Improving the Learning of Physics Concepts by Using Haptic Devices

Luis Neri, Ph.D.
Escuela de Educación,
Humanidades y Ciencias Sociales
Tecnológico de Monterrey
Mexico City, Mexico 14380
neri@itesm.mx

David Escobar-Castillejos
Graduate Student of
Engineering Science
Tecnológico de Monterrey
Mexico City, Mexico 14380
a01170737@itesm.mx

Julieta Noguez, Ph.D.
Escuela de Ingeniería
y Ciencias
Tecnológico de Monterrey
Mexico City, Mexico 14380
jnoguez@itesm.mx

Uzma A.S. Shaikh
Graduate Student of Computer
and Information Technology
Purdue University
West Lafayette, Indiana 47907
ushaikh@purdue.edu

Alejandra J. Magana, Ph.D.
Associate Professor of Computer
and Information Technology
Purdue University
West Lafayette, Indiana 47907
admagana@purdue.edu

Bedrich Benes, Ph.D.
Professor of Computer
Graphics Technology
Purdue University
West Lafayette, Indiana 47907
bbenes@purdue.edu

***Abstract*—Haptic devices are electro-mechanical tools controlled by computers that allow to recreate the sense of touch. They enhance the sense of interaction with virtual objects from purely visual to haptic and visual. One of its application areas is in training environments, where the users can interact with virtual objects to learn procedures or tasks. In this paper we describe the use of haptic devices to improve the learning process of basic physics concepts from electromagnetism and the haptic tools via simulation of magnetic forces in 3D. We have created three scenarios with different distribution of charges: point charge, line charge, and plane charge. Each scenario was properly calibrated and has different force feedback (quadratic, linear, and constant) depending on the scenario. We wanted to investigate how forces are perceived by students. A user study was carried out to assess students' perception and knowledge acquired when they were working with the system. Results suggest that students from the treatment group achieved better understanding than those from the control group. Results also indicate that 95% of the students considered that the use of haptic devices combined with appropriate virtual environments facilitated them to understand the nature and origin of electrical forces.**

Keywords*—Virtual Environments, Physics Simulations, Electromagnetic Forces, 3D Computer Graphics, Haptic Devices

I. Introduction and Previous Work

Throughout history, teachers and their use of lectures have become the most effective way to acquire new knowledge [1]. Nevertheless, as a result of the constant progress in science and technology, new alternative solutions in the area of learner-centered approaches have been developed. One of them are different types of simulations, control systems, and learning environments, some of them used via the internet, establishing the area of Technology Enhanced Learning (TEL). The new options allow students to enhance their learning by allowing them to acquire knowledge and skills via virtual environments [2].

One of the novel areas uses haptic devices that reproduce the sense of touch for users interacting with a virtual environment. Advances in the field of electromechanical and computer technology have enabled the development and creation of various types of applications with haptic devices such as the Novint Falcon® or SensAble Phantom Omni® in Figure 1.

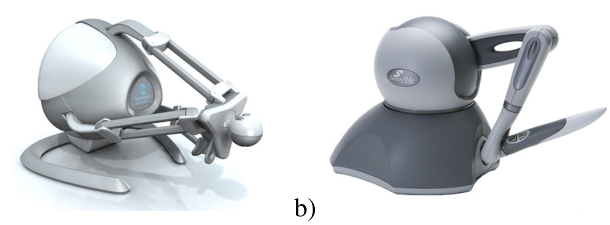
a) b)

Fig. 1. a) Falcon Novint® and b) SensAble Phantom Omni® are USB-connected computer controlled haptic devices that were used in our experiments.

Haptic devices have been used in many fields such as navigation, education, e-commerce, medicine, gaming, and arts [3]. One of the most important areas where haptics have been implemented for teaching is in medicine. For example surgical operations, such as stitching and minimally invasive surgeries, have been used to train doctors [4], [5], [6]. Although haptic devices can be used in many different fields, it usually does not make a big sense to create virtual simulations of structures that can be physically fabricated in real world, such as mass-spring systems. Haptics can be effectively applied in areas where the actual force is either out-of-scale ranging from nano structures [7], [8], molecules [9] to astronomical scales [10], or for complex structures such as granular materials [11].

In traditional physics courses, students often have difficulties visualizing and perceiving basic concepts of physical phenomena. This problem worsens when abstract and non-tangible concepts are involved, i.e., electromagnetic interactions between charges [12], [13]. On one hand, real laboratories and

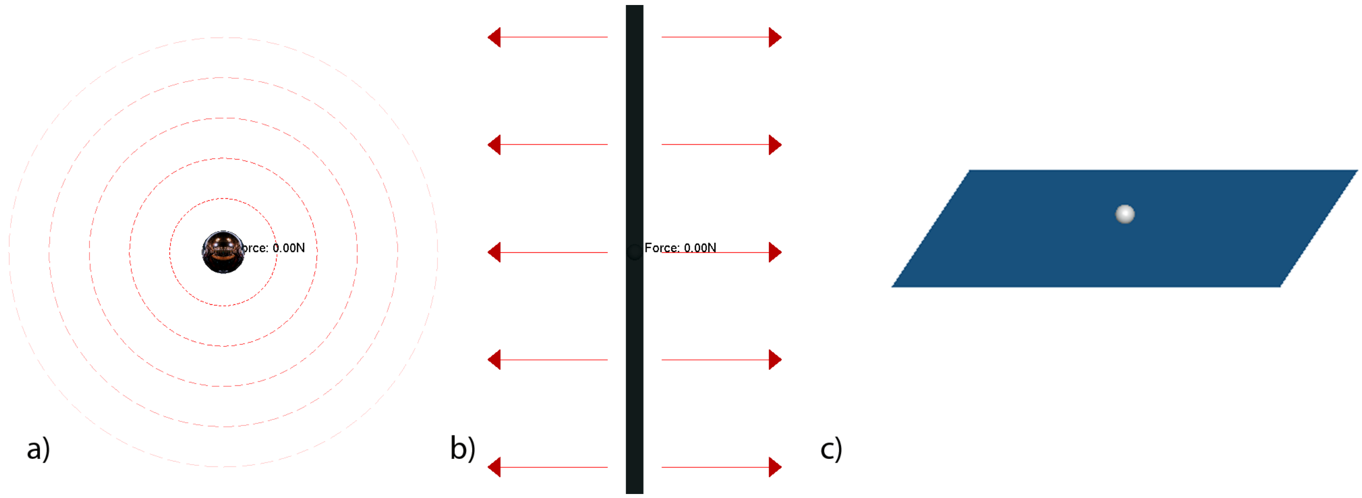

Fig. 2. Three experimental setting used in our testing point charge (a), infinite line charge (b) and infinite plane (c).

online simulators have traditionally been used to help students recreate appropriate physical scenarios [14]. Nevertheless, real laboratories are not always available in educational institutions, or they do not have all the necessary equipment to carry out suitable experiments. On the other hand, although online simulators constitute an alternative to real laboratories, most of them only address the sense of sight and in some cases the sense of hearing [15].

Electricity and magnetism concepts symbolize the basis of many current and novel technologies; however, undergraduate students often find the concepts difficult and confusing [16]. Some of the major deficiencies relate to a qualitative misunderstanding of the Maxwell's equations (expressed qualitatively); misunderstandings about the relationship between the electric fields and its sources, and the application of these concepts in problem solving [17]. Specifically, students have difficulties with electromagnetic induction and electric potential and electric energy [18].

In order to offer students a deeper perception of physical phenomena in virtual simulators, some authors have used haptic devices in online experiments. These studies had been carried in different settings, ranging from elementary school to graduate students, and they covered different physics areas, such as mechanics [19], [20], electricity and magnetism [21], [22], or heat and temperature [23]. However, although these researches helped students to better understand the nature of some physics phenomena, they are not usually applied to the field of electricity and magnetism that serve as the basis for different disciplines.

Physics educational researchers have identified the value of simulations in providing visualization of the different abstractions and complexities found in electromagnetism concepts [18]. We argue that through the implementation haptic technologies, in addition to computer simulations, can enable virtual hands-on laboratories that simulate real life scenarios or even physical abstractions. On the other hand, electromagnetism-related concepts, such as electric fields and distributed charges, are topics that have received little attention in regards to the implementation of haptic technologies. Sanchez et al. [22] investigated the efficacy of using visual only and visuohaptic simulations for improving the learners' understanding of electromagnetic concepts. The findings of this research indicate no significant difference in the two treatment groups. Authors hypothesized that one potential reason for not identifying significant differences was attributed to students' inability to interpret touch in the context of the visualization. In order to test this hypothesis qualitative studies are needed to describe how students conceptually interpret the sense of touch. Host et al., conducted a qualitative study where they explored two different modes of using the haptic simulation in [24]. One was referred to as the force mode and the other one as force-and follow mode. The first mode allowed the learner to experience the force of the electric field and the latter one allowed the probe to be moved along the shape of the electric field. In this study authors found that before students interacted with the visuohaptics model they displayed struggles to distinguish between the concept of polarity and electric field. Host et al., hypothesized that this misunderstanding may be the source of unscientific views that all non-polar molecules are void of an electric field [24]. Authors also proposed that to remedy this problem scenario would be to directly engage electric field concepts into teaching polarity and intermolecular interactions [22]. They concluded that an integration of tactile interaction may induce an active integration of electric field knowledge with molecular charge distribution.

In this paper we explore how haptic devices can be used to effectively aid learning experience in traditionally difficult concepts from physics, namely in electromagnetism. We have developed an interactive simulator that uses three scenarios with different distribution of charges: a) point charge, b) infinite straight line of charge (hereafter, "line charge"), and c) infinite plane of charge (hereafter, "plane charge"). These scenarios can be seen in figure 2. The dependencies of the electric field strength on distance R from these charge distributions are $1/R^2$ (point charge), $1/R$ (line charge), and independent on distance (plane charge) [25]. We used haptic simulation to verify if the students are able to distinguish among the different scenarios and if they can interpret the forces correctly. The experiments were designed in 3D, and they were coupled with haptic devices.

A user study was carried to assess students' perception and knowledge acquired when they were working with the system. They were tested by engineering undergraduate students at Tecnológico de Monterrey in Mexico City and our results suggest that the use of haptic devices combined with appropriate virtual environments facilitate students to understand the nature and origin of electrical forces. Our results show that the use of haptic devices helped students to better understand electrical forces (95%), and 95% of the students stated that they would like to have haptic simulators to visualize other physics scenarios.

II. Experiment Design

Electricity and magnetism provide the basis of many current and novel technologies and although undergraduate students are exposed to these concepts early in their studies they still find the topic difficult to understand. There are several reasons for this problem, among them is the complexity of mathematical concepts, and the difficulty to visualize the actual interaction of charges in the 3D space. Because of this, we have designed three experiments that provide the basic interactions, yet expose the essence of the actual interaction. The three settings were point charge, line charge, and plane charge. Each charge provides different force feedback applied to a point charge in the 3D space. The point charge experiment has quadratic attenuation with the distance. Infinite line experiment (line charge) provides linear attenuation, and an infinite plane experiment (plane charge) applies constant force independently of the location of the point charge.

A. Theoretical Framework

Embodied cognition was the theoretical framework that guided this investigation. Embodied cognition posits that bodily experiences are a key component of cognition [26]. Here, human construction of knowledge is considered closely linked to sensorimotor interactions in the world [27]. Traditional work in the cognitive sciences has primarily focused on the mind as an abstract information processor. These same views have argued that connections to the outside world (via perceptual and motor systems), were not considered relevant to understanding cognitive processes [27]. On the other hand, Artificial Intelligence has been re-thinking the nature of cognition focusing on the fact that thinking and understanding occurs in complex environments and by manipulating external props [28].

Some of the assumptions or views of embodied cognition are that it is situated, is time-pressured, is for action and body based [27]. It is also assumed that embodied cognition is used to offload cognitive work onto the environment and that the environment is part of the cognitive system [27]. In this regard, tactile sensations could stimulate learners to access and integrate embodied knowledge into their cognitive processing of abstract scientific concepts. Therefore, experiencing a coordinated visual and tactile representation of electric field concepts could have a potentially deep-seated influence on students' construction of knowledge concerning invisible and macroscopic phenomena.

B. Point charge

This experiment enables the learner to feel the electric force between two point charges that has quadratic attenuation as the function of the distance of the charges. Charge Q_1 is fixed at the origin of the coordinate system at location $[0, 0, 0]$, and charge Q_2 is controlled by the user. It is connected to the haptic cursor, and it can be freely moved at different distances from Q_1 in the 3D environment (Figure 2 a).

The values of both charges can be chosen in the interval of $-20\mu C$ to $+20\mu C$. If learner chooses values that have different signs ($Q_1^+ Q_2^-$ or $Q_1^- Q_2^+$), he will feel the attraction force generated. On the other hand, if the learner chooses values that have equal signs ($Q_1^+ Q_2^+$ or $Q_1^- Q_2^-$), he will feel the repulsive force generated. The actual force is described by the Coulomb's law

$$\vec{F} = k_e \frac{Q_1 Q_2}{R_{QQ}^2} \hat{r}, \tag{1}$$

where $k_e = 8.987 \times 10^9 Nm^2/C^2$ is the Coulomb's constant, $\hat{r}$ is the radial unit vector, and

$$R_{QQ} = dist|Q_1, Q_2|$$

is the Euclidean distance between the locations of charges Q_1 and Q_2.

The purpose of this experiment is for students to realize that the force between point charges is proportional to the product of the charges magnitude and inversely proportional to the square of the distance between the charges.

C. Line charge

In the second experiment, shown in figure 2 b), the system displays a long straight-line charge fixed along the y-axis and a user-controlled mobile test point charge Q_2.

The values for the linear charge density, λ, of the line charge can be set between the interval of $-20\mu C/m$ to $+20\mu C/m$, and the point charge can be chosen in the interval of $-20\mu C$ to $+20\mu C$. As in previous experiment in Section II-B, the x, y, and z-axes are shown and the forces that the user feels are calculated according to the sign of the values selected for the point charge and the straight-line charge. The equation for the force applied to a charge within the influence of the infinite charged line is calculated according to

$$\vec{F} = k_e \frac{2\lambda Q_2}{R_{Q\lambda}} \hat{r} \tag{2}$$

and

$$R_{Q\lambda} = dist|Q_2, \lambda|$$

is the distance between the point charge and the infinite line. Note that the attenuation is linear as the function of the distance of the charge from the line.

In this experiment the students are expected to understand that the force between a long charge line and a point charge is proportional to the product of the charges magnitude and inversely proportional to the line charge-point charge distance.

D. Plane charge

In the last experiment shown in figure 2 c), the learner senses the force generated by the interaction of a large plane of charge fixed at the yz plane and a user-controlled mobile

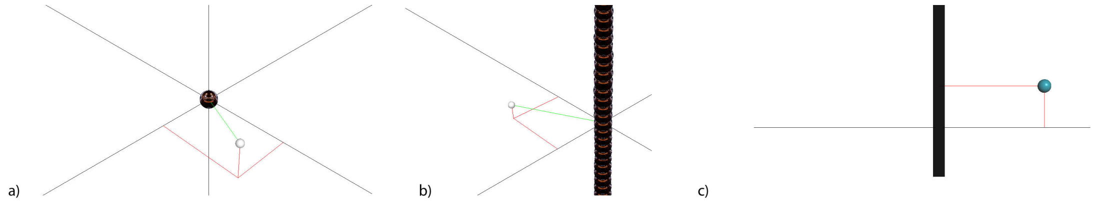

Fig. 3. Guiding lines connected to the coordinate frame were used to better orient the user in the 3D environment in point a) line b) and plane c) configurations.

test point charge Q_2. The exerted force does not depend on the distance and is constant, because the plane is infinite.

The value for the surface charge density σ, of the plane charge can be chosen by the learner between the values of $-20\mu C/m^2 and{+}20\mu C/m^2$. The point charge value can be set between the interval of $-20\mu C$ to $+20\mu C$. As in the previous simulators, the forces that the user perceives are calculated according to the sign of the values selected for the point charge and plane charge

$$\vec{F} = 2\pi k_e \sigma Q_2 \hat{r}. \tag{3}$$

As can be seen, the actual force $\vec{F}$ does *not* depend on the distance from the plane.

The goal of this experiment is to let students realize that the force between a large plane of charge and a point charge is proportional to the product of the charges' magnitude, and it is independent from the distance between them.

III. Virtual Simulator

We have developed comprehensive learning simulation systems that use haptic devices. The system was developed in C++ and uses OpenGL and GLSL for visualization. We used GLM for math processing and Chai3D [29] for haptics rendering.

Our implementation allows to use a SensAble Phantom Omni® or Novint Falcon®. All simulations were executed on a DELL T7500 Workstation equipped with Intel XEON E5620® processor clocked at 2.4 GHz, with 12 GB RAM, and NVIDIA GeForce 9800 GX2® video card, Windows 7 64 bits operating system, and on an ASUS G750JX-MBS1-H laptop, with Intel Processor i7-4700HQ® clocked at 2.39 GHz, with 8 GB RAM, and NVIDIA GeForce 770m® video Card. The user testing were performed by using the laptop and by using the Falcon Novint® haptic haptic device shown in Figure 1 a).

The Point Charge and the Line Charge simulations were developed as 3D environments due to the nature of their interaction forces, as can be seen in figures 3-a and 3-b. The Point Charge, the charge Q_1 was displayed as a small sphere and its interaction forces were calculated to avoid Q_2 penetration. A line was created for the Line Charge to trace a long box. This line was placed on the y-axis and collision detection was enabled to show that Q_2 cannot enter the line. It is important to note that in both simulators the size of the moving object representing the charge Q_2 changes according to its location relative to the user because of the perspective projection to provide a better depth perception. Additionally, guiding lines connecting the haptic cursor with the projection to the axis of the Euclidean coordinate system were used to provide guidance (Figure 3).

The Plane Charge simulator is symmetrical in 3D and was developed as 2D representation showing the x and y-axes, as can be seen in figure 3-c. However, the user could navigate the scenario using the all three axis. The plane was created as a mesh to enable the simulation provide collision detection in the plane. Finally, as in the previous simulators, guidance lines were implemented to locate the user in the space.

Figure 4 shows a student interacting with the haptic device during an experimental session.

Fig. 4. A student interacting with the Plane Charge simulator. Students can freely explore the virtual scenario by using a haptic device. Depending on the position of the haptic interaction point, students can feel the interaction force in that position.

IV. Evaluation Process

During the January - May 2015 term, a focus group of 20 freshmen students of a undergraduate Electricity and Magnetism course at Tecnológico de Monterrey (Mexico City) were invited to test the three developed experiments. The testing sessions were one week long and the students were able to use the simulators coupled with haptic devices.

Each session consisted of a brief introduction and demonstration of how the system works followed by exercises for each simulator. They were asked to explore the system and solve some exercises using the haptic device in order to sense the interaction forces between the different charge distributions, as can be seen in figure 5. Each student explored the system for approximately 30 minutes. At the end of each session, students were asked to provide general comments

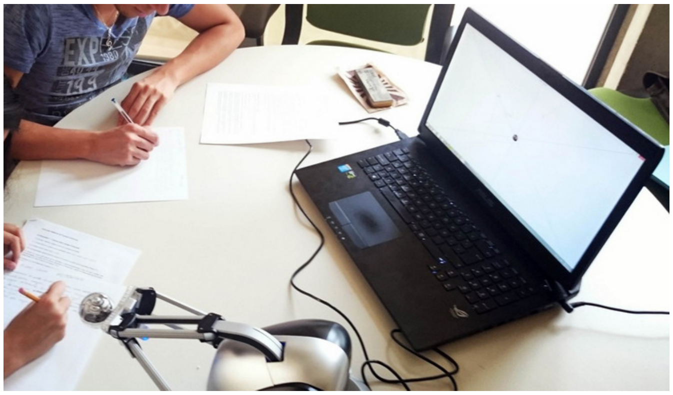

Fig. 5. Students solving exercises using the Point Charge simulator. Students followed instructions for each simulator where they can apply the knowledge they learnt in the classroom to check if the values were correct.

about the virtual systems. After that the students were also asked to answer two short multiple-choice questionnaires:

i) A post-test, which aimed to seek whether they were able to identify the direction of the force and its dependence to the distance between the test point charge and the different charge distributions (Table I).
ii) A perception questionnaire, which was created to assess students' overall opinion to the simulators (Table II). Likert scale was used, in this questionnaire using the values: Total Agreement (TA), Agreement (A), Indifferent (I), Disagreement (D), and Total Disagreement (TD).

By applying both questionnaires, we could measure if the student felt that this system could help them to better understand the nature and behavior of electrical forces. The post-test was also applied to 20 freshmen students of a different Electricity and Magnetism course, a control group, in order to compare the results between both groups. Even though the treatment and control groups had different professors, both groups covered the same syllabus, provided similar exercises, same lectures, and same learning resources about the concepts developed in the simulators. Therefore, students had same academic backgrounds and characteristics.

TABLE I. POST-TEST QUESTIONNAIRE APPLIED TO TREATMENT AND CONTROL GROUP.

Post-test questionnaire				
1) What kind of force is felt between charges of the same sign?				
a) Attractive	b) Repulsive	c) Depends on the magnitude of charges values		
2) What kind of force is felt between charges of opposite sign?				
a) Attractive	b) Repulsive	c) Depends on the magnitude of charges values		
3) The value of the electric force between point charges located at distance R is proportional to:				
a) R^2	b) R	c) Does not depends on R	d) 1/R	e) $1/R^2$
4) The value of the electric force between a line charge and a point charge located at distance R is proportional to:				
a) R^2	b) R	c) Does not depends on R	d) 1/R	e) $1/R^2$
5) The value of the electric force between a plane charge and a point charge located at distance R is proportional to:				
a) R^2	B) R	c) Does not depends on R	d) 1/R	e) $1/R^2$

V. RESULTS AND DISCUSSION

The results of the post-test applied to the treatment and the control group are shown in figures 6 and 7. Results from the perception questionnaire (applied only to the treatment group), can be seen in figure 8.

As can be seen in figures 6 and 7, most students in both groups answered correctly the first two questions which were focused on their understanding of how the interaction force behaves (attraction or repulsive force). Nevertheless, in questions three to five, related to the dependence of the electric force to the distance between the different charge distributions, interesting differences appeared when the treatment and the control group were compared. In question number three, where the right answer is the option "e" - $(1/R^2)$, the results for this question are very similar for both groups (treatment: 60%, control: 55%). On the other hand for question four (electric force between point charge and line charge), the right answer percentage (option "d" - $1/R$), although both percentages are low, was higher in the treatment group (25%) than the one obtained in the control group (only 5%). Finally, in question five, the electric force between a point charge and a plane of charge, 75% of the members of the treatment group answered it correctly (option "c" - Does not depend). This value is higher compared to the one obtained in the control group (only a 50%). In summary, students from the treatment group achieved better results than those from the control group. This result suggest that the use of virtual learning environments coupled with haptic devices can help learners to better recognize and understand the strength of the electric forces.

TABLE II. PERCEPTION QUESTIONNAIRE APPLIED TO THE TREATMENT GROUP.

Perception Questionnaire
1) Point Charge experiment helped me to better understand thebehavior of the interaction force between point charges.
2) Line Charge experiment helped me to better understand the behaviorof the interaction force between a line charge and a point charge
3) Plane Charge experiment helped me to better understand thebehavior of the interaction force between a plane charge and a pointcharge
4) Manipulating Point Charge experiment was easy and intuitive
5) Manipulating Line Charge experiment was easy and intuitive
6) Manipulating Plane Charge experiment was easy and intuitive
7) Point Charge experiments graphics are appropriate and attractive
8) Line Charge experiments graphics are appropriate and attractive
9) Plane Charge experiments graphics are appropriate and attractive
10) The three experiments, as a whole, helped me to acquire betterperception of the interactions forces between the different chargedistributions
11) I would recommend simulations with haptic devices to learn otherconcepts of Electricity and Magnetism
12) I would recommend simulations with haptic devices to learn otherconcepts of Physics

Results of the perception questionnaire suggest, as can be seen in figure 8, that the students of the treatment group totally agree or agree on the fact that the virtual simulator helped them to better understand the behavior of electrical forces. Moreover, they specified that the manipulation and visualization of the system was in general appropriate, and they would recommend simulations that use haptic devices to learn other concepts of the Electricity and Magnetism course, as well as for other physics topics. The average results were calculated using Total Agreement and Agreement. The highest average obtained in the questionnaire was the acceptance that simulators helped them to better understand electrical forces (92% for questions 1 - 3). There is also a high average of 87% stating that the system manipulation was easy and intuitive (questions 4 - 6). On the other hand, the lowest average of acceptance was obtained in the questions related to the visualization of the system (72% for questions 7 - 9). This can be interpreted as the need for the graphics of the simulators to be improved, in particular, in the perception of depth.

The general acceptance percentage was also rather high; 95% in question 10 suggests that students considered that the three experiments helped them to acquire and to better understand the perception of the interactions between different charge distributions. Finally, similar to the previous question, the average result for questions 11 and 12, 95% suggests that haptic simulators are recommended to visualize other physics scenarios. Results from the last part of the questionnaire (questions 10 to 12) can be further supported by the general comments that the students from the treatment group also provided.

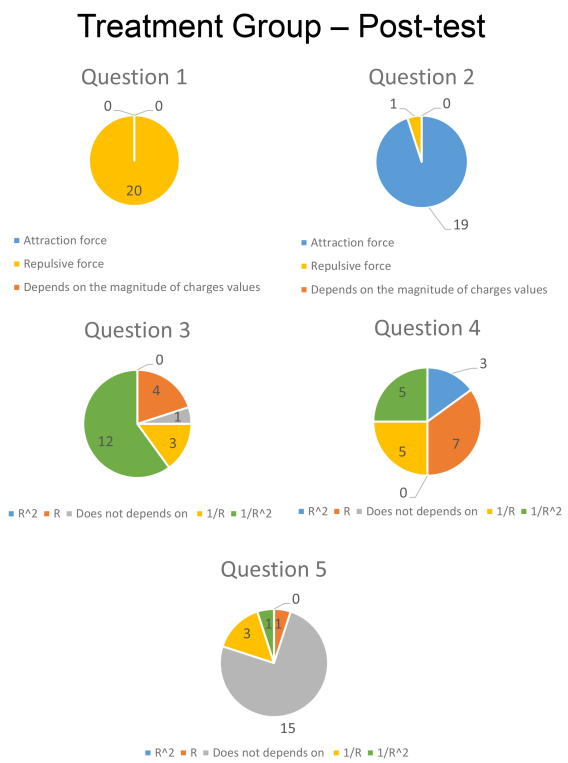

Fig. 6. Treatment group results obtained in the post-test.

Most of these comments were positive and motivating. Typical ones were: "I liked the (haptic) simulator because it shows more realistic scenarios than those seen in class", "they (haptic simulators) helped me to better understand the behavior of electric forces", "the simulations (using haptics devices) are interactive and didactic". Furthermore, there were other comments that invited the authors to improve the visualization of the experiments, the 3D perspective, and other students even encouraged the authors to create new simulators.

We believe that the high failure percentages for the treatment and control groups obtained in the question related to the line charge experiment (question four) is due to the fact that students do recognize that the force strength increases for shorter distances, but they have troubles in disclosing between the linear and quadratic attenuation.

VI. Conclusions and Future Work

We have shown our implementation of a 3D haptic simulations and how it was used to assess learning experienced

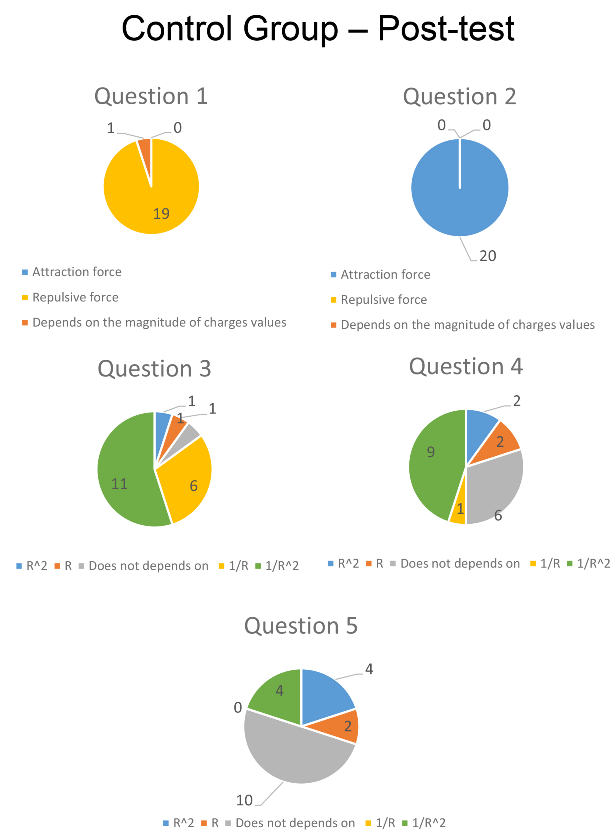

Fig. 7. Control group results obtained in the post-test.

in traditionally difficult concepts from physics - electromagnetism. Our interactive simulator uses three scenarios: point charge, line charge, and plane charge, where each scenario provides different force feedback: quadratic, linear, and constant, respectively. The third dimension was added to enrich the visualization and our system includes a three-dimensional coordinate system that shows the projections of the haptic cursor on the coordinate planes.

A user study was carried out to assess students' perception and knowledge acquired when they were working with the system. They were tested by engineering undergraduate students at Tecnológico de Monterrey in Mexico City and our results suggest that the use of haptic devices combined with appropriate virtual environments may facilitate conceptual understanding of the nature and origin of electrical forces. Results of the post-test for the three experiments were better in the treatment group than in the control group. The best result was obtained when students used the Plane Charge simulation, but positive acceptance was obtained for the Point Charge. The poorest results were found in the Line Charge simulation.

Students' perception of the virtual environments was overall positive. They stated that the experiments helped them to better understand the behavior of electric forces, the manipulation of the experiments was easy and intuitive, and that the visualization was appropriate and attractive, although it still could be improved to provide better perception of the depth. They also manifested that the three experiments helped them to acquire a better perception of the interactions forces between different charge distributions, and they would recommend the

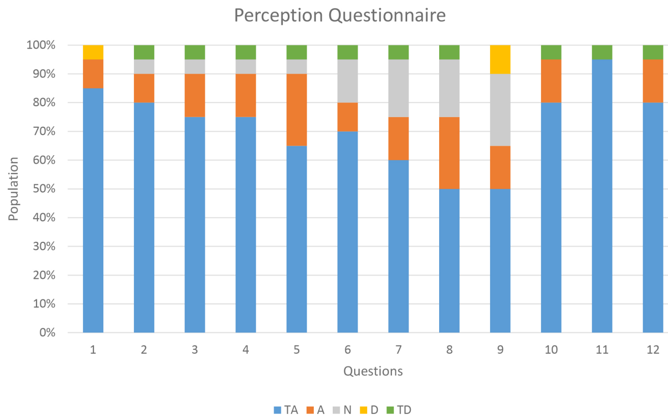

Fig. 8. Perception questionnaire results. This graph shows the acceptance and usefulness of the simulators according to the results obtained in the perception questionnaire.

use of virtual simulators coupled with haptic devices to learn other concepts of electricity and magnetism and other abstract Physics topics.

There are several possible avenues for future work. A more comprehensive study with more participants could be performed. It would be interesting to experiment with other concepts from magnetism, applying forces over wires of arbitrary shapes, among others. Several participants had difficulties in disclosing the force strength dependence on distance (linear vs. quadratic attenuation). It would be beneficial to conduct a novel study that would quantify and describe what were the reasons for these issues.

Acknowledgments

This project was supported by the *Fondo Novus 2014* grant. The authors would like to thank Rosa María García-Castelán for her participation and support during the testing process, and we sincerely thank the reviewers for their insightful feedback.

References

[1] K. Vanlehn, "The behavior of tutoring systems," *International Journal of Artificial Intelligence in Education*, vol. 16, no. 3, 2006.

[2] B. Yanng, "Intelligent learning system based on hmm model," *2011 Intl. Symposium on Knowledge Acquisition and Modeling (KAM)*, pp. 560–564, 2011.

[3] A. El Saddik, "The Potential of Haptics Technologies," *Proceedings of the IEEE*, vol. 77, no. 2, pp. 10–17, 2007.

[4] T. Coles, D. Meglan, and N. John, "The role of haptics in medical training simulators: A survey of the state of the art," *IEEE Trans. on Haptics*, vol. 4, no. 1, pp. 51–66, 2011.

[5] C. Basdogan, S. De, J. Kim, M. Muniyandi, H. Kim, and M. Srinivasan, "Haptics in minimally invasive surgical simulation and training," *Comp. Graph. and App.*, vol. 24, no. 2, pp. 56–64, 2004.

[6] E. Ricardez, J. Noguez, L. Neri, L. Munoz-Gomez, and D. Escobar-Castillejos, "SutureHap: A Suture Simulator with Haptic Feedback," in *VRIPHYS*. The Eurographics Association, 2014.

[7] M. Abdul-Massih, B. Benes, T. Zhang, C. Platzer, W. Leavenworth, H. Zhuo, E. R. Garcia, and Z. Liang, "Augmenting heteronanostructure visualization with haptic feedback," in *ISVC (2)*, 2011, pp. 627–636.

[8] Z. Liang, I. Wildeson, R. Colby, D. Ewoldt, T. Zhang, T. Sands, E. Stach, B. Benes, and R. Garca, "Built-in electric field minimization in (in, ga)n nanoheterostructures." *Nano Lett*, vol. 11, no. 11, pp. 4515–9, 2011.

[9] A. Krenek, "Haptic rendering of molecular conformations," in *Proc. Eurohaptics 2001*, 2001, pp. 142–145.

[10] L. Niy, M. Krzeminskiz, and K. Tuerz, "Application of haptic, visual and audio integration in astronomy education," in *HAVE*, 2006, pp. 152–156.

[11] B. Benes, E. Dorjgotov, L. Arns, and G. Bertoline, "Granular material interactive manipulation: Touching sand with haptic feedback," in *Proceedings of WSCG*, 2006, pp. 295–304.

[12] M. Reiner, "Conceptual Construction of Fields Through Tactile Interface," *Interactive Learning Environments*, vol. 7, pp. 31–55, 1999.

[13] C. Dede, M. Salzman, R. Loftin, and D. Sprague, "Multisensory immersion as a modeling environment for learning complex scientific concepts," in *Modeling and Simulation in Science and Mathematics Education*, 1999, pp. 282–319.

[14] Z. C. Zacharia and G. Olympiou, "Physical versus virtual manipulative experimentation in physics learning," *Learning and Instruction*, vol. 21, pp. 317–331, 2011.

[15] I. Han and J. B. Black, "Incorporating haptic feedback in simulation for learning physics," *Computers and Education*, vol. 57, pp. 2281 – 2290, 2011.

[16] R. Chabay and B. Sherwood, "Restructuring the introductory electricity and magnetism course," *American Journal of Physics*, vol. 74, no. 4, pp. 329–336, 2006.

[17] E. Bagno and B.-S. Eylon, "From problem solving to a knowledge structure: An example from the domain of electromagnetism," *American Journal of Physics*, vol. 65, no. 8, pp. 726–736, 1997.

[18] B. G. Dega, J. Kriek, and T. F. Mogese, "Students' conceptual change in electricity and magnetism using simulations: A comparison of cognitive perturbation and cognitive conflict," *Journal of Research in Science Teaching*, vol. 50, no. 6, pp. 677–698, 2013.

[19] R. L. Williams II, M.-Y. Chen, and J. M. Seaton, "Haptics-Augmented Simple-Machine Educational Tools," *Journal of Science Education and Technology*, vol. 12, pp. 1 – 12, 2003.

[20] R. L. Williams II, X. He, T. Franklin, and S. Wang, "Haptics-Augmented Engineering Mechanics Educational Tools," *World Transactions on Engineering and Technology Education*, vol. 6, pp. 1 – 4, 2007.

[21] F. G. Hamza-Lup and W. H. Baird, "Feel the static and kinetic friction," in *Haptics: Perception, Devices, Mobility, and Communication*, 2012, pp. 181–192.

[22] K. Sanchez, A. J. Magana, D. Sederberg, G. Richards, G. Jones, and H. Tan, "Investigating the impact of visuohaptic simulations for conceptual understanding in electricity and magnetism," in *ASEE*, 2013.

[23] A. M. Okamura, C. Richard, and M. R. Cutkosky, "Feeling is believing: Using a force-feedback joystick to teach dynamic systems," *Journal of Engineering Education*, vol. 91, no. 3, pp. 345–349, 2002.

[24] G. E. Host, K. J. Schonborn, and K. E. Lundin Palmerius, "A case-based study of students' visuohaptic experiences of electric fields around molecules: Shaping the development of virtual nanoscience learning environments," *Education Research International*, 2013.

[25] R. Serway and J. Jewett, *Physics for scientists and engineers with modern physics*. Cengage learning, 2013.

[26] B. Mahon and A. Caramazza, "A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content," *Journal of physiology-Paris*, vol. 102, pp. 59–70, 2008.

[27] M. Wilson, "Six views of embodied cognition," *Psychonomic bulletin and review*, vol. 9, pp. 625–636, 2002.

[28] M. L. Anderson, "Embodied cognition: A field guide," *Artificial intelligence*, vol. 149, pp. 91–130, 2003.

[29] "Chai 3d website," http://www.chai3d.org/, accessed: 2015-04-23.