2 General Procedure for the Student Experiments

	Task	Time
In a regular class Session (75 minutes)	A. Fill the student information sheet and computer use survey	15 min
	B. Purdue Visualization of Rotations (ROT) Test	15 min
	C. Pre-assessment for the five topics	40 min
Lab Session (About 2 hours)	D. Graphics-only or Graphics-Haptics instructional program	50 min
	E. Post-experience interview	10 min
	F. Post-assessment for the five topics	40 min
	H. AIM Survey	5 min

4. DATA COLLECTION AND ANALYSIS

Through the lecture session, we collected the pre-assessment result from 40 students. In the end, only 27 students finished the lab session and the post-assessments. These 27 students were split into two groups: 13 students in the graphics group and 14 students in the haptics group. The data collection and analysis are presented as follows.

4.1 Student Information

The student information is summarized as in Table 3. There are 25% female students. The minority is 32.5% of the whole batch. Altogether the percentage of the students from the underrepresented group is 42.5%. Although all of them have claimed their major as Mechanical Engineering, Industrial Engineering or Civil Engineering, most students are still in the general engineering category (lower division of engineering). They have the option to change their major. Hence we did not classify the students based on the major.

Table 3 All Students Information Summary

(a) Student population breakdown based on gender

Female	10
Male	30

(b) Student population breakdown based on ethnicity

African American	1
American Indian	1
Asian	2
Caucasian	27
Hispanic	8
Caucasian & other	1
Total	40

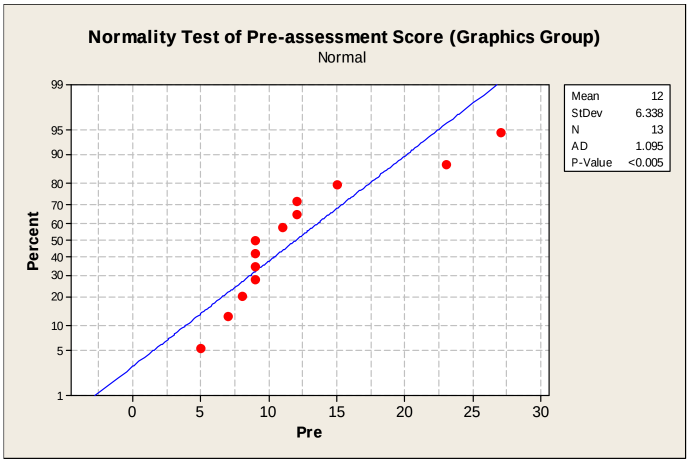
In the end, only 27 students completed either the haptics or graphics sessions. Among these 27 students, 25.9% are female students, 40.7% are minority students and totally 51.9% are from the underrepresented group.

4.2 Pre-assessment and Post-assessment Comparison in Each Group

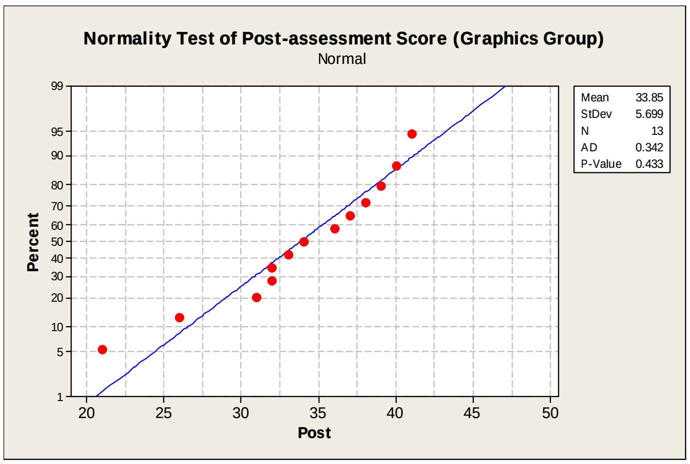
While there are many results coming out from this study, we mainly report one result here. The first result answers the question: did learning occur in each group? For this, we need to compare the scores from the pre-assessment and post-assessment in each group (Graphics Group and Haptics Group). MiniTab™ software was used for the following data analysis.

Since there are only 13 or 14 students in each group, we cannot use the Central Limit Theory to assume that the population has a normal distribution. Therefore, we first conduct the Normality test of the pre-assessment and post-assessment score as show in Figure 9 (For Graphics group) and Figure 10 (For Haptics group). For these normality test, we pick the significance level $\alpha = 0.1$. If the P-Value from a Normality test is larger than α, it passes the normality test and the population can be considered to follow a normal distribution. The post-assessment scores of the Graphics Group, and the pre- and post-assessment scores of the Haptics Group passed the normality test. This means they each form a population under the normal distribution. But the P-value from the pre-assessment scores of the Graphics group is less than 0.005, and is less than the selected significance level α (=0.1).

It means there is insufficient data to support the claim that its population is under a normal distribution.

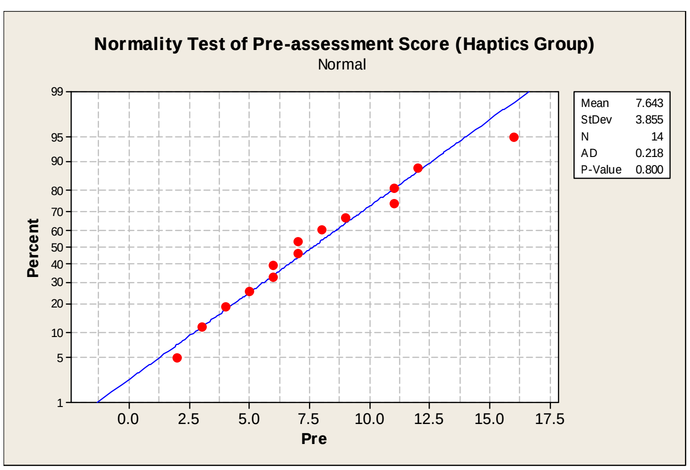


(a) Normality Test of Pre-assessment Scores

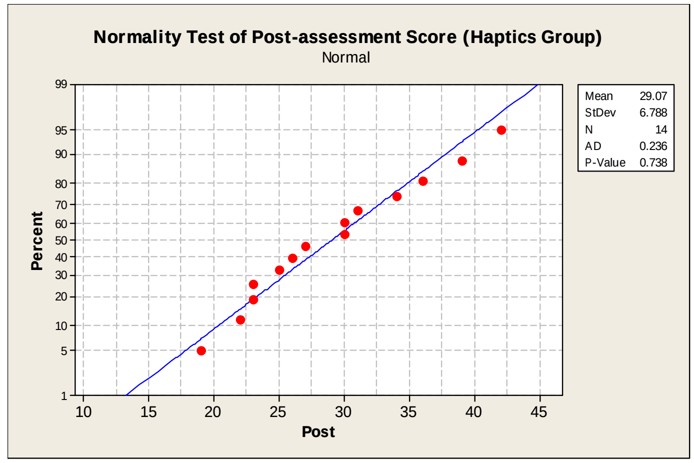


(b) Normality Test of Post-assessment Scores

Figure 9 Probability Plots for the Normality Tests (For Graphics Group)



(a) Normality Test of Pre-assessment Scores



(b) Normality Test of Post-assessment Scores

Figure 10 Probability Plots for the Normality Tests (For Haptics Group)

Given the result from the normality tests, we have to treat each group with different methods. For the Graphics group, since the pre-assessment scores do not have a normal distribution, we have to use a nonparametric test method. We selected Mann-Whitney test to compare the median of the pre- and post-assessment scores to see if learning occurs. As usual, the hypotheses are:

- H0 (null hypothesis): the two population medians are equal
- H1 (alternative hypothesis): the two population medians are not equal.

The significance value α is selected as 0.05, which is corresponding to 95% confidence interval. The Mann-Whitney test result for the Graphics Group is as follows:

```
               N   Median
Post-score    13   34.000
Pre-score     13    9.000

Point estimate for ETA1-ETA2 is 24.000
95.4 Percent CI for ETA1-ETA2 is (16.999,
27.999)
W = 257.0
Test of ETA1 = ETA2 vs ETA1 > ETA2 is
significant at 0.0000
```

The Mann-Whitney statistic is 257 and the associated p-value is 0.0000. Because the p-value is less than α (0.05), we should reject H0 and conclude that the median scores are significantly different. So it can be concluded that learning occurred for the Graphics Group.

For the Haptics Group, since both the pre- and post-assessment scores are under the normal distribution, we can use the Pair-t test to see if learning occurs. As usual, the hypotheses are:

- H0 (null hypothesis): the two population means are equal
- H1 (alternative hypothesis): the two population means are not equal.

The significance value α is selected as 0.05. The Pair-t test result for the Haptics Group is as follows:


```
              N   Mean  StDev  SE Mean
Post         14  29.07   6.79     1.81
Pre          14   7.64   3.86     1.03
Difference   14  21.43   7.02     1.88

95% lower bound for mean difference: 18.10
T-Test of mean difference = 0 (vs > 0):
T-Value = 11.41  P-Value = 0.000
```

Because the P-value (0.000) is less than α (0.05), we should reject H0 and conclude that the median scores are significantly different. So it can be concluded that learning occurred for the Haptics Group.

4.3 Comparison between the Graphics and Haptics Group

The comparison conducted between the Graphics group and the Haptics group provides insight on whether haptics information provides additional help in achieving learning goals. Again, many conclusions can be drawn from the large amount of data we've collected. We presented two main results here. First, we compared the learning improvement results between the two groups to see whether the Haptics Group achieved better learning improvement than the Graphics Group. We selected the Mann-Whitney test to compare the gain scores of the pre- and post-assessment scores. The gain score is obtained by subtracting the pre-assessment scores from the pre- and post-assessment scores in each group. As usual, the hypotheses are:

- H0 (null hypothesis): the two population gain scores are equal
- H1 (alternative hypothesis): the two population gain scores are not equal.

The significance value α is selected as 0.05. The Mann-Whitney test result for comparing the two groups' gain scores is as follows:

```
               N  Median
Haptic-Net    14   23.00
Graphic-Net   13   23.00

Point estimate for ETA1-ETA2 is 0.00
95.1 Percent CI for ETA1-ETA2 is (-7.00,6.00)
W = 194.0
Test of ETA1 = ETA2 vs ETA1 > ETA2

Cannot reject since W is < 196.0
```

The test tells us that insufficient evidence exists to reject the claim that the population medians are equal. In other word, we cannot come to the conclusion that the gain scores of the Haptics Group are better than those of the Graphics Group.

The second question is: are the students in the Haptics Group more positive and interested in the 'Dynamics' course than the students in the Graphics Group. This is assessed with a question from the *Assessment of Instructional Module*: "Are you more interested in the Dynamics course after the lab session?" The students responded with a level from 1 to 6, with 1 as the 'strongly disagree' and 6 as the 'strongly agree'. As usual, the hypotheses are:

- H0 (null hypothesis): the two population medians are equal
- H1 (alternative hypothesis): the two population medians are not equal.

The significance value α is selected as 0.05. The Mann-Whitney test result for comparing the two groups' gain scores is as follows:

```
               N  Median
Haptics-Q2    14   5.500
Graphics-Q2   13   4.000

Point estimate for ETA1-ETA2 is 1.000
95.1 Percent CI for ETA1-ETA2 is (0.000,2.000)
W = 236.0
Test of ETA1 = ETA2 vs ETA1 > ETA2 is significant at 0.0276
The test is significant at 0.0216 (adjusted for ties)
```

The Mann-Whitney statistic is 236 and the associated P-value is 0.0276. Because the P-value is less than 0.05, we should reject H0 and conclude that the medians are significantly different. Thus we can conclude that after the lab sessions, the students in the Haptics Group become more than positive in the Dynamics course than those of the Graphics Group.

5. CONCLUSIONS AND FUTURE WORK

This paper presents our recent investigation on the impact of 3D haptic-augmented learning tools on Dynamics, which is a basic course in most of the engineering education program. Dynamics is considered to be one of the most difficult and non-intuitive courses that engineering students encounter during their undergraduate study because the course combines basic Newtonian physics and various mathematical concepts such as vector algebra, geometry, trigonometry, and calculus and these are applied to dynamical systems.

In this study, 3D haptic-augmented learning tools have been created and used to complement the course materials in Dynamics course. Experiments have been conducted with a group of Mechanical Engineering students in the Dynamics class in the Spring 2008 semester at Lamar University. The assessment result shows that the innovative learning tools: 1) allow the students to interact with virtual objects with force feedback and better understand the abstract concepts by investigating the dynamics responses; 2) stimulate the students' learning interests in understanding the fundamental physics theories.

From the data analysis, it is revealed that Graphics Group data did not have a normal distribution. This implies that we do not have sufficient data to support a more accurate pair-t test. A population of 30, preferably 40 in each group, will allow us to assume a normal distribution with the Central Limit Theory. Hence we plan to conduct more student experiments in the future semesters. We also found out while both groups improved the learning, there are no significant difference in learning improvement between the two groups. According to our interviews with the students, there can be at least two reasons for this. The first reason is: the graphics animations are very well designed to convey the concepts. The second one is: there are no knowledge points that can only be conveyed by the haptic interface. But the attitudinal test clearly supported the claim that students are more positive with the Dynamics course. In the future, we plan to refine our design of the haptic-augmented learning materials to emphasize more on the force feedback in these animation programs. An interesting question exists as whether the haptic learning channel is assistance or distraction in the learning process. To answer this question, more human factor study and educational psychology research need to be conducted. Other than the above research questions, more detailed data analyses need to be conducted with the large amount of data we have collected.

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