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IMPROVING MEDICAL EDUCATION: SIMULATING CHANGES IN PATIENT ANATOMY USING DYNAMIC HAPTIC FEEDBACK

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Abstract

Virtual simulation is an emerging field in medical education. Research suggests that simulation reduces complication rates and improves learning gains for medical residents. One benefit of simulators is their allowance for more realistic and dynamic patient anatomies. While potentially useful throughout medical education, few studies have explored the impact of dynamic haptic simulators on medical training. In light of this research void, this study was developed to examine how a Dynamic-Haptic Robotic Trainer (DHRT) impacts medical student self-efficacy and skill gains compared to traditional simulators developed to train students in Internal Jugular Central Venous Catheter (IJ CVC) placement. The study was conducted with 18 third year medical students with no prior CVC insertion experience who underwent a pre-test, simulator training (manikin, robotic, or mixed) and post-test. The results revealed the DHRT as a useful method for training CVC skills and supports further research on dynamic haptic trainers in medical education.

INTRODUCTION

Surgical residents have traditionally been trained on medical procedures using the Halstedian apprenticeship model of “see one, do one, teach one” (Carter, 1952). Over the last 20 years this method has largely been replaced by virtual patient simulators (Stefanidis et al., 2012) due to stresses on the apprenticeship model such as: increased standards for operating room efficiency (Harders, Malangoni, Weight, & Sidhu, 2006), decreased length of surgical clerkship (Neumayer, Sachdeva, Hebert, & Lang, 1997), and the ethics of practicing on real patients (Frank et al., 2010). These simulators have been praised for their ability to provide a low-stress, no-risk method for training (Kunkler, 2006; Maran & Glavin,

2003) and their potential to transform medical curriculum from a “see one, do one, teach one” model to a “see one, *simulate many*, do one *competently*, and teach *everyone*” model (Vozenilek, Huff, Reznek, & Gordon, 2004).

The use of medical simulation has been shown to reduce complication rates in clinical practice through standardization (Evans et al., 2010) allowing residents to learn at their own pace without consequence thereby reducing operator-dependence errors (Denadai et al., 2014). For example, research on simulated interventional radiology suggests that virtual reality simulators provide sufficient realism for teaching ultrasound guided needle insertion procedures (Magee, Zhu, Ratnalingam, Gardner, & Kessel, 2007). Other research in this area has looked at skill transfer from virtual reality training to real patient scenarios and found that participants performed better than their counterparts on both the specifically trained skills and on generic skills (Johnson, Guediri, Kilkenny, & Clough, 2011). While this research provides support for further research into the use of virtual reality (VR) in surgical training, more sophisticated trainers have not penetrated all areas of medical education due the lack of research on their utility. An illustration of this lack of technological advancement in medical simulators is in Central Venous Catheterization (CVC) training.

CVCs provide direct access to the heart for delivery of caustic or critical medications (A. S. Graham, Ozment, Tegtmeyer, Lai, & Braner, 2007). During CVC placement a hollow tube with control ports (catheter) is inserted through the skin into a large caliber vein – typically the internal jugular (IJ) or subclavian (SC) – with the catheter tip sitting close to the heart (Osborne, 2005). Specifically, to place an IJ CVC, an 18-gauge needle is inserted at the apex of the triangle formed by the sternocleidomastoid muscle and the clavicle at a 30° to 45° angle while aspirating. Once the needle is in the center of the vein a guide wire is inserted followed by the placement of the catheter (A. Graham, Ozment, Tegtmeyer, & Braner, 2013). The needle is typically guided into location using ultrasound guidance; surgeons use their non-dominant hand to move an ultrasound probe over the anatomical area and view the underlying structures (veins, arteries, etc.) on a monitor.

The annual number of CVC insertions performed in the US is estimated above 5 million (Inhoff & Wang, 1992). Up to 39% of CVC patients experience adverse effects (McGee & Gould, 2003) and there is a high rate of morbidity in hospitalized patients (Leape et al., 1991; Merrer et al., 2001). Accidental arterial penetration, occurring in up to 5% of adult patients and 26% of pediatric patients, is attributed to false identification of the target, spatial closeness of the artery and vein, or overshooting at the final position (Kirkpatrick et al., 2008). In summary, variations in patient anatomy may make it significantly more difficult to place a CVC (Denys & Uretsky, 1991) and increase the risk of mechanical complications during CVC placement (Polderman & Girbes, 2002). Despite this, current training systems do not address patient variability.

Current CVC training systems range from low-cost homemade models (Denadai et al., 2014; Di Domenico et al., 2007) to “realistic” manikins featuring an arterial pulse and self-sealing veins (e.g. Simulab CentralLineMan controlled through a hand-pump), see Figure 1. While these “realistic” simulators allow multiple needle insertion and practice trials without consequence, they are static in nature and only represent a single anatomical configuration.

In other words, residents can 'simulate many' of the *exact same* patient scenario. Therefore while researchers have reported that the more realistic CVC models improve eye-hand coordination (Kim, Miller, & Frievalds, 2014) and resident *confidence, or self-efficacy,* with CVC procedures (Barsuk, McGaghie, Cohen, Balachandran, & Wayne, 2009), other researchers have found that this increase is only temporary and skill performance declines over time (Smith et al., 2010). It is possible that this decrease in skill performance reflects a gap in skill transfer from a familiar practice setting to new and different clinical settings. Research suggests that near transfer of skills (transfer to similar environments) is better than far transfer of skills (transfer to different environments) (Barnett & Ceci, 2002).

In light of this prior work, we have developed a Dynamic Haptic Robotic Trainer (DHRT) for CVC placement that can present variations in patient anatomy using both visual and tactile feedback (see Figure 1). The DHRT consists of a 3D Systems Geomagic Touch (Rock Hill, SC), a virtual ultrasound system utilizing an Ascension 3D Guidance trakSTAR (Sheldburne, VT) electromagnetic position tracking system and a 3D printed ultrasound probe, and software visualizations developed in MatLab and Simulink. The Geomagic provides positional data to the simulation, as well as haptic feedback to the user based on needle insertion characterizations. (Gordon, Kim, Barnett, & Moore, 2015). The 3D printed probe uses the electromagnetic tracker in order to navigate a virtual ultrasound environment generated in MATLAB. The simulation has the capability to generate a variety of scenarios with different needle insertion forces, vessel locations, and vessel sizes. These variations are visible on the ultrasound and in the depth the needle must travel to puncture a vessel. Variations were determined via a literature review (Blaivas & Adhikari, 2009; Laurent et al., 2007; Tartière, Seguin, Juhel, Laviolle, & Mallédant, 2009). While the DHRT program has the potential to advance CVC training, this method of training has not been compared to existing methods.

METHODS

The purpose of the current study was to compare the utility of DHRT to existing simulation based practices. Specifically the study was developed to answer the following research questions (RQ):

RQ1—How does training with the DHRT, a manikin, or a combination of both training methods impact medical student CVC self-efficacy or insertion skills? We hypothesize that students will improve their skills and self-efficacy when trained using any of the methods.

RQ2—How does the **method of training** impact gains in medical student CVC self-efficacy or CVC insertion skills? We hypothesize that students who are trained using the DHRT or a combination of the DHRT and manikin trainer will have equal or better performance on CVC skill gains over the manikin trainer alone.

Participants

To answer these research questions, a study was conducted with 18 third-year medical students with no prior experience with central line placement. The participants were recruited from the medical education program at Penn State Hershey Medical Center (HMC). The participants consisted of 11 males and 7 female between the ages of 23 and 35 (Mean = 26). There was one left-handed participant. Participants were remunerated with a $15 gift card.

Procedure

The study was conducted with groups of three participants. At the beginning of each group's training session, the purpose and procedures were explained, questions were answered, and informed consent was obtained. Participants were then asked to complete a Central-Line Self-Efficacy (CLSE) survey regarding their confidence in their ability to perform central line insertion skills and any prior training they had on this or similar procedures (see Survey Instruments Section for details). Once complete, a second year medical resident with expertise in the area gave a demonstration of central-line placement to the group of three participants using a Blue-Phantom Gen II Ultrasound Central Line Training Model (Model #BPH660) manikin including how to use an ultrasound, how to identify and distinguish between the artery and vein, how to use anatomical landmarks as a guidance for line placement, how to insert a needle, how to identify needle location based off of ultrasound feedback and how to confirm needle placement using flash feedback. Importantly, the CVC training procedures used in the study are the same procedures used to train new surgical residents at HMC and the second year resident who gave the training in our study has conducted numerous CVC training sessions at HMC. Following this demonstration all participants in the training group were separated and remained separated for the remainder of the study.

Next, each participant was given a pre-test where they inserted a needle for central line placement into the same Blue-Phantom Gen II Ultrasound Central Line Training Model (Model #BPH660) used for the demonstration while using the think-aloud procedure (Ericsson & Simon, 1980) which is a standard method in clinical training (see discussion in (Meterissian, 2006). Participants were observed and evaluated in the pre-test by the same second year medical resident using a modified Internal Jugular Catheterization (IJ CVC) evaluation form (see Survey Instruments for details). While participants were not provided feedback *during* the pre-test they were informed if they successfully placed the needle and what errors occurred *after* the pre-test was complete. Next, participants from each group were randomly assigned to one of the following training conditions:

Manikin training—Participants performed all of their training on a second Blue-Phantom Gen II Ultrasound Central Line Training Model (Model #BPH660).

Robotic training—Participants performed all of their training on a Dynamic Haptic Robotic Trainer (DHRT) developed by the research team (see Introduction).

Mixed training—Participants performed half of their training (4 needle insertions) on the Blue-Phantom Gen II Ultrasound Central Line Training Model (Model #BPH660) and half of their training on the DHRT.

Importantly, before the training sessions began in the robotic and mixed training conditions, each participant was given a demonstration and a brief explanation on how the (DHRT) worked and was allowed to complete a practice trial on the device. This took about 10 minutes to complete.

Regardless of the training condition assigned, each participant was given, in a random order, eight patient profiles developed by the team (including a vascular surgeon) which accounted for variations in: vessel depth, size, and spacing; tissue density; and skin thickness. For example, profile 7 was: "A 33 year old morbidly obese male with DM, COPD, and CHF presents with necrotizing fasciitis and requires a central line prior to operative debridement for hemodynamic support. Height: 5′ 7″; Weight 282.2 lbs."

For each profile the participant attempted to place a needle in the center of the vein while using the think-aloud procedure. Unlike the pre-test, a researcher gave corrections as participants attempted the procedure. After the participant successfully entered the vein or accidently hit the artery they were given feedback on their performance (e.g. the final needle position, average insertion angle, number of attempts and insertion technique) and any questions they had were answered. This process was repeated until all eight profiles were completed. This training took approximately 20 minutes.

The post-test followed the same procedures as the pre-test and the same medical resident conducted this examination. However, it was completed on a Kyoto CVC Insertion Simulator II (Model # M93UB). This manikin was selected for the post-test because it differed in anatomical structure (e.g. depth and size of vessels, skin thickness, and vessel wall thickness) from both the pre-test and training manikins.

Finally, participants completed a post-training Central-Line Self-Efficacy (CLSE) survey (see Survey Instruments for details) and a Training Evaluation Survey (TES) regarding their experience with the training they received (see Survey Instruments for details). This procedure was repeated for a total of 6 participant groups.

SURVEY INSTRUMENTS

During the study three surveys were used to analyze participant performance and confidence: a Central-Line Self-Efficacy Survey (CLSE), an Internal Jugular Catheterization Evaluation Form (IJ CVC), and a Training Evaluation Survey (TES). Details of the surveys are provided below, and the full list of survey questions can be found at http://www.engr.psu.edu/britelab/projects_cvc.html.

The Central-Line Self-Efficacy Survey **(CLSE)** is a 14 question 5-point Likert scale survey dealing with participants' confidence in their ability to perform the skills necessary to insert a needle for the central line procedure. The scale ranges from 1 (not at all confident) to 5 (extremely confident). Example items include, "Using tactile feedback during placement of the line", "Modifying needle trajectory based on ultrasound feedback" and "placing the introducer needle at the center of the vein in one attempt". Participants completed this survey at the beginning and end of the study.

The Internal Jugular Catheterization **(IJ CVC)** evaluation form consists of 10 tasks including items such as “Selecting the appropriate site for venipuncture”, “confirming vessel entry by aspiration of blood” and “conducting the entire procedure without any mistakes”. During the pre-and post-test the tasks are marked as ‘pass’ (1) or ‘fail’ (0) by an independent evaluator. In addition, the number of attempts needed to insert the needle was also documented.

The training evaluation survey (**TES)** is a 10-question, 5 point Likert-Scale survey dealing with the participant’s perception of the training method they received. The scale ranges from 1 (completely disagree) to 5 (completely agree). These questions included items like “The Haptic Robot (or Manikin) Training … made me sensitive to patient anatomies’ impact on vessel location in the body” and “was an effective method for learning the CVC procedure”. The mixed training participants filled out surveys for both the Manikin and Haptic Robot.

RESULTS AND DISCUSSION

To answer our research questions, statistical analysis was done on the pre- and post-test IJ CVC; pre- and post-training CLSE; and the TES. These analyses and their results are presented in relation to our research questions. All analyses were conducted using SPSS (v. 22.0) with an error rate of 0.05.

RQ1: How, if at all, are medical students skill performance and CVC insertion self-efficacy changed after training?

Our first research question was developed to understand if each method was actually training participants in CVC skill acquisition and increasing self-confidence. To answer this research question, a Wilcoxon Signed Ranks test (used due to the non-parametric nature of likert scale data) was conducted for each training method to compare participant responses on the 14-items from the pre and post CLSE. The results revealed that for each training condition, 13 of the 14 items were statistically different ($p<0.05$) indicating significant self-efficacy gains. For manikin training, there was no significant learning gain for ‘using tactile feedback to help guide the introducer needle’ ($z = -1.80$, $p=0.07$). For robotic training, there was no significant learning gain for ‘Advancing and retracting the introducer needle slowly and steadily’ ($z = -1.86$, $p = .06$). For mixed training, there was no significant learning gain for ‘using tactile feedback to identify the correct vessel for puncture’ ($z = -1.91$, $p= 0.06$).

To understand if there were changes between the pre- and post-test IJ CVC an exact McNemar test was computed for each of the 10 binary items (pass or fail) on the IJ CVC skills. The results revealed no significant differences between performances on the IJ CVC evaluation form for any of the training methods. However, the average scores for all participants on the pre- and post-test were 81.3% and 95.7%, respectively. All participants performed better on the post-test than on the pre-test suggesting that the IJ CVC evaluation form may not be granular enough to detect changes in performance.

These results support our hypothesis that medical students would improve their skills when trained using any of the three methods and are promising for the use of the DHRT as a training method. None of the participants had been exposed to a haptic simulator yet still showed the same increase in learning gains as traditional training approaches. These results support prior findings that simulated training increases resident confidence on CVC procedures (Barsuk et al., 2009) and prior findings that suggest virtual reality simulators as viable methods for surgical training (Johnson et al., 2011; Magee et al., 2007).

RQ2: Does the method of training impact gains in medical student CVC self-efficacy or CVC insertion skills?

Our second research question was developed to understand if a difference exists in training methods with respect to gains in self-confidence or skill acquisition as judged by the IJ CVC. We hypothesized that students trained using the robotic or mixed training method would have equal or better performance on skills and self-efficacy. Prior research suggests VR training can improve trained skills (Johnson et al., 2011).

A MANOVA was computed with the independent variable as the difference between responses for each of the 14 items on the pre- and post-training CLSE survey and the dependent variable as the training method (manikin, robotic or mixed). Three levels of a dependent variable dictated the use of a MANOVA rather than an ANOVA. The results revealed no significant differences in self-efficacy gains between the three training methods for each of the 14-items on the CLSE ($p>0.05$). In other words, no training method had a significantly larger (or smaller) impact on CVC self-confidence gains.

To explore the impact of the training method on performance gains between the pre- and post- IJ CVC evaluation, a chi-square test of independence was performed for each of the 10 items. The results showed no statistically significant result between CVC skill gains in each of the 10 items ($\chi 2$ (4, N=16) < 5.00; $p > 0.144$). In order to compare the number of insertion attempts needed to complete the pre- and post test IJ CVC, a repeated-measures ANOVA was calculated. The results revealed no statistical significant difference between the three training conditions ($F (1,2) =1.97$, $p < 0.184$).

The training evaluation survey (TES) was analyzed to compare medical students' feelings about the utility of the training methods for learning CVC procedures. Specifically, a Mann-Whitney U-test (used due to the non-parametric nature of likert scale data) was computed with the dependent variables as the response to each item on the TES and the independent variable as the method of training (manikin or robotic only). Because participants in the mixed condition completed a training evaluation survey for both the DHRT and the manikin, the sample size for this analysis was 24. The results revealed a marginally significant difference between the conditions for the statement "helped me understand how to modify CVC insertion procedures based on patient anatomy" ($U=32.5$, $p < 0.058$) with participants reporting a higher level of response to the DHRT than the manikin (Mean Rank was 14.05 and 8.95 for robot and manikin, respectively). There were no other significant findings.

For the mixed condition, a Wilcoxon signed ranks test was computed to compare the responses to both training methods. The results revealed a significant effect for 'helping me correctly identify when I had successfully inserted the needle' ($z=-2.06$, $P<0.04$) with manikin (Mean Rank = 4.6) being significantly higher than robotic (Mean Rank = 3).

These results support our hypothesis that the robotic or mixed condition would have equal self-efficacy after training and some support for *higher* self-efficacy and CVC performance gains in relation to modifying the procedure based off of patient anatomy. This supports prior research that shows virtual reality training can improve targeted skills (Johnson et al., 2011). This is especially encouraging for the use of the DHRT as a training method considering the pre- and post-test were performed using a manikin, possibly giving students in the robotic training method a disadvantage due to the need for skill transfer (Barnett & Ceci, 2002). The true impact of adapting to patient variability in a clinical setting remains to be seen. For ethical reasons, this study was only able to examine the impacts using manikins.

CONCLUSION

The goal of the current study was to understand how dynamic haptic training could be used to develop surgical skills in a training setting. The main findings of this study are as follows: (1) Medical students had increased confidence in their ability to perform the skills necessary to insert a needle for the central line procedure when using the DHRT; (2) There was no difference in learning gains or confidence gains between training methods, and; (3) Medical students reported that robotic training helped them understand how to modify CVC insertion procedures based on patient anatomy more than manikin training. This research suggests that students can be trained on CVC skills using haptic simulators just as effectively as static simulators. The advantage of using a haptic simulator is that it can present an unlimited number of patients. This exposure to anatomical variation may reduce complications or improve new resident performance in clinical cases. It is important to note that the DHRT is not designed to replace the manikin training system, but rather to enhance users' ability to detect and *adapt* appropriately to anatomical variations during needle placement.

While the results show promise for dynamic haptic training, there are several limitations of the current study that should be investigated in future work. Most notably, the training sessions were conducted over a 30-minute procedure and the testing was conducted on a manikin. Because of this, it is unclear what long-term effects are caused by differences in training strategies or how this impacts patient outcomes. Future work is currently underway to integrate this training into Hershey Medical Center to investigate this question. In addition, the evaluation of performance on the pre-and post- IJ CVC were conducted qualitatively by a medical resident. Future work should be geared at exploring quantitative differences in training performance, which is now possible due to the real-time data collection capabilities of the DHRT and advances in motion-tracking technologies.

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Figure 1.
Left - Dynamic Haptic Robotic Trainer**. Right –** Static Blue-Phantom Gen II Ultrasound Central Line Training Model (Model #BPH660) mannequin