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Accuracy of ventriculostomy catheter placement using a head- and hand-tracked high-resolution virtual reality simulator with haptic feedback

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Object. The purpose of this study was to evaluate the accuracy of ventriculostomy catheter placement on a head- and hand-tracked high-resolution and high-performance virtual reality and haptic technology workstation.

Methods. Seventy-eight fellows and residents performed simulated ventriculostomy catheter placement on an ImmersiveTouch system. The virtual catheter was placed into a virtual patient's head derived from a computed tomography data set. Participants were allowed one attempt each. The distance from the tip of the catheter to the Monro foramen was measured.

Results. The mean distance (± standard deviation) from the final position of the catheter tip to the Monro foramen was 16.09 mm (± 7.85 mm).

Conclusions. The accuracy of virtual ventriculostomy catheter placement achieved by participants using the simulator is comparable to the accuracy reported in a recent retrospective evaluation of free-hand ventriculostomy placements in which the mean distance from the catheter tip to the Monro foramen was 16 mm (± 9.6 mm).

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Key Words • **haptic technology** • **neurosurgical simulation** • **ventriculostomy** • **virtual reality**

At the 2006 annual meeting of the AANS, the Young Neurosurgeons Committee organized a surgical competition using three different emerging simulators for residents and fellows in the exhibit hall. Ventriculostomy was one of the techniques tested,[15] and the results of this testing are reported here. The performance of 78 fellows and residents was evaluated for accuracy of ventriculostomy catheter placement using the head- and hand-tracked high-resolution and high-performance virtual reality and haptics workstation known as ImmersiveTouch (ImmersiveTouch, Inc.) and a virtual patient's head derived from a CT data set.

Ventriculostomy is a high-volume, low-morbidity technique and is often the first neurosurgical procedure that a young neurosurgery resident will learn and perform on a regular basis. While faculty members or senior residents may proctor early cases, the high volume of the procedure means that most residents must become proficient very early in their training. Our haptic-technology–based, 3D simulator for ventriculostomy placement recreates the surface landmarks that guide catheter trajectory as well as the tactile feedback as the catheter passes through the brain parenchyma and into the ventricle.[10,13]

The ImmersiveTouch augmented virtual reality system was developed at the University of Illinois at Chicago[12] and combines real-time haptic feedback with high-resolution stereoscopic display. An electromagnetic head-tracking system provides dynamic perspective as the user moves his or her head. A half-silvered mirror is used to create an augmented reality environment that integrates the surgeon's hands, the virtual catheter, and the virtual patient's head in a common working volume while eliminating occlusions.

Clinical Material and Methods

Selection Criteria

Participants consisted of 78 fellows and residents selected by the Young Neurosurgeons' Committee at the 2006 AANS annual meeting through an open solicitation. They

Abbreviations used in this paper: AANS = American Association of Neurological Surgeons; CT = computed tomography; SD = standard deviation.

participated in a competition that featured a ventriculostomy workstation based upon a head- and hand-tracked high-resolution and high-performance virtual reality and haptic technology system known as ImmersiveTouch. Accuracy of simulated ventriculostomy catheter placement was evaluated. The ImmersiveTouch software utilizes a series of modules to acquire, process, and render the graphic and haptic data, which are then seamlessly integrated on the hardware platform. A virtual 3D volume of a human head was created using data from a patient at the University of Illinois at Chicago Medical Center. The data were presegmented and assembled from a CT DICOM data set after the removal of all identifying personal data. The 3D polygonal isosurfaces corresponding to the skin, bone, brain, and ventricles were extracted.

The data are based on a one-time performance (single trial) of each participant in inserting the catheter following a detailed explanation during a period in which the participants were permitted to observe other individuals' performances and to ask detailed questions.

The haptic characteristics and graphic rendering for the simulator were modified based on initial feedback from members of the neurosurgical faculty and senior residents at the University of Illinois at Chicago before the device was used at the AANS annual meeting. The final product was universally felt to simulate the tactile and visual components of the actual procedure.

Ventriculostomy Catheter Placement

In the ImmersiveTouch system, an electromagnetic sensor (Ascension Technologies Corp.) attached to the stereoscopic goggles tracks head movements to compute the correct viewer's perspective while the user moves his or her head around the virtual patient's head to locate the landmarks. Another sensor located inside the SpaceGrips (LaserAid) tracks the surgeon's hand to define a cutaway plane and the light source to better view the virtual head volume and its virtual contents.

Based on the position and orientation of the haptic stylus (SensAble Technologies, Inc.), collision detection between the virtual catheter and the imported 3D isosurfaces is computed, and corresponding force feedback is generated through the servomotors of the haptic device. Each isosurface is assigned different haptic characteristics, according to the following parameters: stiffness, viscosity, static friction, and dynamic friction. Therefore, the surgeon can feel the differences in skin, bone, and brain. A viscosity effect is felt as the catheter passes through the gelatinous parenchyma of the brain. As soon as the catheter breaks the dense ependymal ventricular lining, the viscosity effect ceases, providing the surgeon with a distinct "puncturing" sensation.

The virtual patient's head is displayed using the imported 3D isosurfaces. A perspective camera node allows the display of stereoscopic perspective according to the user's position and head orientation. A cutaway tool on the SpaceGrips device permits visualization of deeper surfaces and volumes through synchronization with the user's hand movement and wrist rotation. The graphic images are displayed using a high-resolution cathode ray tube monitor and transreflective mirror. The ImmersiveTouch system offers high display resolution (1600×1200 pixels) and high visual acuity (20/24.74), which is important for clear visualization of the depth markings of the virtual catheter and small details of the head anatomy. There is also a magnification option to help in reading the scale marking on the virtual catheter, which is modeled after a Medtronic ventricular catheter.

The collocation of haptic and graphic information achieved by the ImmersiveTouch is critical to the realistic recreation of the surgical experience. The user sees his or her own hand holding a virtual catheter in the same location and space as it would appear during an actual ventriculostomy procedure; there is no shift in anatomical perspective as with endoscopy or previous computer-based simulations. The user can interact with the virtual objects using both hands: the surgeon holds the haptic stylus in one hand and defines arbitrary 3D cutting planes with the other hand, which holds a SpaceGrips interface (Fig. 1).

The user sits at the worktable space in front of the ImmersiveTouch simulator. The electromagnetically tracked CrystalEyes glasses (REAL D) are worn to stereoscopically view the reflected virtual reality image on the partially mirrored viewing surface. Any movement of the user's head causes a corresponding change in perspective around the virtual patient's head. These changes also collocate with the user's hands as viewed through the transreflective (half-mirrored) viewing surface. The virtual catheter and assorted virtual working tools (light source, cutaway instruments, and dynamic perspective) also project into the collocation space (Fig. 2).

The user is presented with a virtual patient's head. By grasping the haptic stylette, he or she is able to see a virtual catheter with its appropriate measurement markings. This catheter is collocated in the user's hand to convey the perception that he or she is actually holding a catheter.

The catheter tip is positioned over one of the four bur hole selections (labeled east, west, north, and south) at or near the Kocher point while the optimal trajectory is determined (Fig. 3).

Measurement Technique

Data sets from CT studies performed in patients with overt hydrocephalus were selected to simplify the early modeling of the ventricular system. Future renditions will include normal and slit ventricles.

As the catheter is advanced past the calvaria and enters the virtual model of the brain, the user feels a distinct increase in resistance. When the catheter reaches the appropriate volumetric depth, there is a sudden release in haptic resistance corresponding to the puncture often experienced when the ventricle is cannulated. The ruler markings on the ventricular catheter may also be used to gauge the expected depth to ventricular cannulation.

When the user thinks that the ventricular catheter has been successfully placed, the SpaceGrip controller is used to freeze the virtual catheter in position. If the virtual catheter is in the virtual ventricular system it turns green, otherwise it turns red. The user may then use the cutaway tool while moving and rolling the wrist as well as rotating his or her own head to visualize the exact location of the catheter tip and correlate the experience with technique (Fig. 4). For each participant, the final position and orientation of the catheter were recorded in the computer.

FIG. 1. Photograph showing the ImmersiveTouch system in operation.

FIG. 2. Photograph demonstrating catheter insertion in the ImmersiveTouch system.

Results

The mean Euclidean distance from the catheter tip to the Monro foramen in the 78 trials was 16.09 mm (SD 7.85 mm), with a range from 2.68 to 49.62 mm. The mean distance from the catheter tip to the center of the bur hole was 63.63 mm (SD 13.45 mm). The measurements are given in Table 1.

As shown in Table 2, 57 (73%) of the 78 catheter tips successfully reached the ventricle, and 21 (27%) of 78 attempts were unsuccessful. Of the successful attempts, 22 (38.5%) reached the anterior horn of the right lateral ventricle, three (5%) reached the anterior horn of the left lateral ventricle, 23 (40%) reached the body of the right lateral ventricle, six (10%) reached the third ventricle, and three (5%) reached other regions of the ventricular system. Among the 48 attempts that reached the lateral ventricles, the catheter tips were ipsilateral in 45 (94%) and contralateral in three (6%).

The catheter tip was positioned over one of the four bur hole selections (labeled east, west, north, and south) at or near the Kocher point while optimal trajectory was determined (Fig. 3). Fifty-three (68%) of the 78 participants chose west, 13 (17%) chose south, 11 (14%) chose east, and one (1%) chose north. Contrary to expectation, no significant differences were noticed in the mean distance from the final position of the catheter tip to the Monro foramen with respect to choice of bur hole, so this choice did not play a significant part in the participants' performances.

Table 3 shows a directional frequency distribution of the final position of the tip of the catheter based on the three cardinal directions to determine trends in participant performances. For a total of 78 attempts (one attempt per participant), distribution in the left–right, anteroposterior, and superior–inferior directions with reference to the Monro foramen are shown. A majority of the cannulation attempts were toward the right side, anterior to and/or superior to the Monro foramina.

As shown in Table 4, there were no significant differences in the distance from the final position of the catheter tip to the Monro foramen based on the direction of ap-

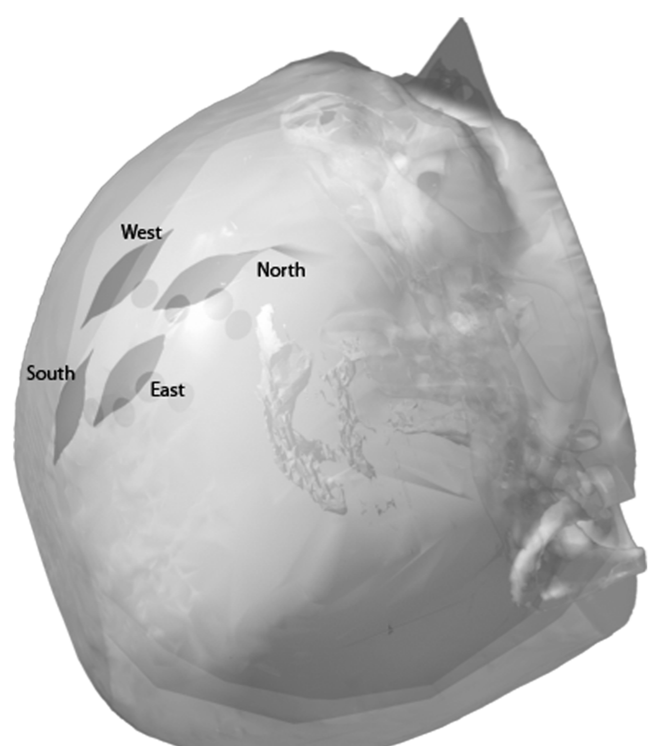

FIG. 3. Virtual patient's head. Three-dimensional reconstruction based on CT data showing the four predrilled bur holes (East, West, North, and South).

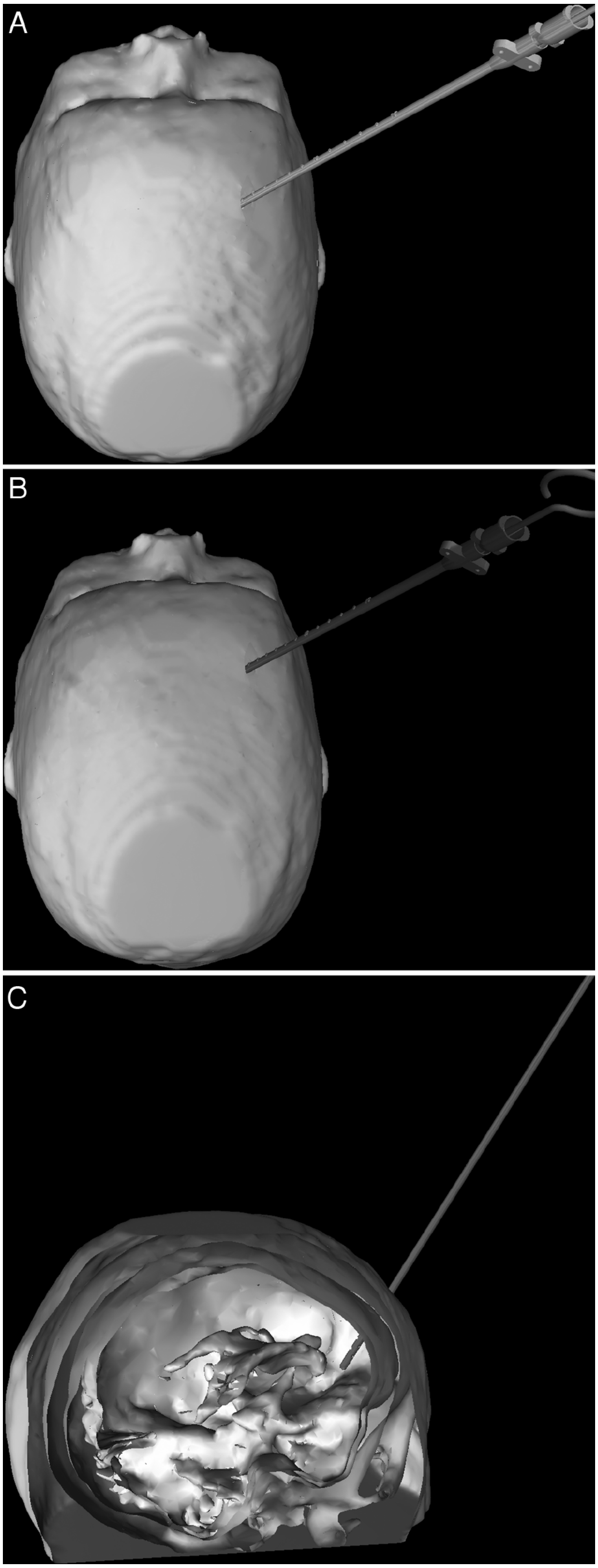

FIG. 4. Workstation images of virtual patient's head during simulated ventriculostomy. Successful ventricular entry (A) is indicated by the catheter turning green; after an unsuccessful attempt (B), the catheter turns red to indicate failure. Also shown is a cutaway view (C) for examination

TABLE 1

Euclidean distance measurement statistics (in mm) for catheter placement

Parameter	Catheter Tip to Monro Foramen	Catheter Tip to Center of Bur Hole
mean	16.09	63.63
min	2.68	30.00
max	49.62	120.00
SD	7.85	13.45

proach. The means and SDs for the three directions are quite comparable.

Finally, we collected data to analyze the impact of the level of training on the participants' performances. As seen in Fig. 5, there does not seem to be a strong correlation between the level of training as measured by the number of years in residency and performance. This finding is a bit surprising; further studies are needed.

Discussion

The goal of imparting full procedural knowledge and psychomotor skills has received a major boost with the advent of surgical simulators.[2,4,11,19,20] Ventriculostomy is one of the most frequently performed neurosurgical procedures.[17] Diagnostic information about intracranial pressure is made available through the procedure. In addition, ventriculostomy may provide lifesaving therapeutic drainage in cases of symptomatic intracranial hypertension. Clear guidelines have been established for the procedure in a variety of neurological diseases including obstructive hydrocephalus and traumatic brain injury.[14] Although performing a ventriculostomy is considered one of the most basic neurosurgical skills, the high volume and critical nature of the procedure make proper technique particularly important.

Trajectory guides can improve catheter tip placement accuracy without altering ventricular cannulation rates.[16] In 2000, Phillips and John developed a cross-platform, web-based ventriculostomy simulator.[6,18] This early simulator allowed virtual catheter positioning and trajectory determination relative to a 3D virtual head. In lieu of tactile feedback, an auditory cue signaled ventricular cannulation. Catheter manipulation with the mouse was rudimentary, and no tactile feedback was provided. This form of visually reinforced learning for ventriculostomy training has also been described with reference to surgical neuronavigational platforms.[7] The effectiveness of these simulators is limited to improving the understanding of anatomical relationships relative to catheter position and trajectory. Many other simulation approaches have also been described.[3,22]

The first generation of haptic ventriculostomy simulators provided tactile feedback using a haptic stylus device during virtual ventricular cannulation.[9,22] The user manipulated the virtual catheter with the haptic stylus in a haptic and virtual reality environment implemented for the Reachin display (Reachin Technologies AB). Although this development created considerable excitement as a novelty device for ventricular cannulation, its usefulness for teaching and measuring neurosurgical expertise was very limited. More recent efforts using haptic-driven ventriculostomy simulators have attempted to correlate simulator training with

TABLE 2

*Frequency classification of the final position of the catheter tip in 78 placement attempts**

Position	Catheter Tip
third ventricle	6
anterior horn of rt lateral ventricle	22
anterior horn of lt lateral ventricle	3
body of rt lateral ventricle	23
body of lt lateral ventricle	0
posterior horn of rt lateral ventricle	0
posterior horn of lt lateral ventricle	0
fourth ventricle	0
other areas of the ventricular system	3
outside of the ventricles	21

* Values represent the number of times the final position of the catheter or its tip was at the given anatomical location.

increased procedural efficacy. Despite graphical "near-to-reality" characteristics, these systems still require "suspension of disbelief" in the user.[21] The reasons and how we have overcome these issues are provided in the following discussion.

An important feature of realistic simulation is perfect overlap of the virtual catheter 3D image with the haptic stylus. This effectively collocates the virtual catheter within the same space as the haptic stylus so that the user feels as though he or she is holding the catheter. This collocated perspective takes into account the user's head position through head tracking. Previous attempts at ventriculostomy simulation were not able to address this issue, and the attention of the surgeon was diverted from the simulated procedure toward overcoming the visual dissociation of real and virtual objects. In effect, the device did not adequately reproduce the ventriculostomy procedure.

The ImmersiveTouch platform appears to resolve these issues.[10] The simulation is very realistic, as demonstrated by good correlation with previous experience among neurosurgical faculty members, residents, and medical students. If there was no correlation with the psychomotor skill set involved in placing a ventriculostomy, then the user's experience should not affect initial success with this simulator. More importantly, the simulator appears to "jumpstart" the learning process by providing immediate and corrective feedback so that real improvement can be measured. The most critical components of this virtual reality simulation of ventriculostomy placement include rendering of actual clinical data, stereoscopic 3D display with dynamic perspective tracking, collocation of real and virtual object space, and tactile feedback through haptic modeling.

The results from this ImmersiveTouch experiment at the 2006 annual meeting of the AANS can be utilized to address an important challenge in validation of ventriculostomy simulation through comparison with clinical ventriculostomy data. Fortunately, Huyette and colleagues[5] have recently performed a retrospective evaluation of the head CT scans performed in 97 patients who underwent 98 freehand ventriculostomy placements in an intensive care unit setting at the University of Missouri in Columbia. This makes the task of comparison with clinical data quite meaningful. At the outset it is recognized that because the

TABLE 3

Directional frequency distribution of the final position of the catheter tip with respect to the Monro foramen

Relative Position	No. of Attempts
rt (−X direction)	58
lt (+X direction)	20
anterior (−Y direction)	51
posterior (+Y direction)	27
superior (−Z direction)	52
inferior (+Z direction)	26

ventriculostomy simulation is part-task, a direct comparison with the clinical procedure is not very meaningful. In this paper we report an indirect comparison utilizing the primary strength of the simulation approach and the primary strength of the clinical approach, namely the ease of repeating the same simulated ventriculostomy procedure for multiple participants, thereby controlling experiment variability in the simulation approach and the ease of retrospectively examining multiple clinical ventriculostomy cases and enhancing realism through clinical approach.

The similarity of the values obtained for mean error as measured by the distance between the final position of the catheter tip and the Monro foramen of about 16 mm and SD of approximately 7 to 9 mm in both the ventriculostomy simulator and freehand clinical ventriculostomy seems to be a significant observation. Whether this observation indicates a trend in these studies with moderate sample sizes is an interesting research question. A similar magnitude of mean error and SD in a set of approximately 80 participants using the simulator and about 100 clinical cases can provide an initial hypothesis regarding the degree to which a simulator can replicate the experience of an actual clinical case and can serve as a basis for further studies involving more patients.

We observed that the ipsilateral lateral ventricle was more often the site of entry in both simulated and clinical cases. A review of our simulated cases showed a contralateral/ipsilateral lateral ventricle site ratio of 3:45, which is comparable to the ratio observed in the clinical setting by Huyette and colleagues.[5] This finding is expected given that a frequent target for ventricular catheter placement is within the ipsilateral frontal horn just anterior to the Monro foramen.[1]

With respect to reaching the ventricle, there was no significant difference between the success rate observed in our study using the simulator (73%) and the success rate in the clinical setting as reported by Huyette and associates (79%).[5] It should be noted that the simulator results are based on the performance of participants drawn from a pool made up primarily of residents, whereas the clinical results were more likely to be based on the performance of senior and experienced neurosurgeons. Once again this represents an interesting initial observation on how closely a simulator can capture a real situation. Given the fact that the initial success rates are roughly similar, it is possible that the simulator could be used to represent cases of complexity equivalent to those encountered in the clinical setting.

In our study each participant was allowed only one attempt. In a frequently cited study, Krotz and coworkers[8]

TABLE 4

Rectilinear distances (in mm) between the final position of the catheter tip and the Monro foramen

Statistic	Right–Left (X direction)	Anteroposterior (Y direction)	Superior–Inferior (Z direction)
mean	7.37	8.29	8.84
min	0.28	0.01	0.12
max	24.03	26.85	42.13
SD	5.5	6.19	7.18

reported a mean of 1.3 attempts per successful placement with CT-guided ventriculostomy and 1.5 attempts with conventional ventriculostomy. Thus our experiment imposed a more stringent condition.

As noted before, the 98 ventriculostomy procedures studied by Huyette and colleagues[5] were performed in 97 different patients, whereas in our study the 78 participants attempted the simulated procedure in one virtual patient. The strength of the virtual reality approach is the capacity for standardization, that is, multiple participants all attempting the procedure in what amounts to a single case; the weakness is that it is a part-task simulator.

Although the part-task simulator can certainly demonstrate an individual's spatial skill in placing a catheter, it cannot be used to measure the temporal skill. Ventricular catheters are normally placed in emergency settings and because the procedure can be life-saving, time is of the essence in addition to accuracy.

There does not seem to be a strong correlation between the level of training as measured by the number of years in residency and performance, as shown in Fig. 5. Further study is required to explain this finding. A possible explanation is that accuracy may be determined by the actual number of procedures performed rather than the level of training.

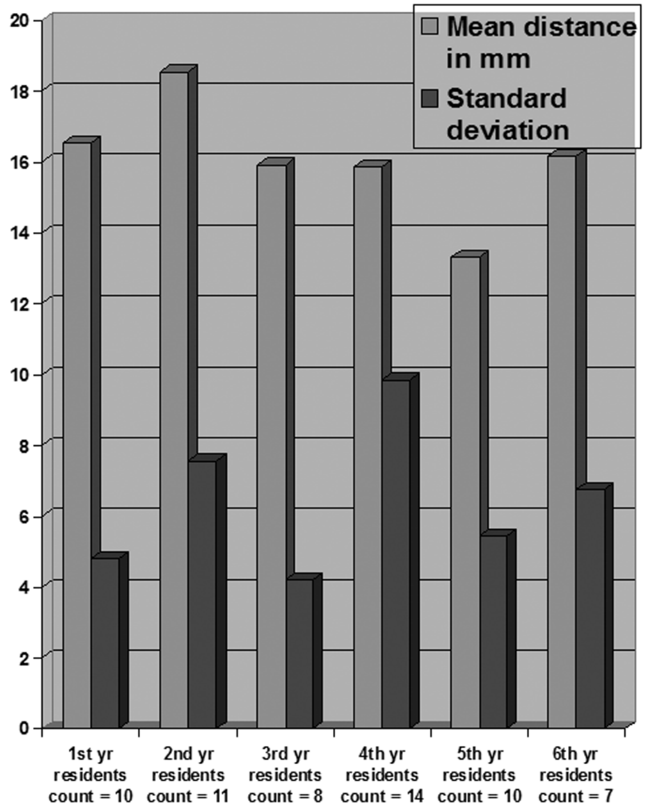

FIG. 5. Graph illustrating the results of performance evaluation stratified by number of years of training.

Conclusions

We have introduced a new realistic haptic-technology–based, augmented, virtual reality simulator for neurosurgical education in general and ventriculostomy training in particular. The ImmersiveTouch system creates a virtual reality environment using stereoscopic, perspective-based rendering, haptic feedback, and virtual/real-world object collocation. The simulator accurately reproduces the part-task experience of cannulating the ventricle with a virtual ventricular catheter. Given the importance of neurosurgical simulation for training and recertification, this simulator represents an important step forward. The results from testing with 78 neurosurgical residents and fellows at the 2006 annual meeting of the AANS seem to replicate some results (such as the mean and SD for distance between the final position of the catheter tip and the Monro foramen) from a previously reported clinical study based on 98 procedures performed in an intensive care unit setting and hence lays a strong foundation for further investigation.

Future developments will include permutations to the original data set to recreate slit or shifted ventricles for the purpose of increasing complexity and simulating more extreme possibilities. Our goal is to continue with the development of procedure "modules," each simulating a single technical component (for example, bur hole trephination). Several modules could then be assembled in order to reproduce an entire procedure using a part-task simulation paradigm. The ImmersiveTouch ventriculostomy simulator can also make an impact in telemedicine education (for example, the data sets from the ImmersiveTouch simulator can be downloaded at geographically dispersed sites).

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Disclosure

Presented at the 2006 AANS annual meeting, this study was sponsored by the AANS Young Neurosurgeons Committee, which does not claim the superiority of the ImmersiveTouch system over another system.

The ImmersiveTouch technology has been licensed to ImmersiveTouch, Inc., by the University of Illinois at Chicago.

Coauthors Dr. Charbel and Dr. Banerjee both own stock in ImmersiveTouch, Inc.

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A movie clip accompanies this article:

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