Augmented Reality Haptic Simulation for Craniospinal Surgical Training and Sensory-Motor Skill Evaluation

BY

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THESIS

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The only true wisdom is in knowing you know nothing.

Socrates

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LIST OF ABBREVIATIONS

SDK	Software Development Kit
OPSI	Open Pedicle Screw Insertion
AANS	American Association of Neurological Surgeons
ACGME	Accreditation Council for Graduate Medical Education
ADEPT	Advanced Dundee Endoscopic Psychomotor Tester
HST	Higher Surgical Training
DOF	Degrees of Freedom
GPU	Graphics Processing Unit
SDH	Subdural Hematoma

SUMMARY

This thesis focuses on the development of a suite of medical modules for the ImmersiveTouch® Surgical Simulator. The ImmersiveTouch® Simulator is a system that combines augmented reality along with user head tracking and haptics to create a virtual working environment that the user can easily observe from multiple perspectives; this system also provides haptic feedback when users interact with virtual objects and volumes. The goal of this project was to investigate the viability of creating a multitude of applications for this platform, ranging from training and examining the clinical skills of surgeons in simulated medical procedures to abstract evaluation of a persons sensory-motor aptitude. Modules were developed using the Sensimmer SDK™. The ImmersiveTouch® Surgical Simulator also serves as a solid research platform due to the ability to record a surgeons precise movements and score them objectively using the same simulations and scoring algorithms. Since the simulations are run from software and do not require any additional materials or equipment, evaluations can be repeatedly performed and data is automatically collected as compared to traditional methods such as physical manikin based evaluations.

Several modules developed as part of this thesis were also used in research studies. The results from those studies will be presented and evaluated in this work.

CHAPTER 1

INTRODUCTION

Virtual reality in medical education is a rapidly growing field. A large number of simulators have been developed and their efficacy in training has been validated. Initial research in virtual reality simulators demonstrated their ability to increasing the performance of residents performing laparoscopic and endovascular procedures. (1)(2)(3) Laparoscopic and endovascular procedures are well suited for virtual reality simulations due to required movement constraints which reduce some of the technical challenges with creating an immersive experience. (4) Recently, the procedures that can be simulated in virtual environments have shifted to performing tasks in which more complex movements and interactions between tools and tissues are required. Neurosurgical procedures serve as an excellent area for virtual reality simulation because the tasks performed require extensive practice due to the severe consequences and risks to a patient that may result from improper performances of such procedures. The philosophy behind the Immersive Touch virtual reality system, initially geared towards neurosurgical procedures such as ventriculostomy, was that surgical procedures can be decomposed into individual modules that allow surgeons to practice specific aspects of a procedure. (5) Creating modular simulations helps balance the computing power in current processor and graphics technologies with realism that can be achieved to provide an immersive experience. As the technology powering simulations continues to develop and grow, these modules can be combined to help create a seamless surgical experience.

While immersive environments can be created to mimic surgical environments and procedures it is important to study the effectiveness of learning and skills transfer that may or may not be taking place. The ImmersiveTouch® has been validated in procedures, such as ventriculostomy, to increase performance of neurosurgery residents, both in normal, slit, and shifted ventricle cases. (6)(7) Methods to utilize the ImmersiveTouch® platform as a research tool in areas such as dexterity and motor skills research were investigated. A number of modules were developed to showcase how the ImmersiveTouch® Simulator could be used not only to train surgeons in simulations of procedures but also to objectively evaluate their performance in more general sensory-motor skills that are believed to be relevant to the success of a surgeon. Determining baseline sensory-motor skills has a strong potential for application in the selection process of candidates for medical residency programs due to the high cost of time and resources required to train a surgeon. The created modules are discussed and compared to more traditional methods of instruction currently. Several of these modules were utilized in research studies and the results will be discussed as well as future improvements that could be made to the modules. These modules also serve as a foundation on which new research can be performed to objectively study how environments, surgeon restedness, and even relationships between occupational tools, such as surgical gloves can affect the performance of a surgeon.

CHAPTER 2

BACKGROUND

2.1 Medical Education

While simulation is not an unfamiliar idea in medical education, dating back centuries when clay and stone models were used to teach disease states, the form of which simulation takes has changed over the years (8). Traditional tools for medical education have typically consisted of animals, cadavers, and actual patients; however, each of these tools have certain drawbacks in their usefulness. Animals do not have the same anatomies or physiological reactions as humans and therefore do not accurately serve to emulate interactions during a medical procedure. Cadavers have the correct anatomy for students to learn from, however their cost, low availability, limited capability to repeat procedures, and tissue degradation are some of the main drawbacks. While actual patients serve as the most realistic learning tool, inexperience can cause an operation to be performed incorrectly, even under the guidance of an expert mentor, leading to avoidable patient discomfort and complications. In addition, this inexperience may put patients at risk of permanent health damage and even death (9). For a long time medical education has followed an apprenticeship-based model of training in which learning involves experiencing errors under the guidance of a mentor and, in turn, these learning opportunities vary for each student depending on the patients and procedures that they encounter (9)(8). With the changing landscape in medical education, which is aimed towards improving quality of patient care and reducing avoidable errors (10) as well as increasing interest in critically evaluating medical resident competency, virtual reality simulations may become an irreplaceable component in medical education both as a learning and evaluation tool.

2.1.1 Duty-Hour Restrictions

The rapid growth of virtual simulators used as a learning platform in the medical field is due to changes in educational rules and regulations as well as improvements to the technology and realism of the simulators. Recent regulations, such as duty-hour restrictions imposed by the Accreditation Council for Graduate Medical Education (ACGME) are meant to ensure the safety of patients being cared for currently, patients that will be cared for in the future, and the overall quality of the learning environment in which residents develop their professional skills. However, there are strong concerns over how these regulations will affect the quality of a residents education.

After an extensive literature review, which included 1,515 studies on duty-hour limits, the authors concluded that there was a clear indication of the positive effects restedness has on performance and alertness, noting that there are many complex relationships between the variables within a learning environment making it impossible to make an unqualified statement about whether patient care has improved due to implementation of duty-hour limits (11). Other studies noted a negative effect in neurosurgical resident education measured both by objective and subjective analysis, concluding that further reductions in duty-hours would merit significant changes to resident training to ensure proper competency and quality of patient care (12).

While a residents total experience in an operative room may be reduced due to duty-hour restrictions, this is not a complete indicator of their technical competence. It is recognized that residents are at times utilized as a inexpensive labor pool, meaning that the tasks they perform may not heavily contribute to the quality of their education (12). An interesting idea proposed is the use of simulated skills training to create "pretrained novices", which are individuals trained in the aspects of psychomotor skills and spatial judgements almost to the point of automation. This allows residents to focus more on learning the steps of the procedure and how to handle complications as opposed to spending valuable operating room time on the initial refinement of technical skills. (13) In turn this may lead to more efficient utilization of resources and a higher quality of education because simulated experience can complement and improve the value of operating room experience.

In addition to performing medical procedures, it is beneficial for residents to experience rare anatomies, anomalies, and other complications. Bringing up the question of how residents can be better prepared for complex cases is important because even veteran surgeons may only experience rare and complex cases a few times during their careers. Statistically, the number of complex cases that residents experience during their education varies, which makes a strong case for the use of virtual reality simulators to catalogue various complex cases to be used in procedure simulations. These complex cases can then be repetitively practiced by residents as part of their curriculum. By practicing all available complex cases within the catalogue, residents can gain experiences, which traditionally educated surgeons may encounter only a few times in their careers, essentially allowing them to rapidly learn from a "lifetime" of experience.

Therefore virtual simulators may serve to accelerate and improve the broadness of a residents education, even with duty-hour restrictions; this will still provide a high quality education while improving the safety of current and future patients that the residents may be responsible for.

2.1.2 Medical Residency

Medical residency programs are large time and resource investment for both residents and the institution involved.

When screening applicants for surgical programs there is usually only anecdotal evidence with regards to motor skill testing. When considering applicants to surgical programs, a certain level of innate motor skills are required to perform procedures adequately; however, these programs rarely, if ever, evaluate these motor skills. In a study involving master surgeons who are or have been directors of surgical training programs, dexterity was unanimously as the most important factor for determining the ultimate technical proficiency a resident can acquire with training.

One study utilizing the Advanced Dundee Endoscopic Psychomotor Tester (ADEPT), identified a first year resident with diminished manual dexterity, who was later unable to complete the surgical curriculum and was advised to change career paths in their third year. (14) This anecdotal example is unfortunate and likely caused hardship both to the resident and the training program. Because of huge investment in time and resources to train surgeons, institutions seek the best candidates for training, which would ideally be selected by a process that is rigorous, objective, transparent, and fair. (15) However, identification of the attributes which best predict who will make a good surgeon is still elusive.(15)(16) In the Republic of Ireland, an objective assessment for selection of surgical trainees was developed. Results from this assessment showed a large and statistically significant difference between candidates who were shortlisted and those that were not, as well as the difference between candidates selected for higher surgical training (HST) and those that were not. Overall the assessments used in the selection program were deemed to produced a highly predictive statistical model for competitive selection that was both fair and transparent. (15) Objective assessments, like those used in the previous example, are useful for trying to find the best candidates for surgical programs; however basic motor skills aptitude was still not tested or taken into account. One study tried to evaluate motor skills aptitude of medical students by allowing them to perform exercises that are included as part of the da Vinci Skills Simulator. A total of 125 participants completed 3,250 total exercises on the skills simulator. Interestingly after the results were analyzed, it was found that the population of medical students who are least talented in terms of manipulative and psychomotor abilities was twice as large as the population of medical students who were specially gifted. (14) Interestingly this seems to suggest that it may be more critical to filter students who are not suited for the surgical profession, as opposed to trying to find those who are most suited. This is important because motor skill aptitude is not the only factor involved in determining the overall quality of a surgeon, since there are many non-technical skills involved. An anonymous survey of 68 consultant surgeons from all specialties in Scotland, identified 70 skills which were considered important in a successful surgical trainee: 19 skills were technical, 22 were clinical, and 29 were related to communication, teamwork, and the application of knowledge. (17) Students with average manipulative and psychomotor abilities may demonstrate success in other non-technical areas, however, students with severe deficiencies in manipulative and psychomotor abilities may not be able to overcome their lack of technical skills, even with success in non-technical skills.

To investigate how sensory and motor skills differ amongst potential applicants to a neurosurgery residency program, a battery of modules was developed to see if these skills were normally distributed; these included a spatial orientation and memory module, and a stereognosis, or haptic perception, module. Another module was used to test sequence, timing and precision skills as simulated by cauterization in a brain cavity, however this module was not developed as part of this thesis. These tasks were chosen because they were believed to represent core neurosurgical skills. While there is no guarantee whether these tasks serve as a good indicator of future surgical performance, we believed that the results would help us identify average performance and show outliers. Because further research still needs to be performed to determine the exact skills which determine future competency, this array of tests may better serve as a way to flag outlier applicants whose motor sensory skills may be deficient and may prevent applicants from completing the residency program successfully. When developing this battery of tests, no previously published studies on testing sensory and motor skills in neurosurgery residency program applicants were found. (16)

2.1.3 Competency Evaluation

Due to a lack of standardization and evaluation of a residents technical skills in medical education, it is hard to quantitatively record and compare the competency levels achieved. For example, in the neurosurgical field most trainees are evaluated by cognitive examinations and internal evaluations of technical competency. (18) However these evaluations do not take into account the large amount of variations in the operative procedures that residents may experience. The goal of one study was to survey general surgery residency program directors and categorize procedures into groups of varying familiarity and competency required. Group A categorized procedures that graduating residents should be competent enough to perform independently. Of 300 surveyed procedures, 121 of them were considered as group A procedures. The experiences of residents graduating in the US from general surgery programs in 2005 were compared, and on average it was found only 18 of the 121 group A procedures were performed more than 10 times during residency. 83 of the group A procedures were performed on average less than 5 times, and 31 procedures less than once. The mean was also found to be a poor indicator of overall experience, because the mode of 61 procedures was reported as 0, which indicates significant discrepancies between operative experiences and residents in their respective programs. (19). This creates a large gap between operative experience gained among varying medical programs, a gap which virtual reality simulations may help bridge. As the technology and number of modules available for virtual reality simulation increases, a resident may soon be able to practice all of the procedures with required competency, multiple times and on multiple patient anatomies.

Not only can virtual reality simulators be used as a tool to investigate an individuals sensory-motor skills in regard to their possible future success as a competent surgeon, but they can also be used as a tool to measure if an individual has successfully completed their education at there required competency level. Currently medical education lacks an objective assessment of surgical skills and the surgical experiences of two individuals can be vastly different. With the changes occurring in medical education and rising concerns for patient safety, virtual reality simulations may become standard practice in medical education. This will allow residents to supplement their operating room experience with effective simulation of numerous skills and different patient anatomies without the risks involved in traditional medical education. Virtual reality also has the benefit of non-biased scoring, which is a common flaw in assessments that may be carried out by different evaluators; this limitation that is noted by the Objective Structured Assessment of Technical Skills (OSATS), an objective skill assessment first developed by the University of Toronto. OSATS is an examination utilizing bench models and an evaluator to score participants with 8 stations, however this becomes a time intensive and costly process. Overall OSATS showed a positive correlation between postgraduate year and scores obtained, this helped create a more standardized evaluation of surgical trainee skills. (20) With the flexibility and objectiveness made possible with virtual reality simulation, it may one day become a standard by which the quality of medical education is evaluated and deemed suitable for competent, independent practice.

CHAPTER 3

SURGICAL PROCEDURES

3.1 Introduction

In this chapter the procedure modules created for the ImmersiveTouch® will be introduced. In Figure 1 we can see the overall diagram of the ImmersiveTouch® system and the modules created. The orange blocks represent interfaces to the ImmersiveTouch® system which include: haptic device(s), foot pedals, keyboard, mouse, an iPod touch, speakers, head tracker, and a stereoscopic display. In the implementation details of each module the relationship between the interfaces and software will be described in more detail. The medical procedures developed consist of Open Pedicle Screw Insertion, Hematoma Removal, and Epidural Injection.

The Open Pedicle Screw Insertion is a module created to simulate the insertion of pedicle screws into the pedicles of a patients spine. The Hematoma Removal procedure was created to simulate the process of removing a hematoma from a patients cranial cavity when trauma may cause a subdural formation of a hematoma. Lastly an Epidural Injection procedure was created to assist in practicing the insertion an epidural needle into the epidural space. These procedures will be discussed in detail in the following sections.

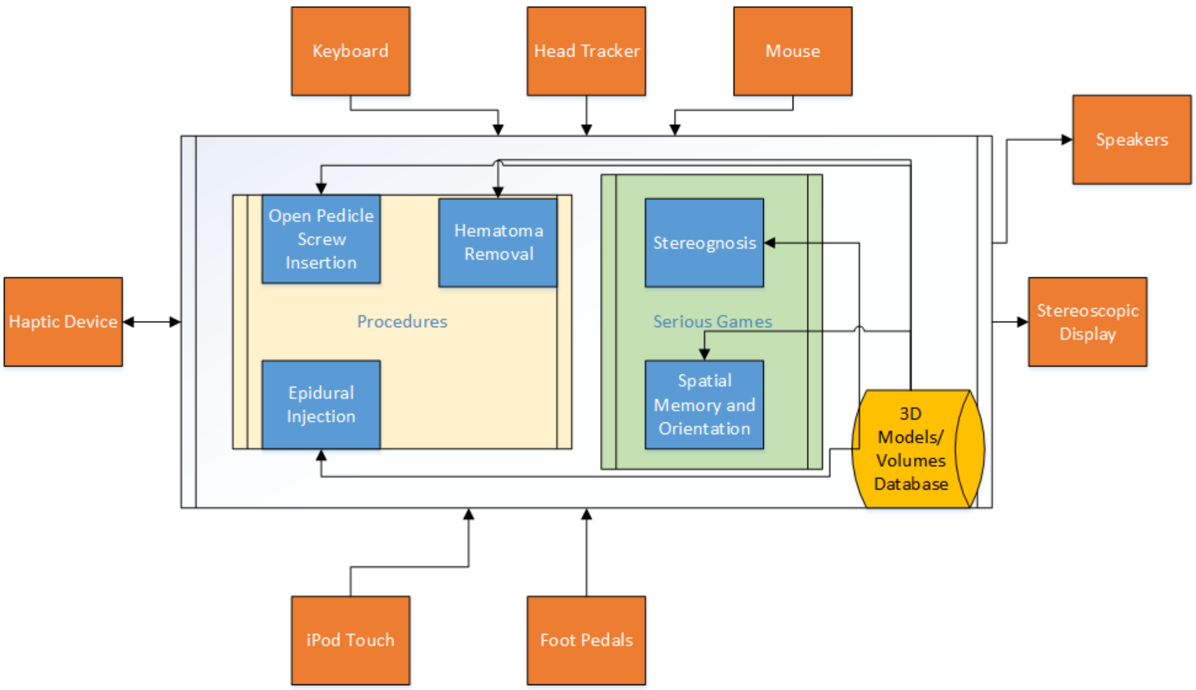

Figure 1. Overview of the ImmersiveTouch System and created modules

3.2 Open Pedicle Screw Insertion

3.2.1 Background

Pedicle screws are an important part of spinal fusion surgeries, serving as an anchor point to be later connected by a rod, which aids in fixation of the spinal segment. Normally, placement is performed in the lumbar and thoracic spine. Pedicle screw placement is a difficult procedure due to varying patient anatomies and possible complications if the screws are not placed properly.

Improper placement can lead to complications such as breeching the pedicle, resulting in lower biomechanical strength which may put patients at risk of the screw loosening or failing. (21) Other complications of improper screw placement can be as severe as harming vascular, neural, and other vital structures in patients. These complications serve as a driving force for surgeons to investigate new approaches and technologies to improve the accuracy and precision of screw placement. (22)

One of the divisions in pedicle screw fixation is whether the procedure is open or percutaneous. Open pedicle screw fixation typically requires significant dissection of paraspinal muscle, which is then retracted to identify the entry point. Percutaneous pedicle screw fixation was developed as a way to reduce the dissection of paraspinal muscle, as well as reducing recovery time and postoperative pain, but due to the limited target view, an image guidance system must be used. Until recent years a comparison between the accuracy of open and percutaneous pedicle placement has never been performed. The first and only study investigating such a comparison came to the conclusion that pedicle wall penetration rates between the two approaches were not different, however the direction in which the penetration occurred differed. This penetration direction is important since the open approach produced lateral wall penetration, whereas penetration in other directions was more prominent in the percutaneous group. (23) A study which examined biomechanical implications of incorrect screw placement discovered that screws which had a penetration in the mediolateral direction had limited impact in determining the stability of the screw, however, violations in the craniocaudal direction produced a major reduction in the pullout force of the screws (24). Limitations of this study included the use of porcine vertebrae, which may not perfectly emulate the physiological and anatomical behavior of human vertebrae due to differences in bone characteristics, also the pullout forces measured did not consider a cantilever-bending moment, which is more representative of normal physiologic loads placed on pedicle screws (21)(24). Simulation of pedicle screw fixation is an ideal application which would allow surgeons to repetitively practice pedicle screw insertions to hone their skills without putting real patients at risk.

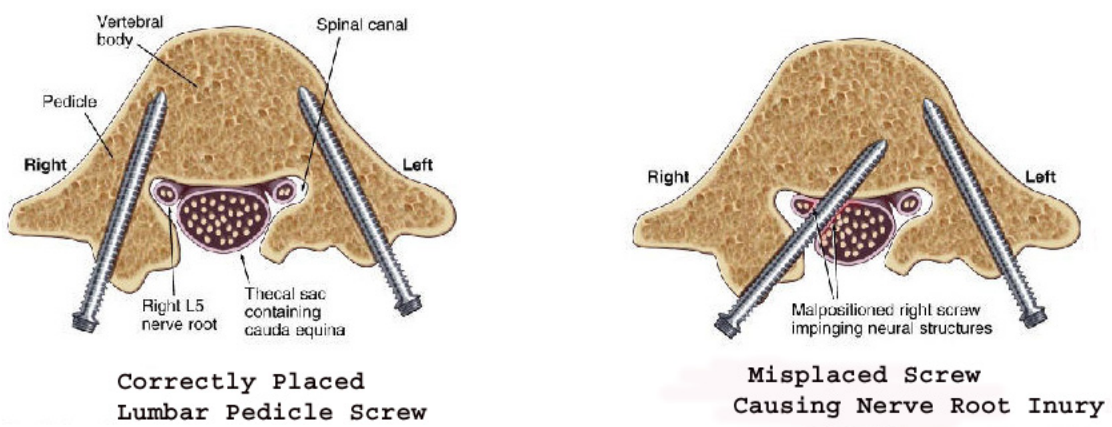

Figure 2. Example of correct and incorrect pedicle screw placement. Illustration courtesy of Neil R. Holland (25).

The development of the Open Pedicle Screw Insertion (OPSI) module stemmed from enhancements to a previously developed module for thoracic pedicle screw placement. (26)(27) The initial module was first studied at the 2009 American Association of Neurological Surgeons (AANS) annual meeting, in which 51 fellows and residents, who were selected by the Young Neurosurgeons Committee, participated in a competition placing thoracic pedicle screws. The error rate detected in pedicle screw insertions as completed by the participants was shown to be consistent with results from clinical practice, with improvement in performance being demonstrated after the initial training session. Participants also reported satisfaction with the realism of the simulation. (27) The module was then further improved by adding more representative tools such as a drill which simulated material removal, a pedicle finder used to prepare the screw hole, visualization of screws to be selected and inserted, and a considerable overhaul in realism of the skin and paraspinal models. Several of the haptic effects were also improved, increasing the realism of the simulation, such as obstructing lateral movement when the finder is within the vertebrae and bone friction effects.

3.2.2 Implementation Details

Figure 3 shows an overview of the implementation of the Open Pedicle Screw Insertion module. The physical interfaces of the ImmersiveTouch® are shown as dark red blocks, databases are shown as yellow blocks, processes shown in green are sub-processes of graphics rendering, orange blocks represent sub-processes of the haptics rendering system, and blue blocks represent general system logic. All of the sub-processes will be described in the following sections.

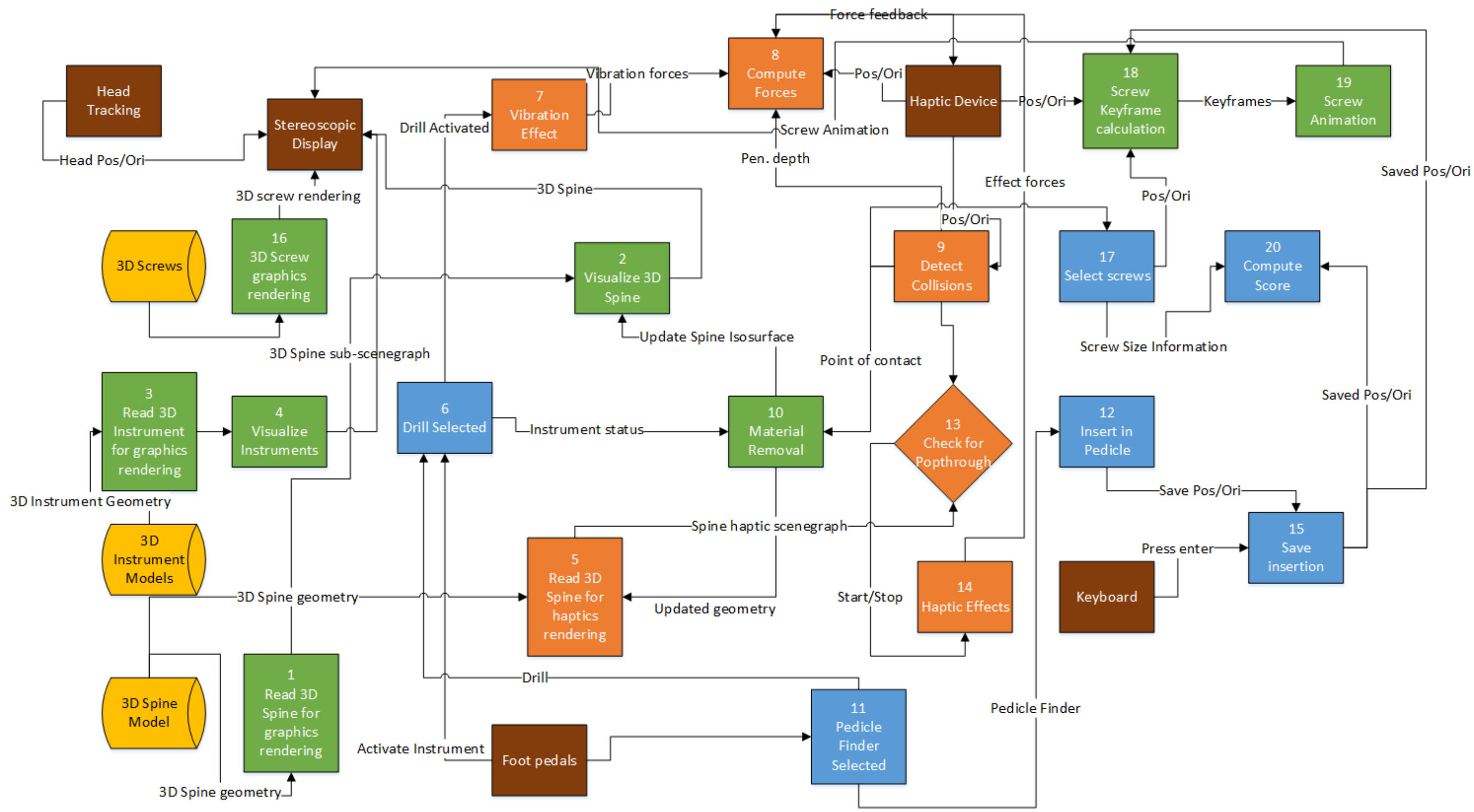

Figure 3. Overview of the implementation of the Open Pedicle Screw Insertion module

Read 3D Spine for graphics rendering

This process reads the "scene.iv" file and loads the relevant files that store 3D geometry and graphics materials of the spine, skin, discs, and surgical cloth. The geometries and materials are loaded as Open Inventor nodes. Open Inventor is a high-level 3D graphics library designed to work on top of OpenGL. It helps abstract away lower-level functions by providing a scene-graph structure as a way to visualize objects. Sensimmer SDK utilizes Coin3D, an open source version of Open Inventor for graphics rendering.

Visualize 3D Spine

The sub-scenegraph containing all of the spine nodes for the Open Pedicle Screw Insertion is added to the main scenegraph and rendered by Coin3D. Most models in the OSPI scene graph are polygonal meshes, except for the spine which is a volume. To handle the rendering of volumes in Sensimmer SDK, a previously developed Marching Cubes implementation in CUDA was utilized, which computes the polygonal isosurface of the volume and renders the triangles using a class derived from the Coin3D class SoIndexedFaceSet. (28)

Read 3D Instrument for graphics rendering

This process reads the "cursor.iv" file and loads the relevant files for the tool 3D geometry and graphics materials. In the Open Pedicle Screw Insertion there is two different instruments that are utilized, a drill tool and a pedicle finder.

Visualize instruments

The sub-scenegraph containing all of the instrument nodes is added to the main scene graph and rendered by Coin3D. The tool currently selected is active in a group and the other tools are not rendered.

Read 3D Spine for haptics rendering

The 3D geometry information contained in the "scene.iv" file is also used by OpenHaptics to render the scene objects as haptic objects. Volumes are rendered differently and they are defined from a set of voxels using transfer functions; this avoids the need to generate polygonal meshes which is slow. (29)

Drill Selected and Activated

The user initially starts with the instrument as a drill. The instruments can also be cycled with the foot pedals, as well as be activated by the foot pedals. When the drill is activated there is an associated vibration haptic effect which is part of the OpenHaptics SDK. The forces calculated are sent to the force feedback of the device and are felt as vibrations at the stylus.

Collision Detection

The position of the tip of the haptic device is used in detecting collisions with objects. The haptics library checks for point collisions between the tip of the instrument and any of the polygonal models used in the haptic scene. For volumes that are haptically rendered the collision detection is an algorithm which is part of Sensimmer that extends API calls to OpenHaptics to notify the library whether the proxy intersects with shape surfaces. The algorithm utilizes the previous haptic frames proxy position as well as the current haptic frames proxy position as a line segment which is then compared to the shape surface which is defined as voxel intensities as opposed to isosurfaces. (29)

Compute Forces

The forces computed in OpenHaptics come from two sources: haptic effects and collisions with objects. When computing forces from a collision with an object, OpenHaptics takes into consideration material properties such as: spring, damper, static friction, and dynamic friction. The interface to these material properties is also exposed in Sensimmer when haptic objects are defined, this allows for the object properties to be changed in their Open Inventor files or at runtime. If a collision is detected the haptics proxy is fixed at the surface and a spring-damper model is used to calculate the forces depending on the material properties, position of the proxy, and the position of the haptics device. (30)

Material Removal

When the collision between the activated drill and a volume with removable material such as the spine is detected, we can use GPU processes to change the values of voxels at the point of contact. The rate and pattern of removal can be adjusted and this allows for simulation of bone drilling. When drilling the spine a spherical area of removal is used with adjustable rates and radius. (28)

Pedicle Finder Selected and Inserted into Pedicle

By pressing the foot pedal the user switches to the next instrument for the procedure which is the pedicle finder. To simulate the hardness of the cortical bone as described in the software section, the ability to pop through using the pedicle finder is now allowed, however when the drill is used to remove some cortical bone the pedicle finder can then be used to pop through.

Check for Popthrough

Each haptic object has haptic material properties such as stiffness (spring), damping, static friction, dynamic friction, and popthrough. When the instrument tip is in contact with a haptic mesh, the calculated forces are compared to the popthrough threshold and if they exceed the required forces a popthrough event is registered as having occurred. Normally a popthrough event switches the touchable face of a haptic object to simulate the sensation of having penetrated the object.

Haptic Effects

Haptic effects are normally associated with specific meshes or instruments. OpenHaptics provides several built in effects such as: constant, spring, viscous, and friction; however there is also a callback effect type which allows for users to calculate the force provided to the device which allows for custom effects. Several other effects have also been developed as part of the Sensimmer SDK, these include a line effect and fulcrum effect. When simulating the insertion of the pedicle finder into bone, a custom line effect combined with a friction effect are utilized. The line effect was modified to increase the magnitude of the trajectory correcting force as the pedicle finder is deeper in the bone. The friction effect helps simulate the pedicle finder moving through the spongy cancellous bone.

Save Insertion Data

When the user is satisfied with placement of their pedicle finder they can use the keyboard to save their insertion data. The position and orientation of the instrument as reported by OpenHaptics is saved for later use in subprocesses, such as scoring and pedicle screw animation.

3D Screw graphics rendering

Similarly to the spine scene graph, models of pedicle screws of varying lengths are read in from a database and added to the main scene graph to be rendered by Coin3D.

Screw Selection

The screw geometry is also added the haptic scene graph so they are able to be touched by the haptics device. The user is then tasked with selecting a screw of the proper length to go into the pedicle, when they have picked a screw, they only need to touch the screw with the haptic device.

Screw Keyframe calculation

Using the selected screw position and orientation as well as the saved insertion data, a set of position and orientation keyframes are calculated as a shortest distance path.

Screw Animation

The previous calculated keyframes are combined with interpolators to smoothly traverse through all of the keyframes and create the animation of the screw moving to position and then being rotated into the pedicle.

Score Computation

The score is computed by using the saved insertion data and calculating the euclidian distance between the entry point and ideal entry point as well as the target point and the ideal target point. The screw length selected is also recorded and checked against the insertion depth to detect whether too long of a screw had been selected.

3.2.3 Software

The OPSI simulation module begins with the user drilling at the entry point to remove cortical bone allowing for easier access with the pedicle finder. When the user removes the voxels designated as cortical bone, the pedicle finder can be used to enter the cancellous bone at the core of the pedicle.

After creating the initial entry point using the bone drill, the user needs to switch to the pedicle finder, which is inserted through the cancellous bone to create a path for the pedicle screw. The user is also allowed the use of virtual fluoroscopy which uses volumetric ray casting to create a 2D fluoroscopy image in realtime, users can also predefine lateral and anterior/posterior views in the virtual fluoroscopy. The total number of fluoroscopy shots are recorded and count against the overall score of the user, with the intention of teaching users to reduce the total amount of radiation that a patient is exposed to. Once the user is satisfied with the placement of the pedicle finder, a button is pressed to save the tool's orientation and depth. The pedicle finder is then retracted and the user is presented a set of standard pedicle screws ranging from 35 mm to 55 mm in length. Screw insertion is then simulated visually wherein the user is not actively involved in the process. The goal in screw selection is to score the user's ability to select a proper screw length and then to visually see if the size and trajectory of the approach was correct.

In future iterations of the module there is interest in the simulated use of a pedicle tap to create the thread for screw insertion. With the currently used hardware, which consists of the Geomagic Touch and Geomagic Touch X, both devices are 3 degrees of freedom (DOF) and do not include torque feedback for stylus rotation. While digital encoders provide rotational measurements, this rotation is limited, therefore simulation of a pedicle tap using the current hardware would require a ratcheting motion to account for the limited stylus rotation.

3.2.4 Results

At a 2012 AANS Top Gun competition, participants using the OPSI module logged a total of 76 practice data sets and 156 test data sets. An analysis of the data showed that the differences in accuracy scores between practice and test data sets were relatively insignificant, while the overall cumulative score was improved after practice. The difference in score was largely due to a reduction in the average number of fluoroscopy requests. (31)

To our knowledge, there is no other virtual haptic training platforms in which surgeons can practice open pedicle screw insertion. Compared to traditional methods of learning, such as cadavers, animal models, and even real patients, our simulator allows for repetitive practice and feedback on pedicle screw placement. While currently only one case has been created, a library of patient spines can eventually be modified and used for this procedure allowing for varying anatomies and complex cases with severe scoliosis.

3.2.5 Future Work

This module demonstrates the use of the ImmersiveTouch® simulator as a tool to train surgeons in performing open pedicle screw insertions. The overall user feedback was very

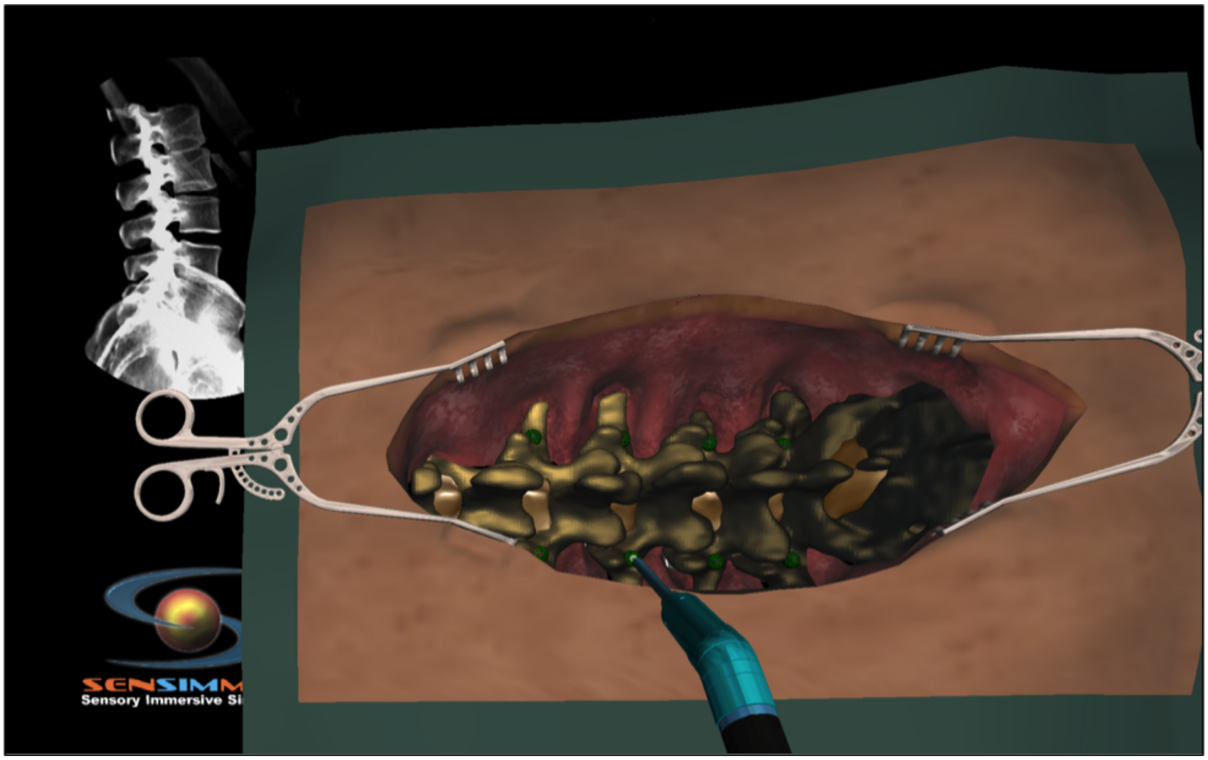

Figure 4. Screenshot of vertebrae cortical bone drilling performed during OPSI module

positive and users reported that the haptic effects effectively replicated the feeling of cortical bone drilling and travel through the cancellous bone. While this module is only a portion of the full procedure, it is an important step in creating a thorough pedicle screw insertion simulation. Data collection from more users and feedback will allow us to iterate and create a more complete experience. Currently there is a strong interest in further developing the OPSI module by allowing surgeons to be actively involved in the screw insertion process as opposed

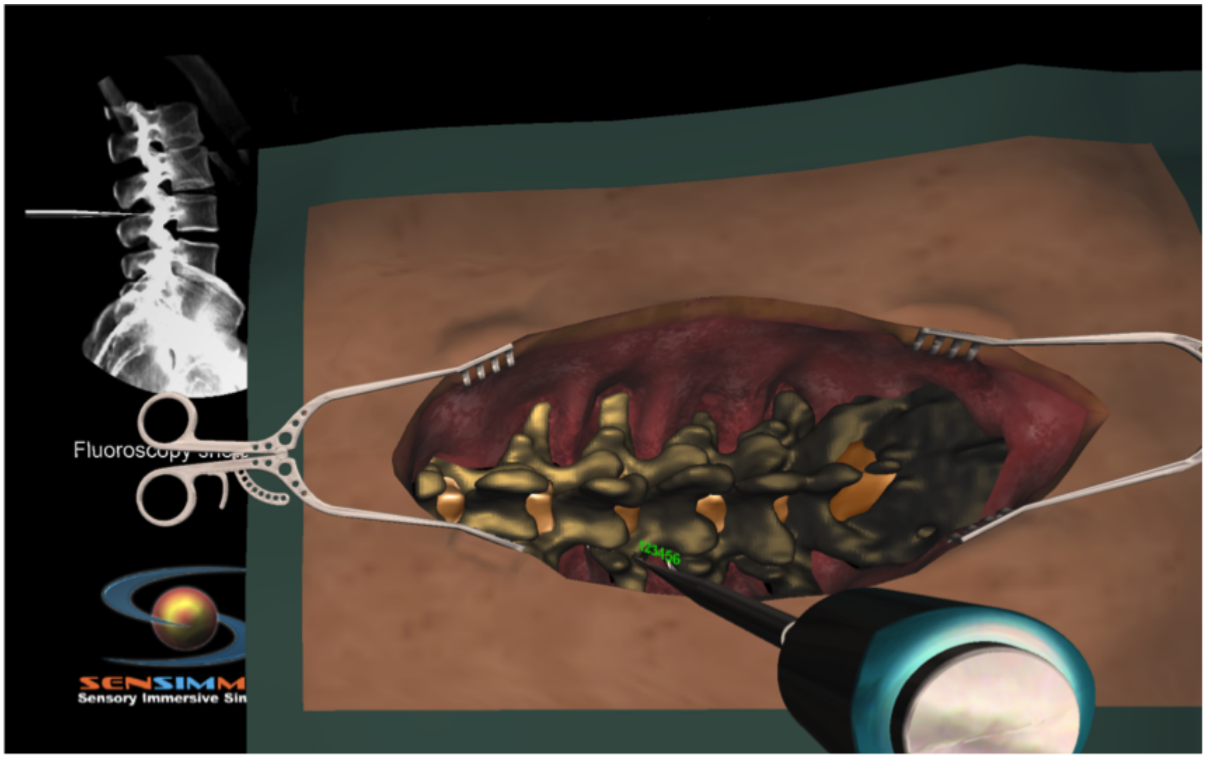

Figure 5. Screenshot of pedicle finder insertion into vertebrae during OPSI module

to just a visual representation. The first stages of implementation would involve participation with minimal haptic feedback due to previously mentioned constraints in the haptic devices currently used, and would likely consist of simulation of the pedicle tap by allowing the users to rotate along the axis of the stylus.

Also as the module is currently implemented the overall scoring is computed by calculating the euclidean distance between the actual target and entry points and the ideal target and

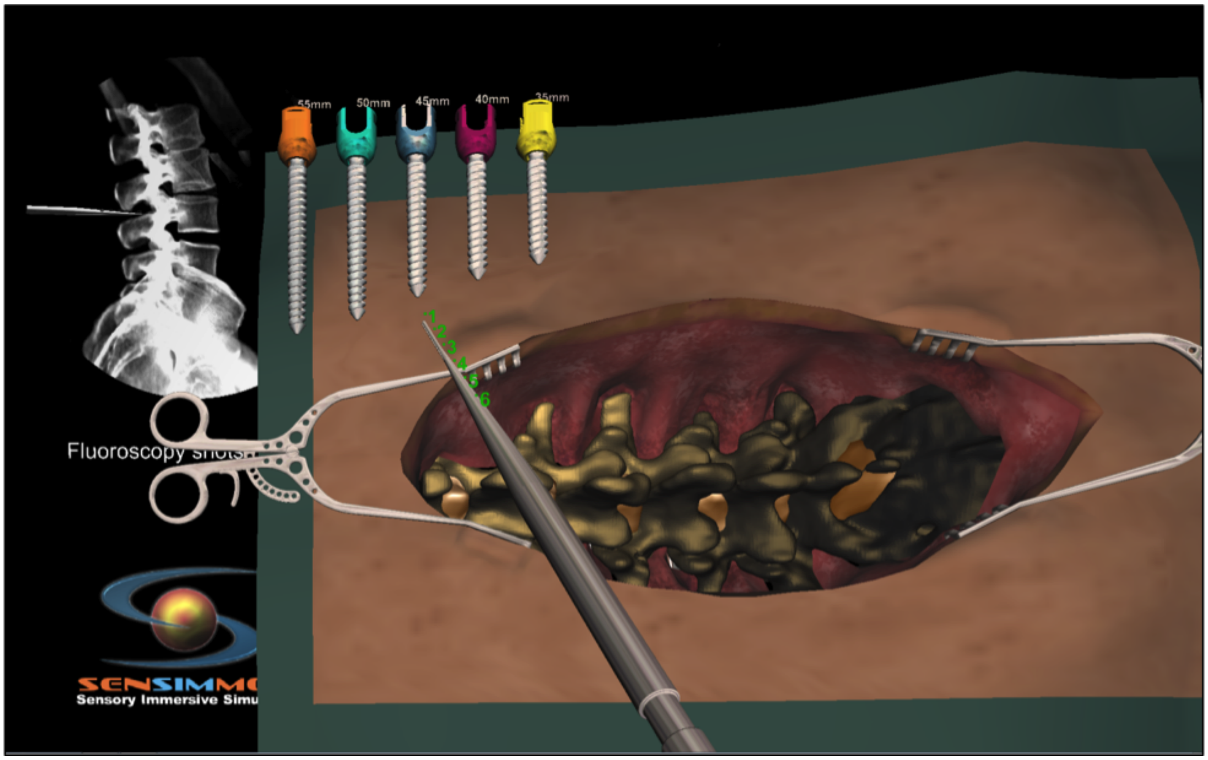

Figure 6. Screenshot of pedicle screw selection during OPSI module

entry points. Currently it is still very informative for users of the module to receive feedback from surgeons with seasoned knowledge of pedicle screw fixation. By using cutting planes to view the trajectory of the screw placed, users can be evaluated on their approach and chosen screw length. In future versions it would be beneficial to provide users with feedback on their approach and report if they had any violations or breaches. Future upgrades may also include

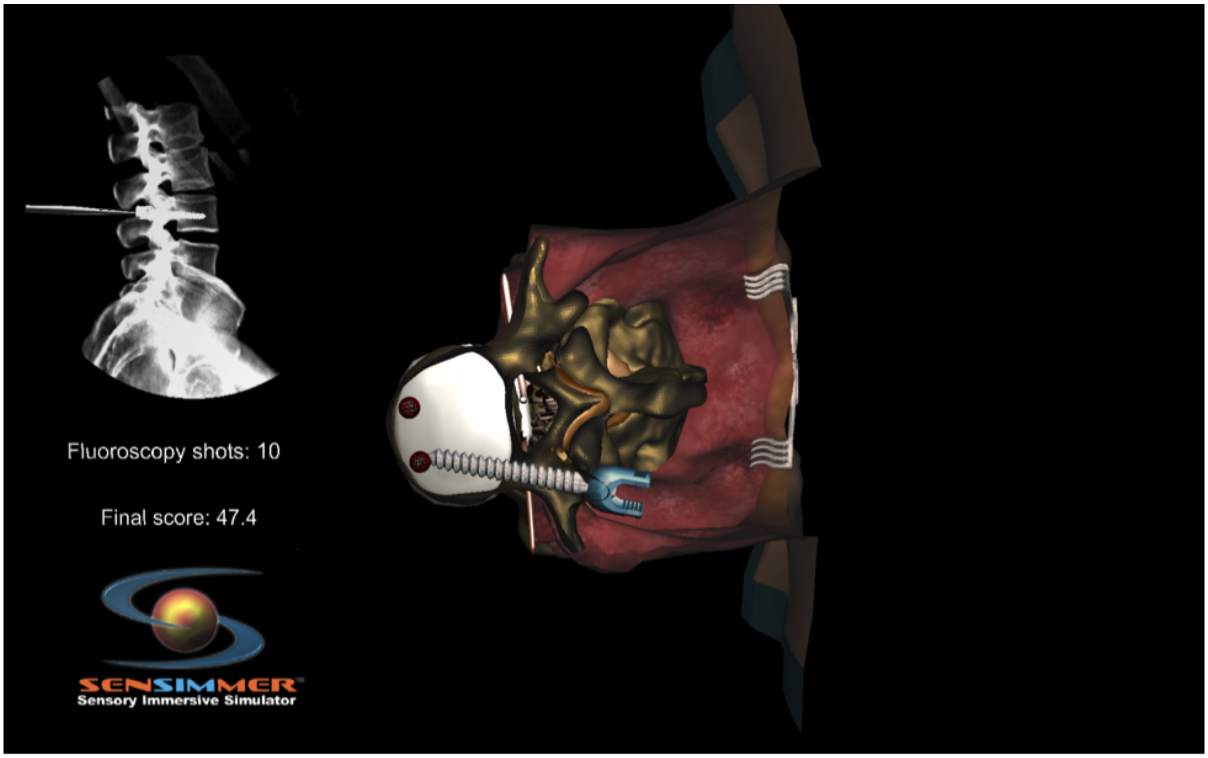

Figure 7. Screenshot of final pedicle screw placement during OPSI module

updating the procedure include newer technologies such as robotic guided screw positioning, which could be simulated both for open and percutaneous screw placement.

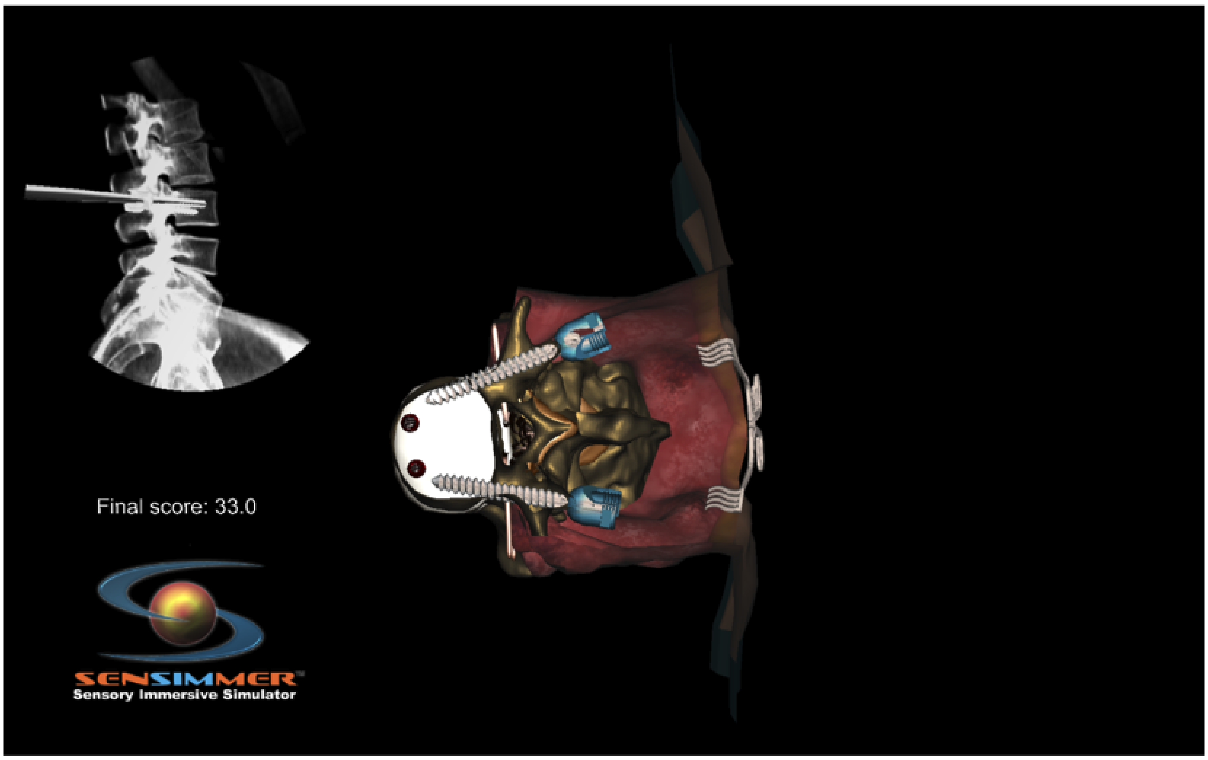

Figure 8. Screenshot of final pedicle screw placement for multiple screws during OPSI module

3.3 Subdural Hematoma Removal

3.3.1 Background

A subdural hematoma (SDH) is normally a result of a traumatic brain injury, where blood collects on the surface of the brain under the dura. This can lead to compression of brain tissue for long periods of time, resulting in tissue damage and death. Subdural hematomas are normally caused by traumatic brain injuries, however they are also common in elderly and alcoholic patients due to brain atrophy. Acute subdural hematomas are normally treated with craniotomy or craniectomy due to the coagulation of blood which cannot be drained with treatments such as burr hole drainage. Correct diagnosis is very important because of minimal signs and slowly developing symptoms, caused by slow intravenous blood flow.(32)

Subdural hematomas have previously reported mortality rates ranging from 22% to 66%. In a more recent study conducted in a level one trauma center a mortality rate of 14% was found in a population of 1,427 patients. The the reduction in mortality rate was postulated to be due to the more widespread use of computed tomographic (CT) scan imaging, which has helped detect patients with less severe subdural bleeding in which an evacuation by craniotomy or craniectomy may have not been necessary. (33). Another study analyzing national data for frequency, cost, and mortality rates in subdural hematoma cases, found that the rate of SDH admissions has grown annually when corrected for population growth. The authors of the study postulated that the increase in SDH cases may also be the result of a growing elderly population, which are more susceptible to SDH due to increased likelihood of falling, incrusted extra axial spaces, and increased used of anticoagulation and anti-platelet agents. (34) Subdural hematomas were also found to be present in over 15% of combat related head injuries as reported by a study of patients at Bethesda who were injured during service in Iraq.(35)

Due to the rising rates of SDH cases and the high mortality rate it serves as an excellent procedure for both civilian and military neurosurgeons to practice virtually. As part of this initiative to create a subdural hematoma procedure the necessary modules were found to be split into three main parts: craniotomy, subdural hematoma removal, and a hemostasis component. These three modules were developed in parallel and in this section we will be concerned with the development of the subdural hematoma removal module.

3.3.2 Implementation Details

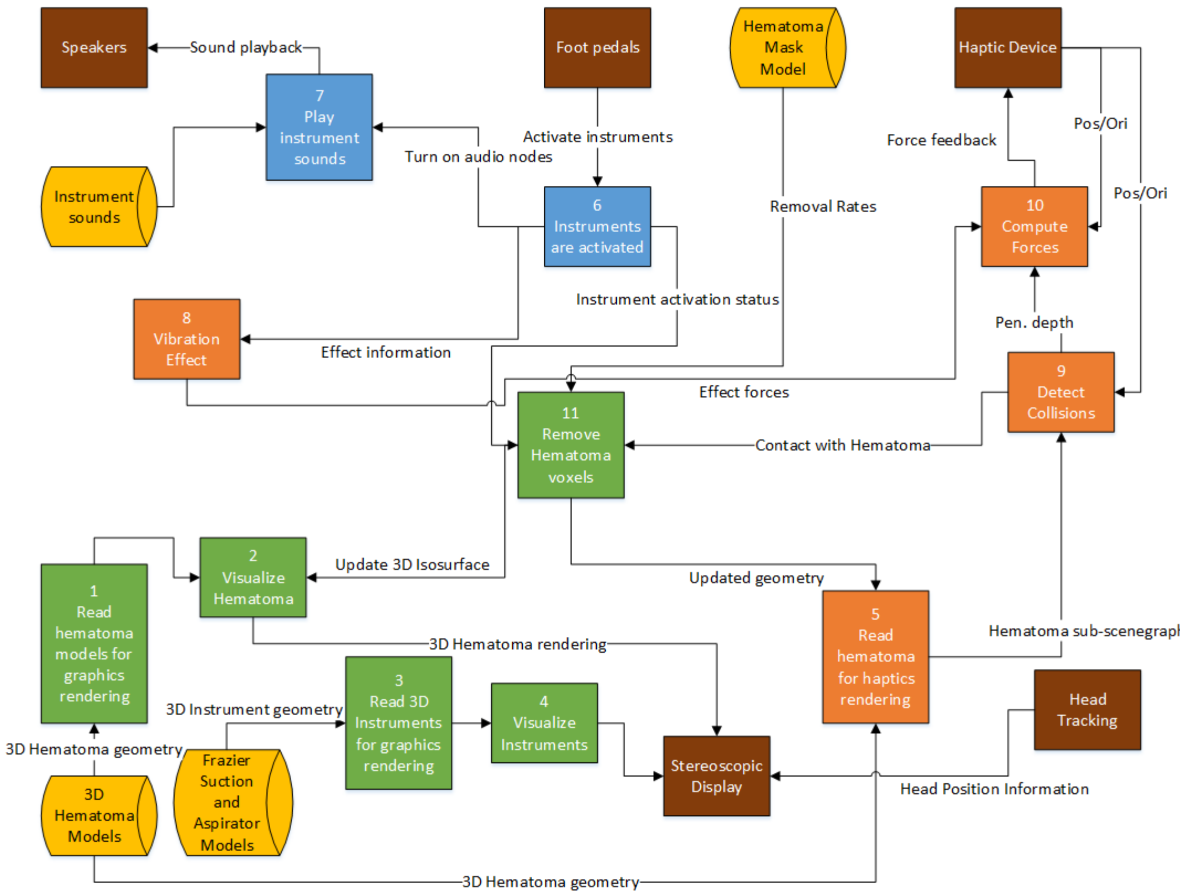

Figure 9. Overview of the implementation of the Hematoma Removal module

Read hematoma models for graphics rendering

This process reads the hematoma and relevant models from a file which contains 3D geometry and graphics materials. The geometries and materials are loaded as OpenInventor nodes.

Visualize Hematoma

The sub-scenegraph containing all of the nodes for the Hematoma module is added to the main scene graph to be rendered by Coin3D.

Read 3D Instruments for graphics rendering

The files containing the tool 3D geometry and graphics materials are read in. Depending on the configuration the simulation can use one or two instruments simultaneously, these instruments are the Frazier suction tool and an ultrasonic aspirator.

Visualize Instruments

The sub-scenegraph containing all of the instrument nodes is added to the main scene graph and rendered by Coin3D.

Read hematoma for haptics rendering

The 3D geometry of the hematoma models is added to the haptics scenegraph to be rendered by OpenHaptics as described in the OPSI implementation section.

Instrument Activation and sound playback

The Frazier suction tool and the ultrasonic aspirator can be activated similarly to the drill. Pressing a foot pedal will activate the instruments which each contain references to a sound database which has different audio tracks for when the instruments are idle and when they are being used to remove hematoma. The ultrasonic aspirator also contains a light vibration effect which is activated as the foot pedal is pressed to simulate the effect of holding a real ultrasonic aspirator.

Collision Detection

Please refer back to the OPSI module implementation section for details regarding the implementation of the collision detection sub-process.

Force Computation

Please refer back to the OPSI module implementation section for details regarding the implementation of force computation.

Remove Hematoma voxels

When contact with the hematoma is detected and the instrument is activated the instruments can remove material as described in the OPSI implementation section. The main difference is that a secondary volume is loaded to act as a mask to determine the material removal rates. This simulates the non-uniform properties of the hematoma. The original bone removal algorithm was also modified with gaussian smoothing to avoid the appearance of rigid material removal.

3.3.3 Software

The Subdural Hematoma Removal module was built using previously developed algorithms for real-time voxel removal, which were primarily developed for bone drilling and removal. (28) These algorithms were modified to emulate tools such as a Frazier suction tool and an ultrasonic aspirator, which are typically used in removal of hematoma tissue.

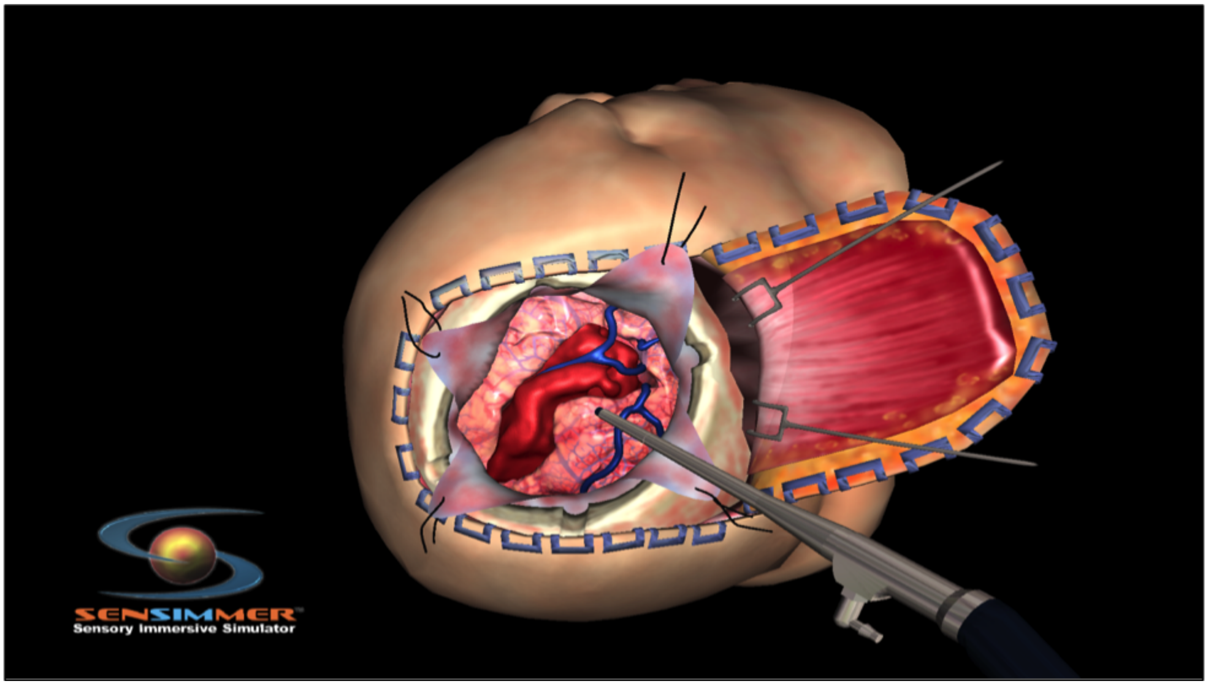

Figure 10. Screenshot of initial view of hematoma module with only one instrument

A hematoma typically consists of non-uniform areas of varying haptic properties. One of the main technical challenges in the creation of the hematoma removal module was to simulate these non-uniform areas of tissue and how they would be removed using the previously mentioned surgical tools. Implementation of these areas of varying properties was developed using a reference volume as a mask to determine the properties of each area of voxels. The reference volume serves as a index table for the haptic properties of each voxel with regards to material removal, and this factor is taken into consideration with the tools removal rate to calculate the

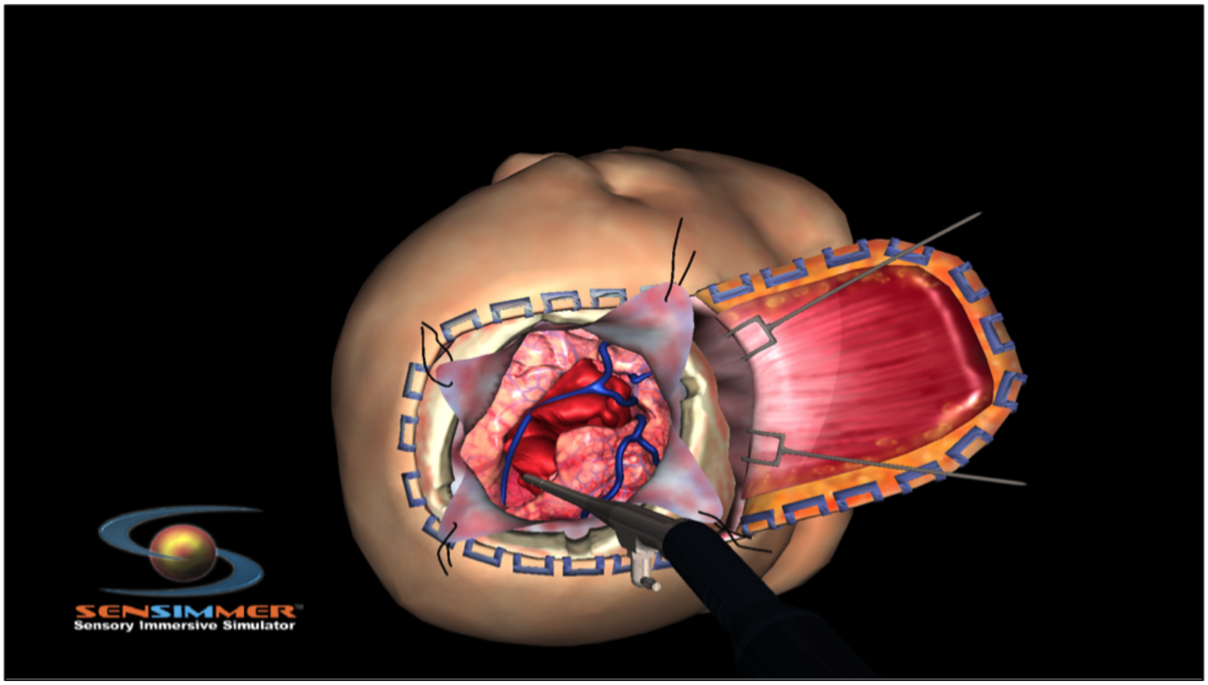

Figure 11. Screenshot of hematoma module with hematoma partially removed

rate of material removal. One of the technical challenges was that two volumes would have to be rendered which would increase the computational burden on the graphics card. To optimize this we used indices in a volume with scaled resolution to reduce the amount of memory and computation power used. This is important especially when the volumes used for simulation are of a high resolution, because the reference volume would cause the frame rate in both graphics and haptics to drop down to unusable levels.

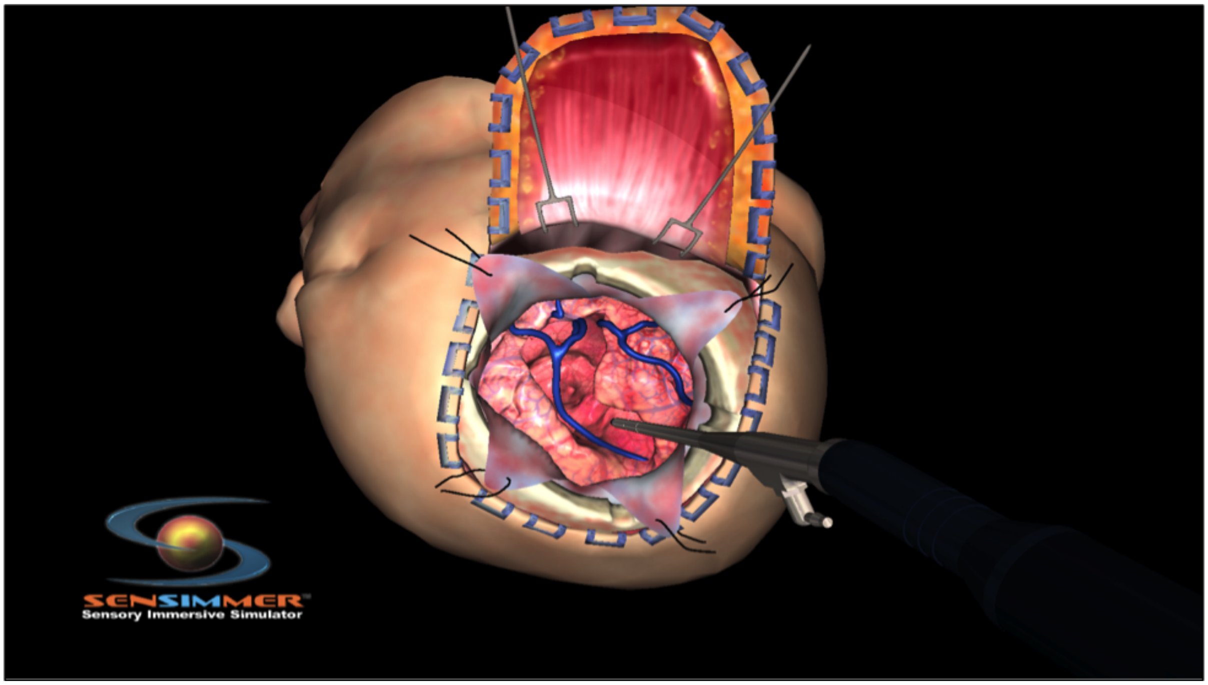

Figure 12. Screenshot of hematoma module with hematoma fully removed

To our knowledge, this is the first simulator allowing surgeons to practice a subdural hematoma removal. The benefits of performing this procedure using augmented reality and haptics as compared to traditional manikin based simulators are numerous, including the ability to create a library of cases and the ability to run the software an infinite number of times unlike physical manikins which need to be replaced after a certain number of uses.

The use of a physical manikin is also not a viable tool to simulate a hematoma removal procedure because each use of the manikin would require desecration, as well as a variety of materials to accurately represent tactical feedback from tissue which would need to be molded in a precise fashion so that each area of the hematoma would have the correct density and physical properties. Utilizing a physical based manikin would increase material costs due to single use replacement as well as not allow for the ability to automatically evaluate the users score or penalize them for damaging healthy tissue.

3.3.4 Future Work

Currently the module does not take any sort of score into consideration, ideally it would be implemented as a time based objective with the total volume of tissue removed accounting for part of the score. Penalties for excessive force that would cause damage to normal tissues should also be taken into consideration.

Current work involves the need to perform validation studies and consult with neurosurgeons about the haptic and visual feedback, as well as the scoring mechanisms that should be used. Technical upgrades to future versions of the software would also involve creating a more dynamic structure for the hematoma that would also emulate the suction of chunks. This would require simulation of a highly viscous fluid or gelatinous substance. (36)(37)

3.4 Epidural Injection

3.4.1 Background

Epidural refers to the procedure of epidural analgesia (pain relief) or epidural anaesthesia (blocking sensation), frequently used for pain relief during childbirth, chronic back pain, post-operative pain relief, or as anesthesia during specific procedures. (38)(39). Epidural needle insertion is a common procedure for anesthesiologists who typically develop most of their experience in the obstetric population. A study from 27-states in 2008 reported that 61% of women who had a singleton, vaginal birth received epidural or spinal anesthesia. (40). Epidural needle insertion passes through five tissue layers: skin, subcutaneous fat, supraspinous ligament, interspinous ligament, and ligamentum flavum. The target location of the needle is typically determined through a loss of resistance as it enters the epidural space. Skilled physicians are known to use a mental model of anatomy and the physiological properties of the tissue to determine where their needle is at. (39)

Epidural needle insertion, while common, poses risks of complications. One complication that may arise is accidental dural puncture which may lead to a postural puncture headache, persisting for days to weeks. It is reported that the incidence rate of accidental dural puncture in labor analgesia varies from 0.04% to as high as 6% in some centers. (41). More severe complications include vertebral abscess, hematoma, and direct nerve injury, some of which may lead to paralysis in rare cases. (38)(42)

Virtual simulation of epidural needle insertion may be a very effective tool to train physicians to feel the needle as it moves through the various tissues, without putting patients at risk for complications. Haptic devices provide fine control over how forces are programmed, and by simulating each layer of tissue with physiologically correct parameters, novice physicians can learn to feel for loss of resistance which indicates the target location. By utilizing realistic haptic sensations experienced during epidural needle insertion as well as virtual models, physicians can use a combination of tools, such as the ability to change transparency of meshes and cutting planes helping develop a mental model of the anatomy, which maps to the physiological haptic sensations experienced. Virtual simulation of epidural needle insertion may prove as an invaluable resource to reduce the risk of patient complications and allow the users to become competent at the procedure.

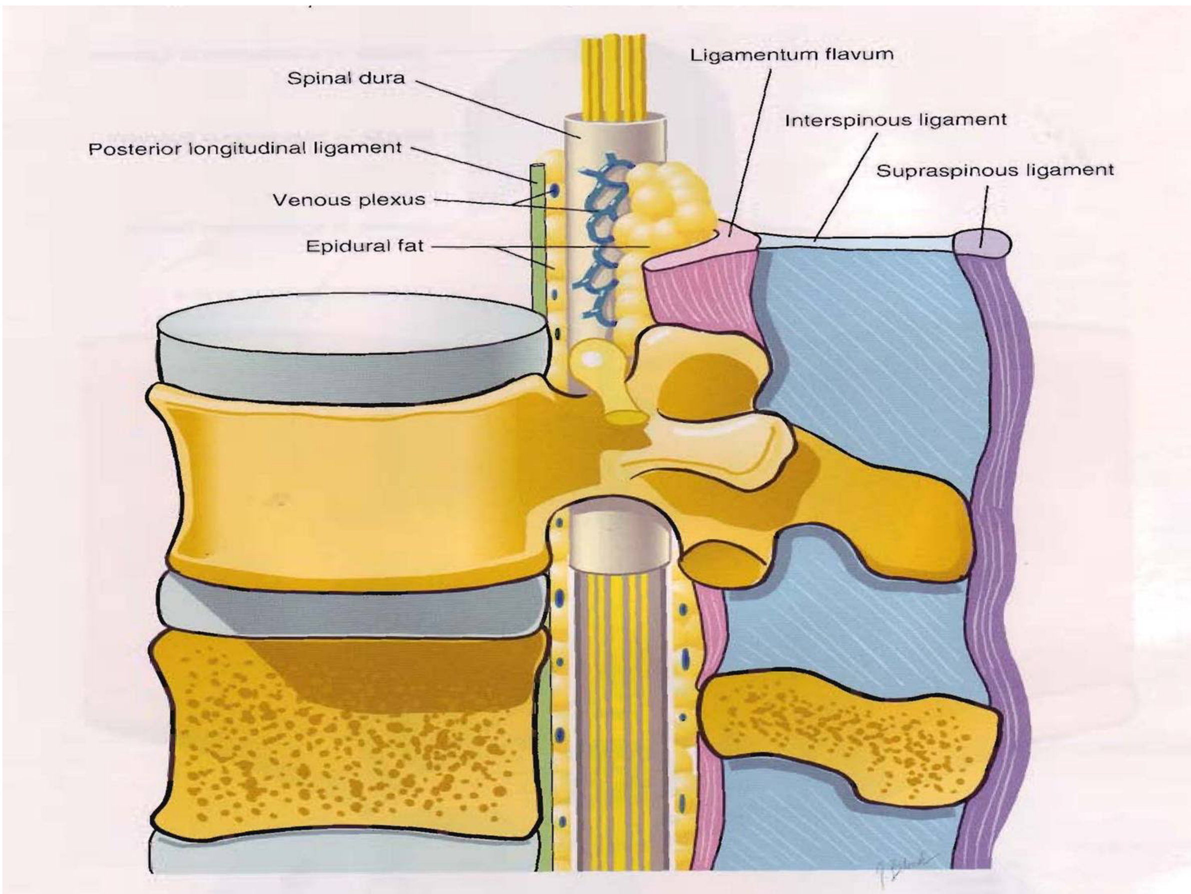

Figure 13. Anatomical drawing of epidural space. Illustration courtesy of Karzazi et al (43).

3.4.2 Implementation Details

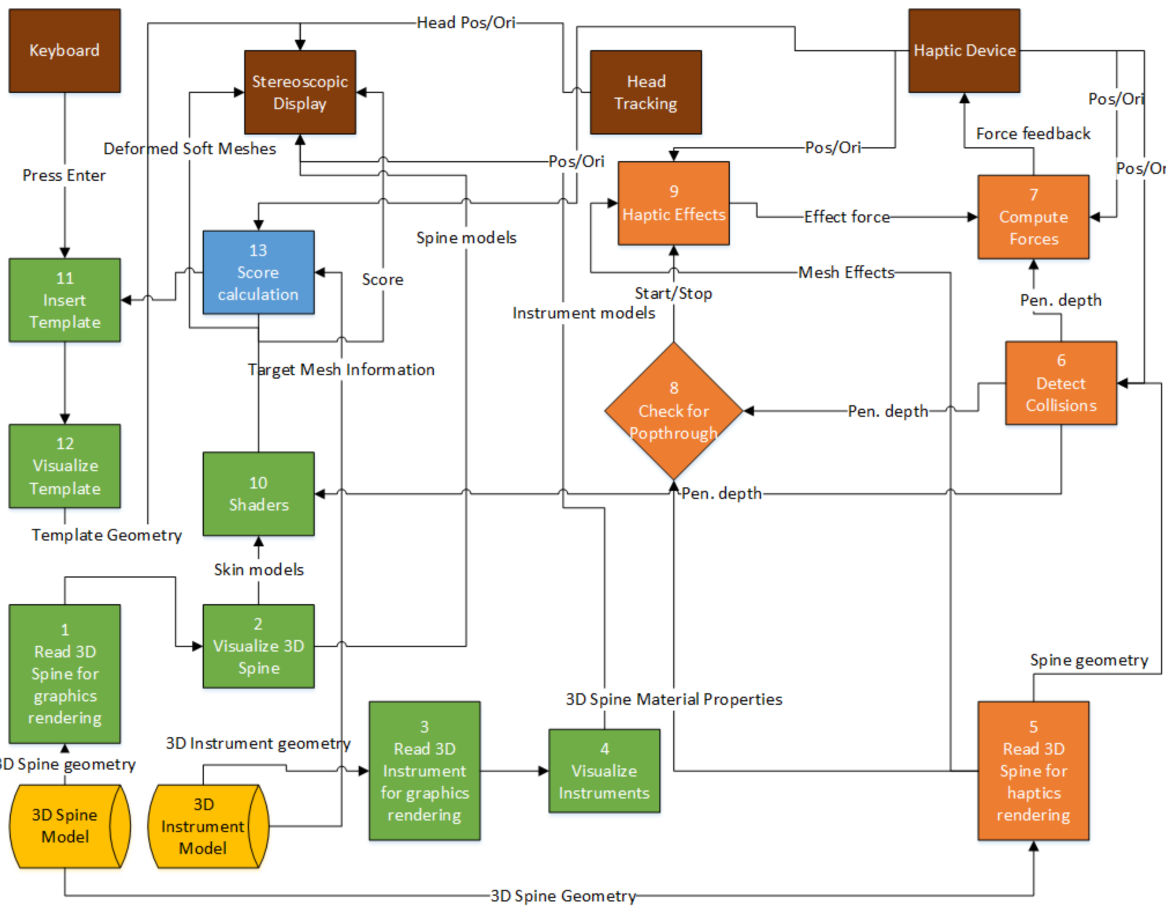

Figure 14. Overview of the implementation of the Epidural Injection module

Read 3D Spine for graphics rendering

This process reads the "scene.iv" file and loads the relevant files that store 3D geometry and graphics materials of the spine, skin, discs, ligamentum flavum, and other tissues. The geometries and materials are loaded as OpenInventor nodes.

Visualize 3D Spine

The sub-scenegraph containing all of the spine nodes for epidural injection is added to the main scenegraph and rendered by Coin3D. The OPSI implementation section describes the rendering of the meshes and volumes in more detail.

Read 3D Instrument for graphics rendering

This process reads the "cursor.iv" file and loads the relevant files for the tool 3D geometry and graphics materials. In the Epidural Injection module only an epidural needle is utilized.

Visualize instruments

The sub-scenegraph containing the instrument node is added to the main scene graph and rendered by Coin3D.

Read 3D Spine for haptics rendering

The 3D geometry of the spine models is added to the haptics scenegraph to be rendered by OpenHaptics as described in the OPSI implementation section.

Collision Detection

Please refer back to the OPSI module implementation section for details regarding the implementation of the collision detection sub-process.

Force Computation

Please refer back to the OPSI module implementation section for details regarding the implementation of force computation.

Check for Popthrough

Please refer back to the OPSI module implementation section for details regarding popthrough detection.

Haptic Effects

In the Epidural Injection module, many of the meshes have haptic effects associated with them which are activated upon the detection of a popthrough event. The skin mesh contains both a viscosity and fulcrum effect to help with the sensation of inserting a needle into tissue. Other meshes also activate viscosity effects to varying degrees of magnitude. The most important haptic effect in the simulation of epidural injection is the loss of resistance felt when entering the epidural space, the details of the effects implementation are described in the software section.

Shaders

To enhance the realism of soft-tissue deformation shaders are used to create the visual effect of deformation. The point at which the soft-tissue mesh is touched along with the penetration depth and normal are used in a GLSL shader to show deformation in the mesh. (44)

Insert and Visualize Template

It is sometimes beneficial for users of the device to save a frozen "template" or virtual copy of their instrument as they check their score. This allows them to visualize their exact trajectory, orientation, and position by using the other tools such as the virtual cutting plane and using the haptic stylus to move the spine to the desired position and orientation. When the user is satisfied with their inspection they can press enter and remove the template from the scene graph.

Score calculation

Scoring in the epidural injection module is a pass/fail system which measures to see if the needle is correctly placed in the epidural space. Placement of the needle is cross-referenced against popthrough events to determine which mesh the needle has passed through, complications such as a dural puncture are also recorded and count as a failure for the purpose of the simulation.

3.4.3 Software

The Epidural module was developed as an extension to a previously existing lumbar puncture module. As part of the update, the software was refactored to allow a more object oriented approach in which tools and models encapsulated actions and objectives. This meant that the large library of existing spines could be used alongside the new application logic to create a common application for multiple spine procedures which could be scripted using OpenInventor scene description files (.iv).

A challenge in the creation of the epidural module included creation of haptic effects to realistically simulate the viscosity in the ligamentum flavum. The change in tactile sensation upon the needle exiting the ligamentum flavum is used by surgeons to know if the epidural needle has reached the proper location. The viscosity model originally developed by Geomagic in the OpenHaptics SDK did not perform adequately due to limitations in magnitude for the viscosity effect. The SDK version of the viscosity effect was based on Coulombic friction with the main difference being a low damping constant and a high clamp value. The OpenHaptics SDK did not provide an API to change the constants of the friction or dampening constants, while it did provide a way to set the magnitude of the force, there was no way to set the value higher than 1, a value which did not provide a sufficient viscosity effect. The OpenHaptics SDK did provide support for custom effects, which allows for manual calculation of force during each haptic frame at a rate of 1000 Hz. A custom viscosity effect was initially implemented to allow for increasing the constants in the computation of viscosity. Increasing the dampening constant would theoretically create a stronger viscosity force, however, since the equation depends on velocity, small changes in velocity were found to cause instabilities and vibration in the device. One approach would be to try to filter these changes in velocity to reduce instabilities, another approach which is actually previously used to solve calculation of forces between haptic devices and surfaces is the use of a proxy with damper and spring calculations. To calculate viscosity we used a virtual point mass model which was attached to the haptic device. Inertia force is calculated based on pulling around the point mass around with a spring. The opposite of this force is sent to the device, while Euler integration is also performed to calculate the acceleration, velocity, and position of the point mass. Using a point mass allowed for a viscosity effect with adjustable magnitudes that would still perform with no vibrations or discontinuities even at large forces. The value can then be manually adjusted to allow residents to experience deviations in viscosity inside of the ligamentum flavum from one patient to the next.

In the epidural module the inner and outer ligamentum flavum meshes are only separated by a few millimeters, as they are in real life, unfortunately this small separation between meshes causes problems in the OpenHaptics SDK. When haptic meshes are layered very close to one another this can lead to race conditions in the haptic software when users pass through different layers of tissue, these race conditions can then cause malfunctions to the haptic effects and mesh property logic. The OpenHaptics SDK originally allowed for changing the properties of haptic materials to allow for pop through events, however the API did not provide information if and when a pop-through event occurred. In Sensimmer SDK™ custom algorithms were developed to allow developers to utilize callbacks upon pop-through events, however, the race conditions caused by haptic meshes in close proximity were not initially considered. In the creation of the original pop-through algorithms it was not considered that multiple pop-through events could occur in the same haptic frame (1000 Hz), which was discovered to be cause of the race conditions when close meshes were utilized. By adding new logic external to the OpenHaptics SDK close proximity meshes were now possible and the effects behaved accordingly.

In the course of testing issues with two meshes that were close or overlapping, some flaws were found in the OpenHaptics SDK. Internally the software was found to completely miss collisions when meshes overlapped. Because the SDK is closed source we were not able to investigate what might have been causing the issue or investigate possible solutions. OpenHaptics support was notified of the issue, however no solutions or patches were created. Hopefully this issue will be fixed in future versions of the OpenHaptics SDK.

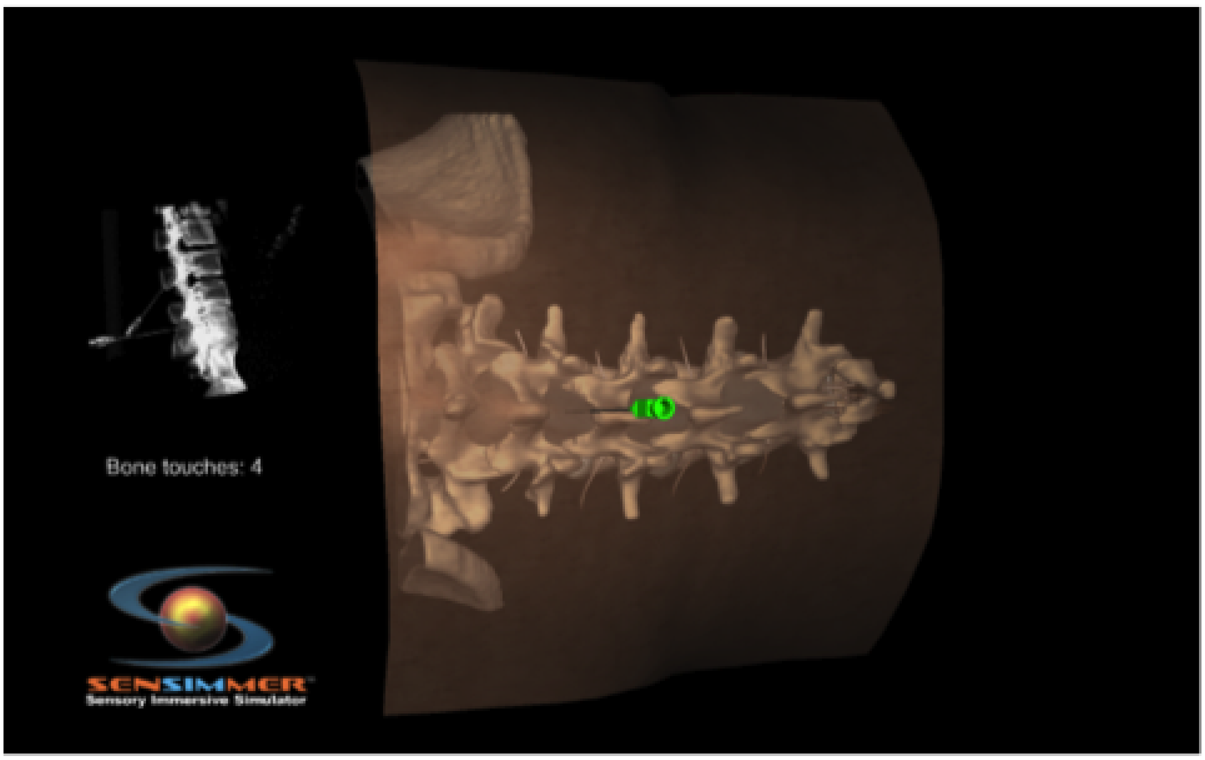

Figure 15. Screenshot of epidural module with correct needle placement

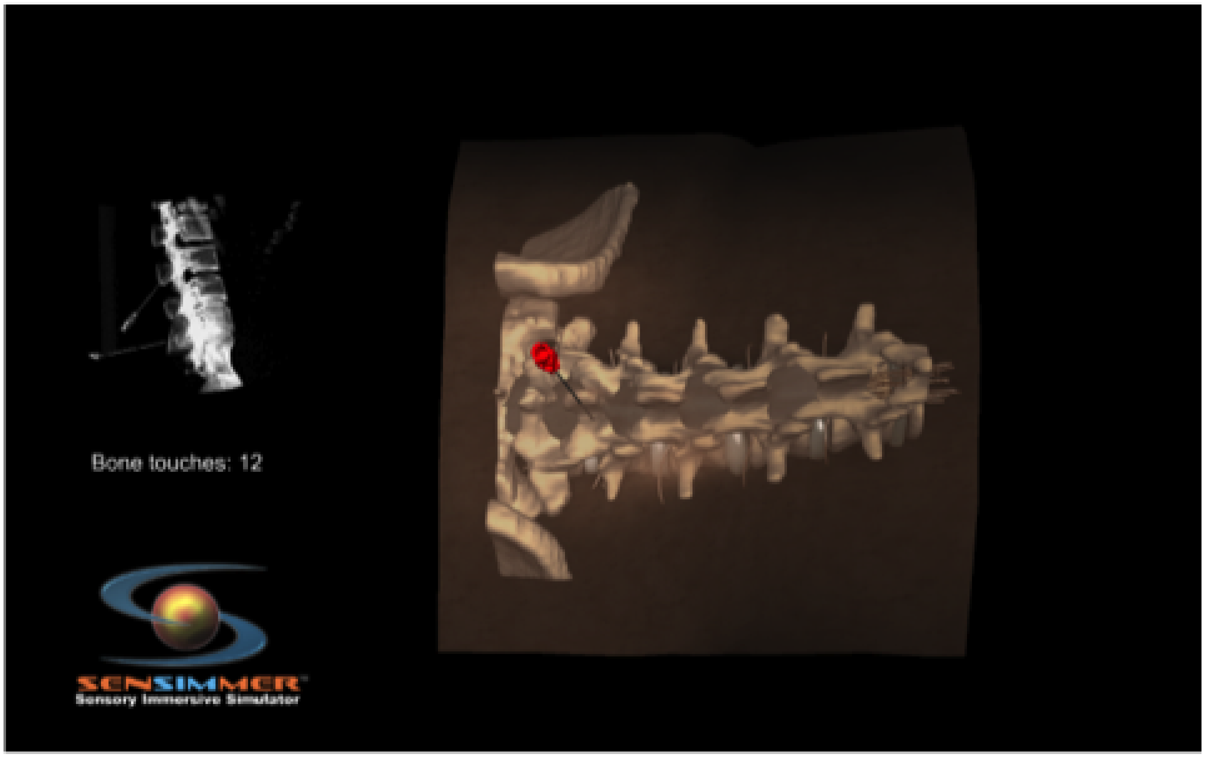

Figure 16. Screenshot of epidural module with incorrect needle placement

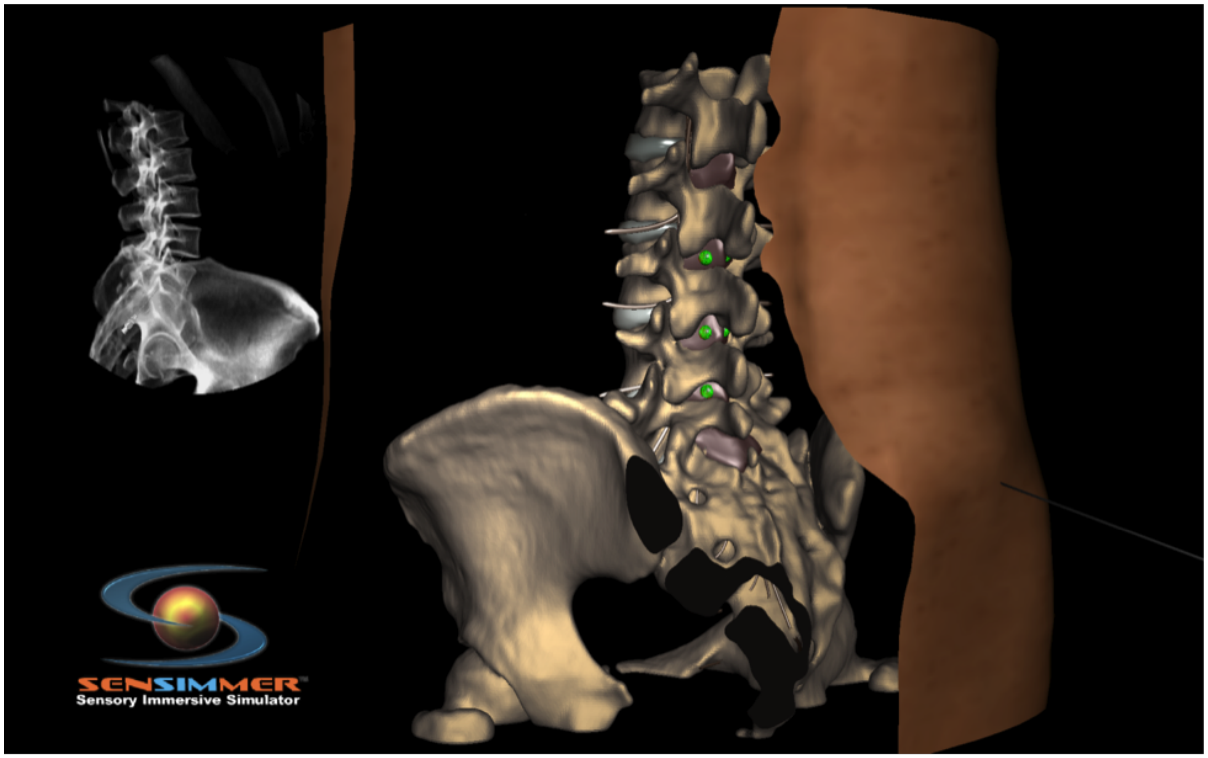

Figure 17. Screenshot of epidural module with cutting plane being used to investigate the anatomy

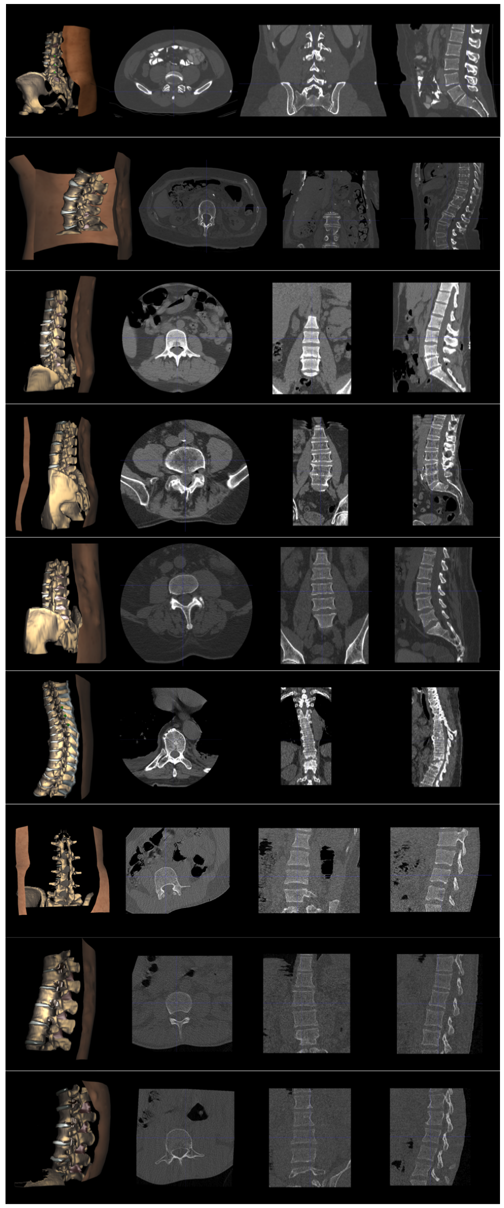

Figure 18. Example of spinal case library for use in spinal procedures with 3D rendering and original MRI slices

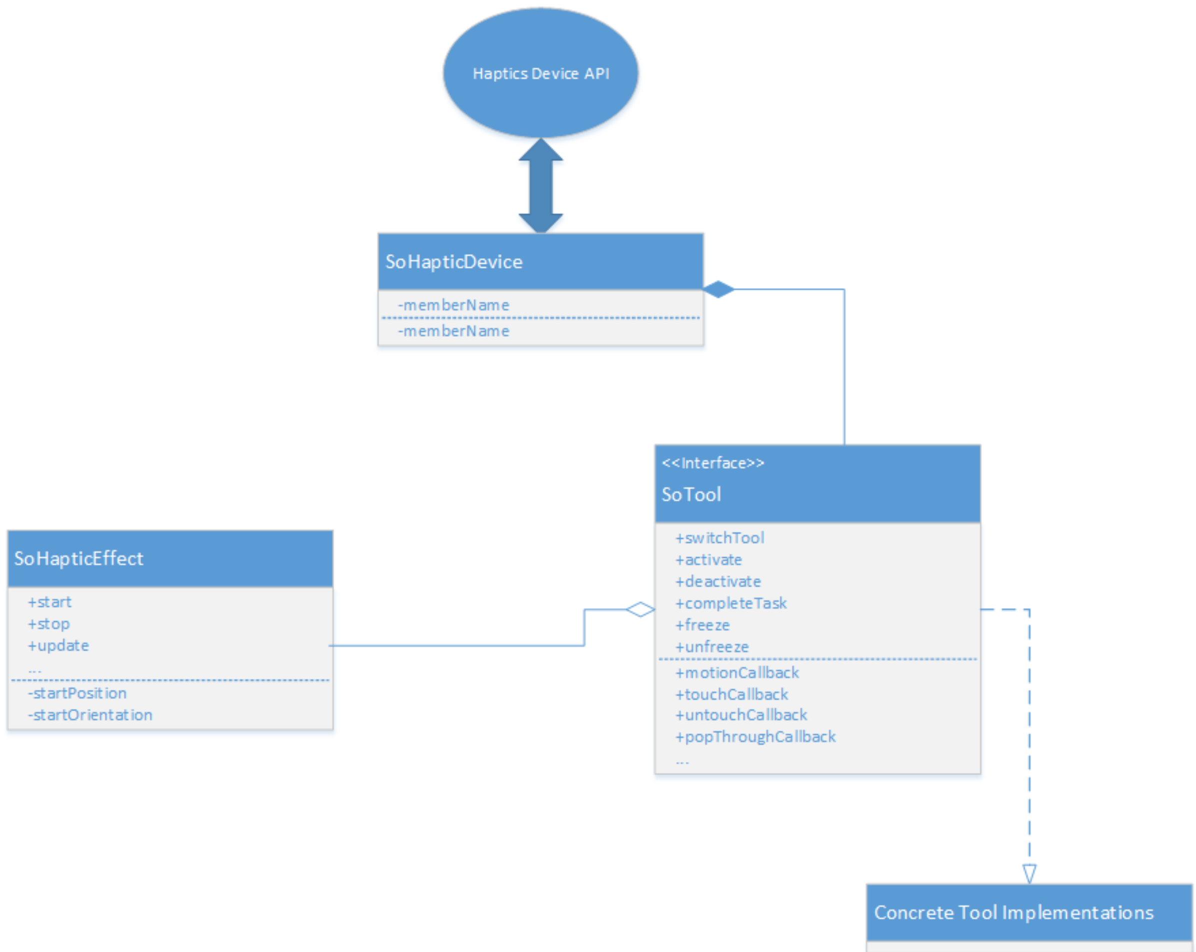

Figure 19. UML Diagram of relationship between SoTool and SoHapticDevice

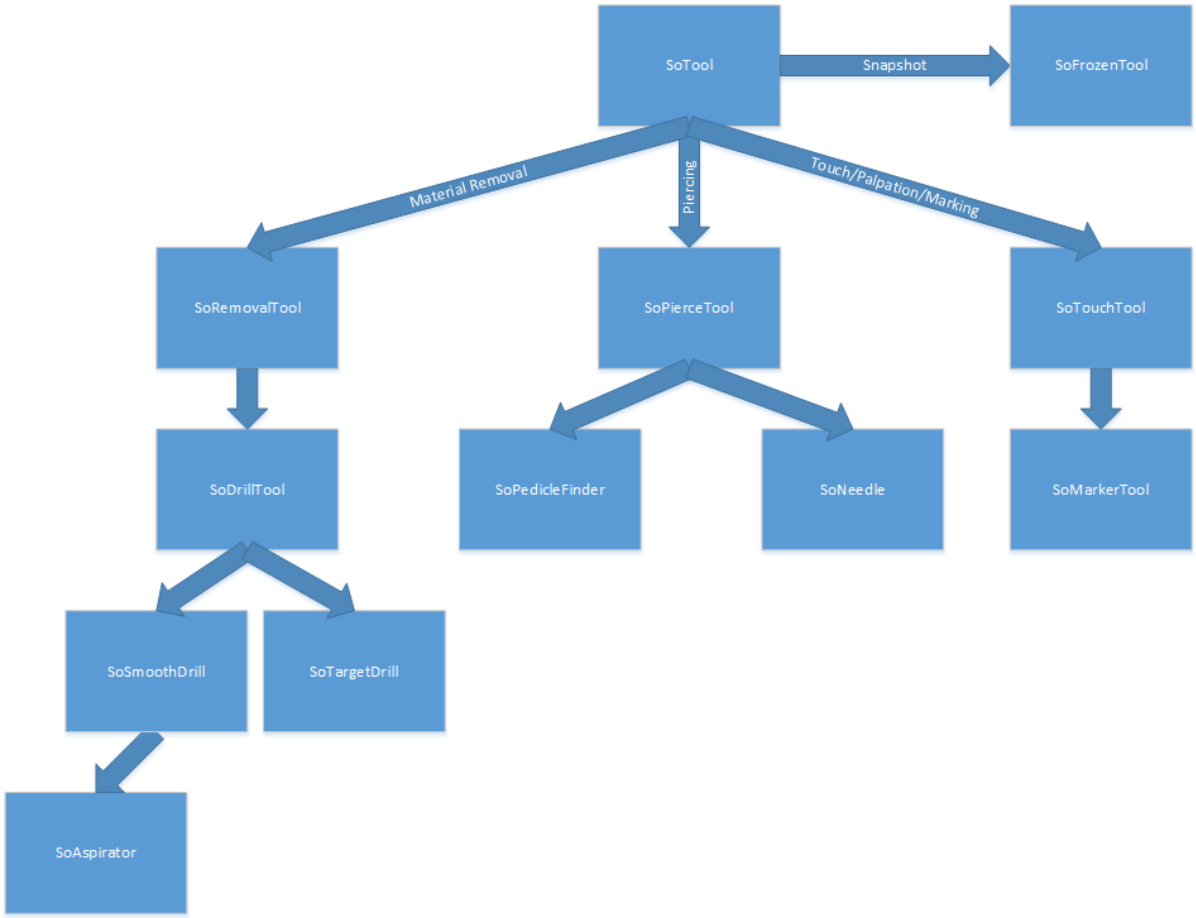

Figure 20. Haptic tool hierarchy

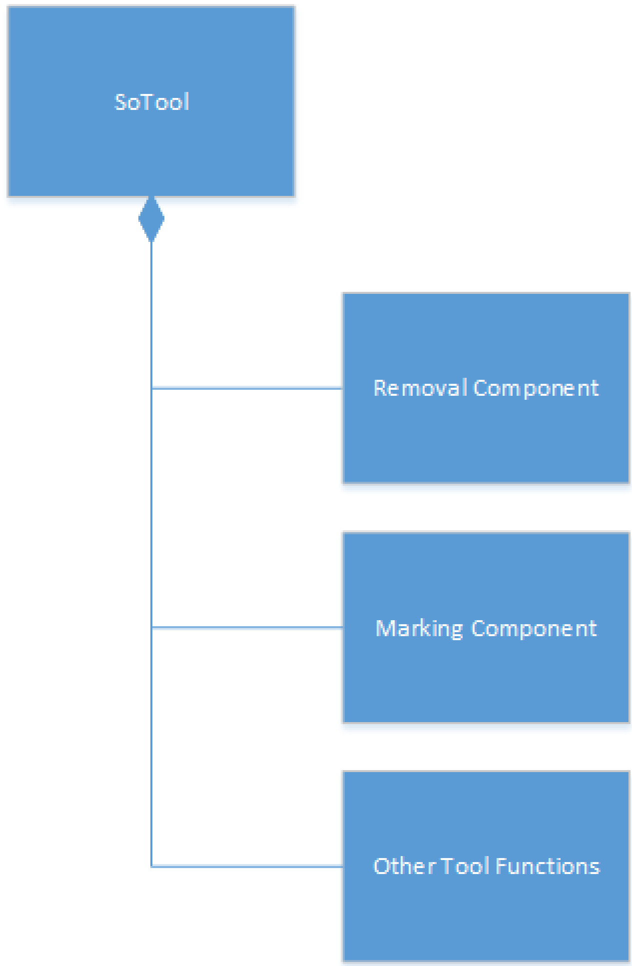

Figure 21. UML Diagram of Tool as Composition of Functions

3.4.3.1 Haptic Tool Library

When working on creating spinal procedures a common observation was a large duplication of source code, which contained minimal changes between situations other than logic for tools and effects. The haptic device classes were also created per simulation and started to grow quite large while trying to contain all of the tool logic. This prompted an exploration into modularizing the simulations into more object-oriented components that could be integrated into the Sensimmer SDK™. The first area explored was the modularization of tools in the simulation. A common interface called SoTool was created, this was integrated with the existing haptic device class to allow for a structure containing all of the tools for a certain simulation to be iterated through as needed. This also allowed for a common interface to switch, activate, deactivate, freeze, unfreeze, complete tasks, and other actions which can be completed by tools. A UML diagram of the relationship between SoTool, SoHapticDevice, and SoHapticEffect is shown in Figure 19 Initial design was completed as a tool hierarchy in which the majority of surgical tools were found to be a member of 3 distinct families of tools. The three families included tools for removal (drills, suction tools, etc), piercing tools, and tools for touching or marking. The tool hierarchy in the prototype implementation of the tool library is shown in Figure 20. Initially the tool library worked out very well, it allowed for quick creation of custom tools for new simulations in which only certain procedure logic needed to be changed, however, scalability started to grow as concern due to the quick growth of the tool hierarchy. The tool library was implemented in a number of modules, and was found to be successful in reducing complexity and allowing for modules to be more rapidly prototyped. However, other better solutions may exist for problems such as this. In the design, development, and use of the tool library, it was noted that a hierarchy of tools may not be the best design choice because problems such as multiple inheritance and tools falling into multiple classifications would add extra complexity. More recently in software composition has been favored over inheritance to create more dynamic relationships. Research into software engineering techniques in such fields as the gaming industry showed a change from inheritance to composition/modularization of components. For example the tool library could be re-imagined as containing components for removing material or marking objects as shown in Figure 21 These objects could be then added to a general tool object to create an object that both removes material and marks the surface. This would prevent the creation of deep inheritance hierarchies with the need to inherit all of the parents functions when only a subset of the features may be needed.

These types of design patterns would also open up the option of using scripting files to allow the behavior of tools to be changed without requiring the compilation of native code. In this way, new simulations could be rapidly prototyped by using scripting languages and existing components. If new components need to be created they would be programmed natively and then used on the scripting side. All of the higher level programming logic would be contained on the scripting side, such as objectives of the simulation, how it is to be scored, and how tools and meshes interact. The low level functions of graphics rendering, haptics rendering, and the physics engine would not need to change.

3.4.4 Future Work

The simulation has been created and optimized under the feedback of doctors from the University of Chicago. However, research still needs to be performed to examine if there is a positive benefit to practicing needle insertions on the simulator.

CHAPTER 4

SERIOUS GAMES

4.1 Introduction

In this chapter the serious game modules created for the ImmersiveTouch® will be introduced. Looking at Figure 1 we can again see the overall diagram of the ImmersiveTouch® system and the modules created. The serious games developed consist of Stereognosis and Spatial Memory and Orientation.

The Stereognosis module was created to train and evaluate the stereognosis abilities for neurosurgical residents and surgeons. The Spatial Memory and Orientation module was created to train and evaluate the spatial memory, orientation, and trajectory planning abilities of neurosurgical residents and surgeons in an abstract way that did not require previous medical knowledge. These modules along with their implementation details will be discussed in detail in the following sections.

4.2 Stereognosis

4.2.1 Background

Stereognosis is defined as the ability to perceive the form and properties of an object by using the sense of touch; it is a highly complex sensorimotor-perceptual skill, integrating information from both the kinaesthetic (proprioceptive) and the tactical (cutaneous) systems (45). This is an important skill for surgeons when visual feedback cannot be used. A stereognosis module was developed with the goal of creating a computer based haptic trainer to both evaluate and improve the stereognosis ability of neurosurgical residents and surgeons.

4.2.2 Simulation Objectives

The module consists of multiple levels with varying difficulties, which presented the user with three spheres of different tactile properties. The user is tasked with the goal of differentiating between spheres by detecting the softest sphere. When the user is correct, the program plays a positive reinforcement sound and then the next level begins, otherwise the user receives an unpleasant buzzing sound accompanied by the haptic stylus vibrating. To prevent users from using the process of elimination to guess the spheres, the spheres are shuffled after each incorrect attempt. The number of attempts for each level are tracked and used to calculate the users performance. As levels progress, the absolute difference between the spheres is reduced, increasing the difficulty of sphere differentiation.

4.2.3 Implementation Details

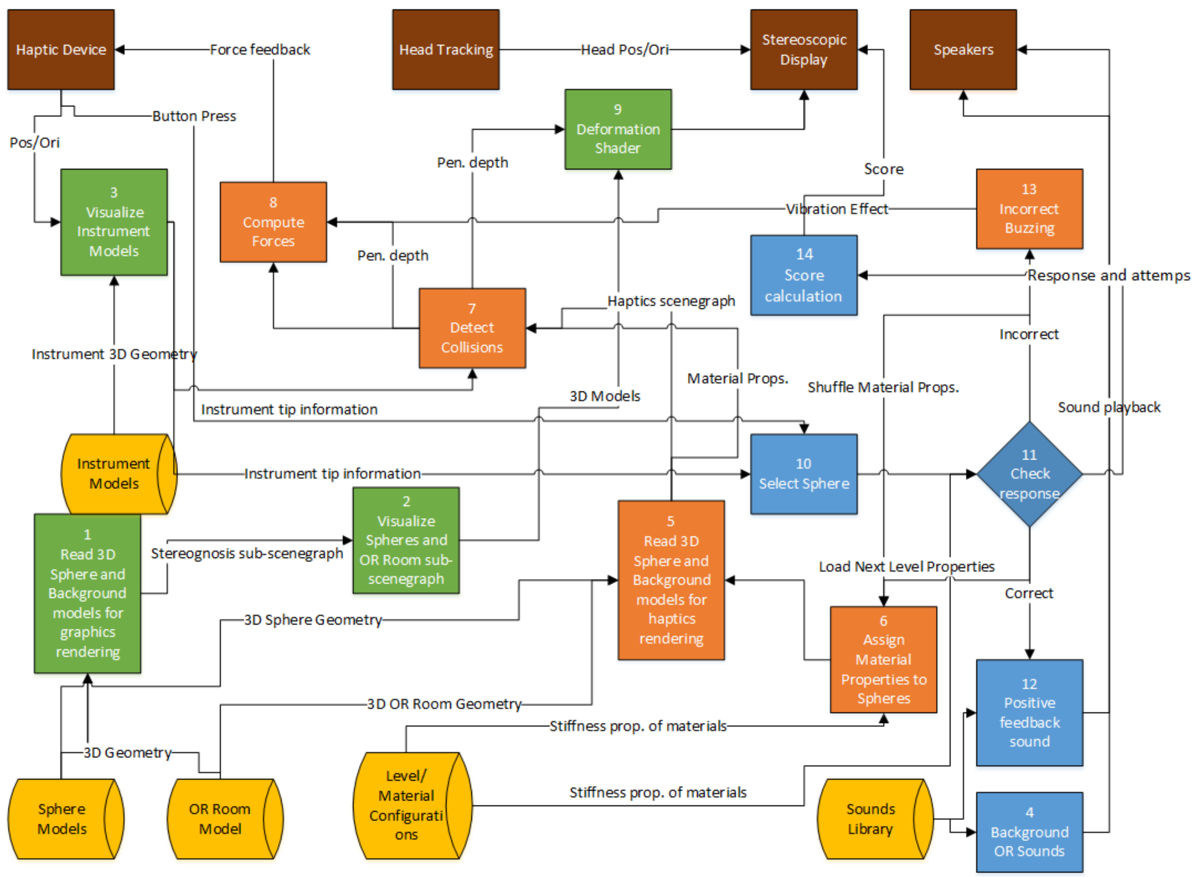

Figure 22. Overview of the implementation of the Stereognosis module

Read 3D Sphere and Background models for graphics rendering

This process reads the files that store 3D geometry and graphics materials for the spheres as well as the OR Room model which serves as the background of the module.

Visualize Spheres and OR Room sub-scenegraph

The sub-scenegraph containing all of the stereognosis nodes is added to the main scenography and rendered by Coin3D. Visual feedback consists of a virtual operating room model with three spheres of varying colors atop an operating table; a non-stereoscopic screenshot of the program upon initialization is shown in Figure 23.

Visualize instrument Modules

The sub-scenegraph containing the instrument nodes is added to the main scene graph and rendered by Coin3D. The virtual instruments that are collocated with the users haptic stylus' are a Malis bipolar and a Frazier suction tool, in the right and left hand, respectively.

Background OR Sounds

OR sounds are loaded as an ambient loop to help simulate the user as being in an operating room environment. This is also used to distract the user from the task at hand and is implemented to be used in future attentiveness studies.

Read 3D Sphere and Background models for haptics rendering

The sub-scenegraph containing the sphere nodes and OR table is added to the main scene graph and rendered by Coin3D.

Assign Material Properties to Spheres

A file containing the configuration for each level is read in and the spheres are randomly assigned a stiffness for the current level. In addition to assigning the haptic material properties, a random color is also assigned to the spheres for graphics rendering.

Detect Collisions

Please refer back to the OPSI module implementation section for details regarding the implementation of the collision detection sub-process.

Force Computation

Please refer back to the OPSI module implementation section for details regarding the implementation of force computation.

Deformation Shader

To further enhance the users realism of differentiating between object properties, GPU based elastic object deformation is used which provides visual feedback regarding sphere deformation at the contact point of the instruments(44); these visual cues may be turned off using a transparency value. This feature can be used to investigate the importance of visual cues in haptic perception; however this feature was not utilized in the reported studies.

Select Sphere

When the user is satisfied that they have found the softest sphere they can touch the instruments against the spheres and press the button on the haptic stylus.

Check response

The user's response is checked against the current sphere material values to see if the softest sphere is selected. If the correct sphere is selected then the user is played a positive feedback sound and the next level is loaded. If the incorrect sphere is selected then a negative feedback vibration effect is activated. The sphere materials properties are also rearranged to prevent the users from guessing by process of elimination.

Score calculation

The basic scoring algorithm used to evaluate the users' performance consisted of awarding 10 points for a correct answer on the first attempt, 5 points for a correct answer on the second attempt, and no points for subsequent attempts; the number of attempts for each level was also recorded.

4.2.4 Software

4.2.4.1 Tactile

As part of the development of this software module, updates to the Sensimmer SDK™ were required to allow for bimanual tool manipulation. Previous support for two haptic devices, available in Sensable's GHOST SDK, was broken in the updated version of the OpenHaptics toolkit. Many areas of the Sensimmer SDK™ were modified, including effect and cursor handling as well as initialization and cleanup. With these new updates to Sensimmer SDK™, custom haptic effects per tool were made possible, as well as allowing mesh effects to work on each tool independently.

4.2.4.2 Dual Haptics Support

Support for two haptics devices was broken when the Haptics SDK was switched from GHOST to OpenHaptics. Work was then started to refactor the Sensimmer SDK ™ to add support for two devices again. One of the main technical challenges was dealing with two or more

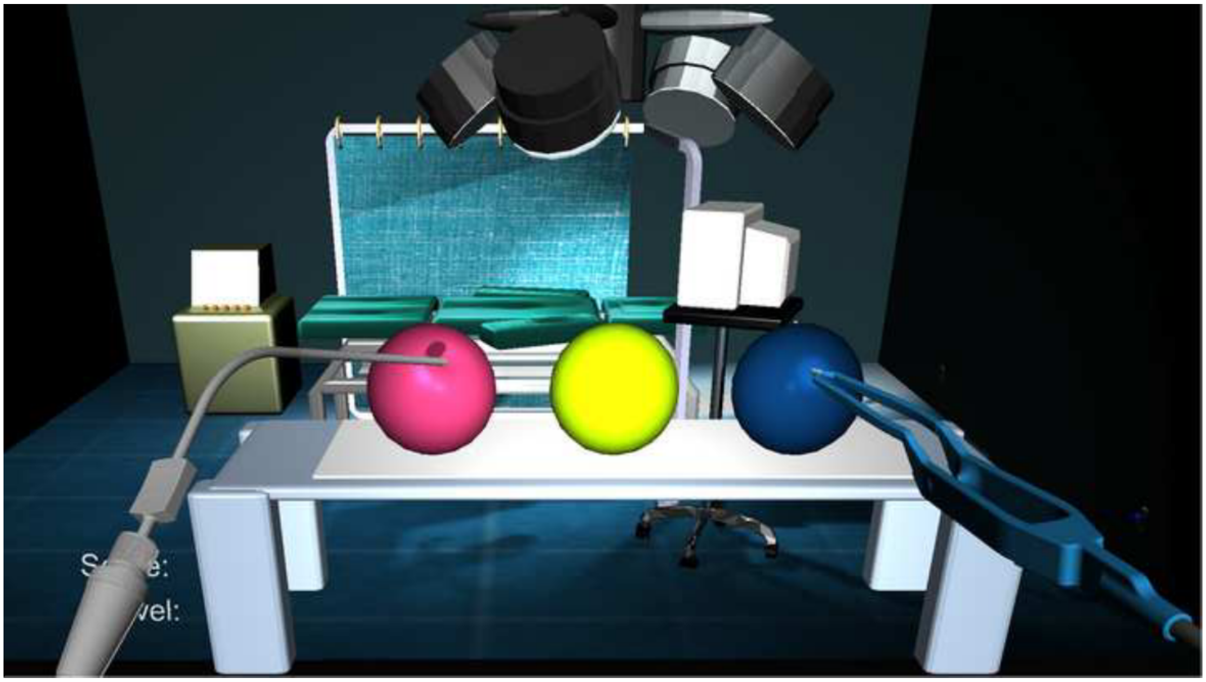

Figure 23. Tactile Training Module

device contexts. Each haptic device has a context in which haptics rendering is performed. This includes contact with 3D models and also calculation of special haptics effects. The diagram of the haptics context can be seen in Figure 24 in which we can see two haptic device contexts, this figure also shows the event system which will be explained in detail further on. Each haptic device creates a servo and collision thread. The servo thread handles direct communication with the haptics device, tasks which include getting the position and orientation information as well as sending the required forces to the device. This thread needs to run at approximately

1000 Hz for the haptics to be smooth due to the high sensitivity of human touch. The collision thread determines which geometry is in contact with the haptic device proxy. The collision thread only runs at 100 Hz, however the information from the collision thread is used to create local approximations of the shapes in contact which allows the servo thread to still function at high rates even with a large number of geometric primitives. Last the client application also has a client haptic thread, which interacts with the haptics API. This thread is useful for creating callbacks to button presses, or programming events such as popping through a mesh. Events and forces may occur in the incorrect context and therefore need to be routed to an event handling system to be queued for later activation in the correct context. This was accomplished with the use of queues and lambda functions which wrap function calls that were made in an incorrect context. This same architecture was also used to help facilitate changes to the physics engine which required manual changes to take place at a certain position in the physics engine pipeline.

In Figure 24 we can also see how the event queue relates to the whole haptic rendering system. Modifications to the haptic device classes were also necessary to facilitate the addition of per device effects and constant effects. This allows the simulation of gravity by adding a constant effect to the haptic devices. Initial implementation of gravity effects consist of a constant downward force, however in future iterations support for inertia and center of gravity would be useful additions for added realism.

The addition of multiple device contexts adds additional overhead to creating mesh effects. Since the mesh effects are children of the mesh object each haptic device has to make a reference to the effect object so that effects can be calculated for each device. Some effects such as line effects or spring effects require the use of initial position or orientation when the effect was started, for this reason some effects were modified to contain static arrays, which were indexed by the haptic device contexts. Currently only two devices are supported for some effects, however this implementation could be changed to use a hash map or vector so that there is not limit to how many devices a single effect can support other than any limitations imposed by the actual haptics SDK.

4.2.5 Procedure

In a study utilizing the stereognosis module, 20 medical students were equally and randomly distributed between a control and experimental group. The experimental group was trained on the stereognosis module consisting of 15 levels of difficulty, while the control group did not complete any training on the module. These groups were asked to identify six elastothane targets which were implanted in a urethane foam cavity meant to simulate a brain; these targets ranged from 1 to 3.5 cm^2 in size with 0.5 cm^2 increments. The tools provided to detect the targets were a bipolar and suction tool, similar to the tools utilized in the simulation. The density of the urethane foam used for the brain cavity was 0.1-0.13gm/cm^3 in comparison to the targets which were 1.1 g/cm^3. Other notable material properties include urethane foam with a rough and porous surface, as compared to the elastothane targets which had a smooth and rubbery surface. Students were allowed to identify the targets with their eyes open, however an opaque glass was used to obstruct their view and the study was performed in a dim environment. Each student was given a maximum of 15 attempts or 10 minutes, ending at whichever limit came first. The simulation objective was for students to identify and name the targets aloud to a proctor who recorded the results; no feedback was given during or after the exercise. After the conclusion of the study, students in the experimental group were asked to complete a survey about their stereoagnosis module simulator experience, remaining unaware of their performance and results. (93)

Another study, previously discussed, also utilized the use of the stereognosis module, as part of a suite of applications, to evaluate whether motor skill performance was normally distributed; 45 out of 55 neurosurgery residency applicants participated in this study, voluntarily. (16)

4.2.6 Results

73.3% of medical students in the experimental group were able to correctly identify where the targets were located, compared to 53.3% of students in the control group (p = 0.0183). The experimental group was also able to identify smaller targets (<2.5 cm^2) at a 72.5% success rate compared to the control group which was 40% (p = 0.0032). The experimental and control group scored 75% and 80% (p = 0.7747), respectively, when identifying objects greater than 3 cm^2, indicating no statistical significance.

The majority of survey feedback supported the idea that the stereognosis module is beneficial in improving hand-eye coordination, depth perception, and obstacle detection. Nine survey participants reported that the simulation was useful or very useful in improving hand-eye coordination, seven participants reported the simulation was useful in improving depth perception, and six participants reported that the simulation was useful for improving obstacle detection.

Data analysis may lead to the conclusion that objects greater than 3 cm^2 could easily be identified by both groups, explaining the minimal difference in detection rate. The survey feedback also showed that only 60% of the participants in the experimental group believed that the stereoagnosis module improved their ability to detect obstacles; this may be explained by the fact that no feedback was given to participants, making them unaware of their performance and results. (93)

In the study evaluating neurosurgery residents, data analysis indicated the presence of a bell curve distribution when analyzing the level of difficulty reached in the application. It was observed that four participants could not even reach beyond level 1, and there was a large variability observed between the number of individuals that completed 10 versus 11 levels. There was initial concern that difficulty levels were not aligned optimally, however, performing regression analysis comparing the average number of attempts per level and the level, showed that the difficulty gradually increased($R^2 = 0.6281$). (16)

4.2.7 Future work

The success of the stereognosis module warrants further research in training and evaluating the tactile differentiation abilities of individuals from multiple expertise levels, such as residents to seasoned neurosurgeons. To our knowledge, there is no other existing work researching how tactile abilities in neurosurgery can be developed. The benefit of using a virtual simulator is that the scenario and environment can be carefully controlled to allow researchers to isolate the experimental variables. The program logic and scoring algorithms are also guaranteed to be objective, allowing results to remain consistent and unbiased when compared to methods in which feedback from an instructor is necessary for evaluation. While the module is currently abstract due to the fact that the spheres are not representative of medical objects, eventually a simulation in which surgeons actually have to detect target tissue in a cavity could be created. For our research involving residents and residency candidates, we felt that abstracting the concepts for stereognosis was beneficial in simplifying the objective.

Using applications such as the stereoagnosis module can lead to interesting research scenarios in which the effects of a surgeons performances versus fatigue, noise in the environment, and other factors relevant to the operating room can be investigated. These type of research questions may aid in establishing methods to improve a surgeons skills or may help create evidence to support the creation of new regulations if a surgeons performance is found to be detrimentally affected by fatigue to the point where a patient's safety may be in danger. Other occupational hazards such as vibrating tools or the use of two surgical gloves can examined using the stereognosis module as a way to determine how these variables affect a surgeons tactile discrimination.

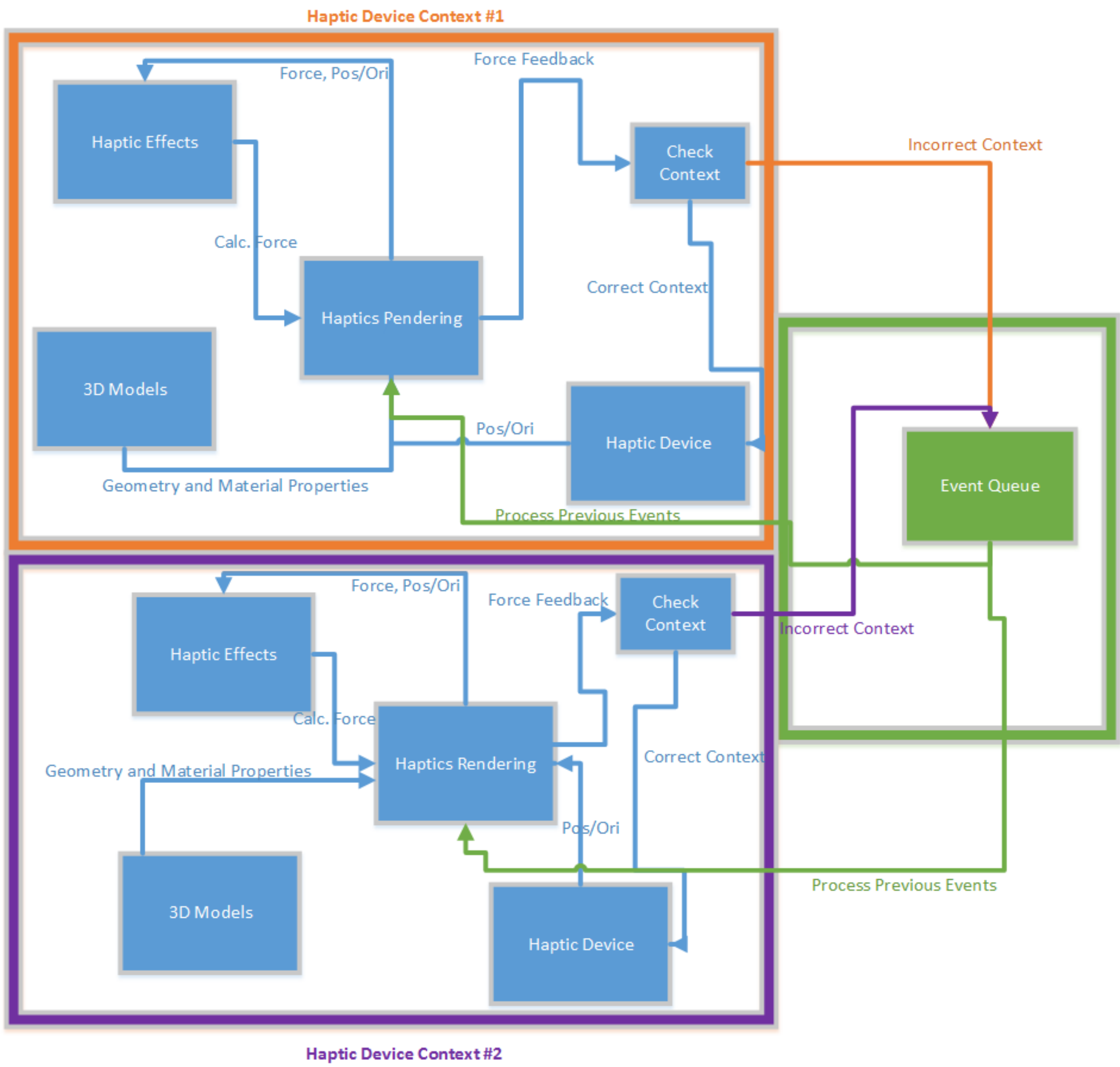

Figure 24. Haptics Rendering System

4.3 Spatial Memory and Orientation

4.3.1 Background

Spatial orientation and 3D memory are important skills for surgeons due the growing use of 2D and 3D medical imaging technologies in the operating room, in addition to use of anatomical knowledge in determining the best approach. The goal of the creation of the Spatial Memory and Orientation module was to examine the skills of users by allowing them to plan and execute a trajectory in three dimensions from memory. In addition to testing spatial memory and orientation, other independent factors were also involved when completing this module which include hand tremor and dexterity. A requirement in creating the spatial memory and orientation module was to test these abilities in a more abstract way that does not require knowledge of a certain medical procedure or anatomy. This allows the module to be used by incoming residents, regardless of their anatomical or medical procedure knowledge.

4.3.2 Implementation Details

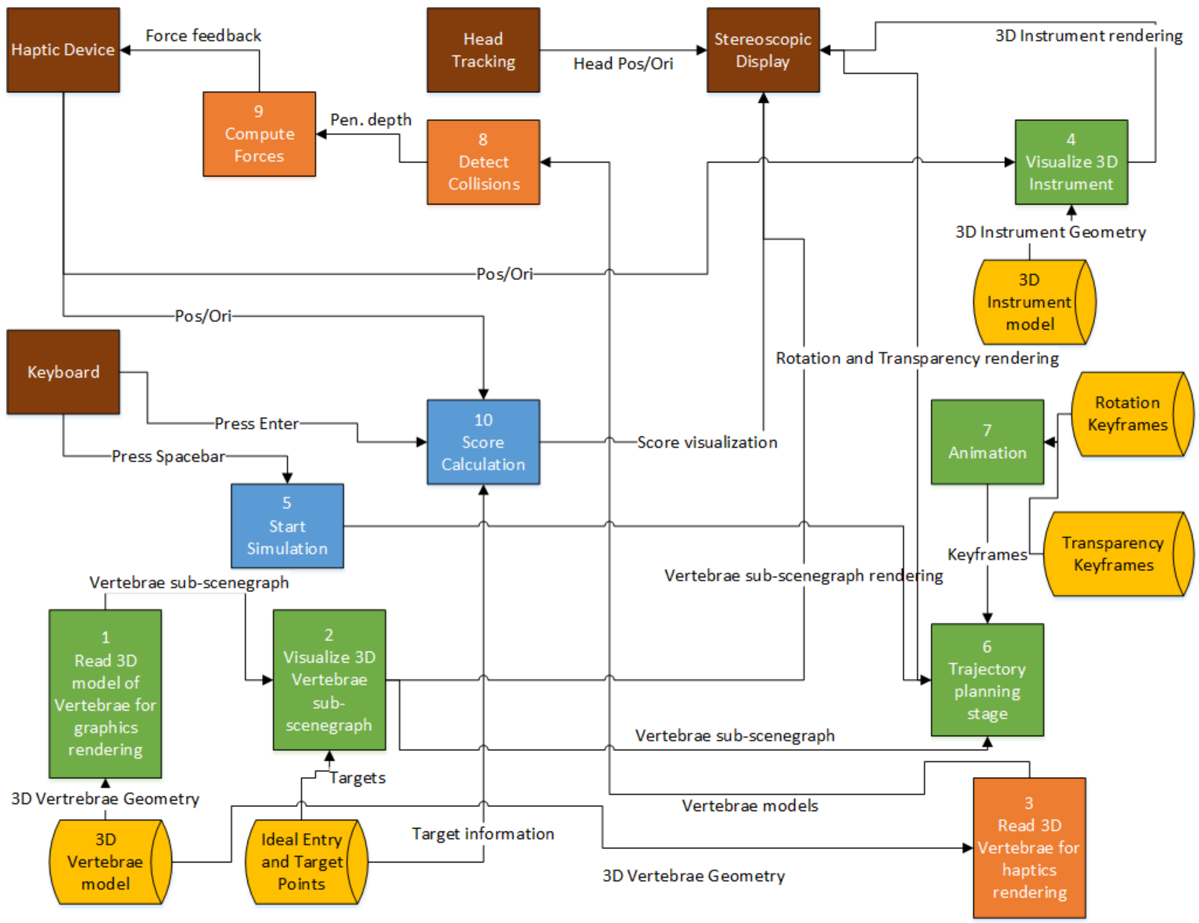

Figure 25. Overview of the implementation of the Spatial Memory and Orientation module

Read 3D model of Vertebrae for graphics rendering

This process reads the files that store 3D geometry and graphics materials for the vertebrae. The materials are loaded as OpenInventor nodes.

Visualize 3D Vertebrae

The sub-scenegraph containing the vertebrae is added to the main scenography and rendered by Coin3D.

Read 3D Vertebrae for haptics rendering

The 3D geometry of the vertebrae is added to the haptics scenegraph to be rendered by OpenHaptics as described in the OSPI implementation section.

Visualize instrument

The sub-scenegraph containing the instrument node is added to the main scene graph and rendered by Coin3D. The virtual instrument that is collocated with the users haptic stylus' is a drill.

Trajectory planning stage

The user starts the simulation by pressing the Spacebar. At this point the vertebrae's material properties are set to a semi-transparent value and the spheres which represent as the ideal target and entry points are made visible. The trajectory planning stage also includes an animation of the vertebrae spinning an adjustable number of rotations while slowly changing in its material's transparency value. The animation is performed by using pre-calculated rotation and transparency keyframes through which a position and color interpolator iterates through.

Detect Collisions

Please refer back to the OPSI module implementation section for details regarding the implementation of the collision detection sub-process.

Force Computation

Please refer back to the OPSI module implementation section for details regarding the implementation of force computation.

Score Calculation

When the user is confident in their insertion they can press the Enter key and they are provided a score which measures the euclidean distance between the tip and the target and the euclidean distance between the actual entry point and the ideal entry point. Meaning that a score of zero indicates a perfect score.

4.3.3 Software

The module presents the user with minimal anatomy, consisting of of a single vertebrae, with the ideal entry point indicated with a green sphere. The goal of the module is for the user to memorize the trajectory and then correctly insert a pedicle tap as close as possible to the entry and end targets. The module begins with a segment during which the vertebrae is presented as a semitransparent object both with a green sphere at the ideal entry point, and a red sphere at the target point. The vertebrae is then rotated for 10 seconds going through a complete 360rotation, eventually becoming fully opaque near the end of the rotation. This period of rotation is the period during which the user is tasked to orient themselves and memorize the target trajectory.

The primary instrument used during the module is a pedicle tap which is inserted into the vertebrae at the requested trajectory. The main challenge in the creation of this module was scripting the events occurring in the simulator, which included the vertebrae going through a rotation and changing the transparency. In the prototype implementation nodes of interest in the scene graph were searched for and saved as references, this included the transform and shaders used for positioning and drawing the vertebrae. Through the use of interpolators, rotation and a time based function of vertebrae transparency were created. During the initial development of the modularization of the tool library described earlier it also became apparent that events in the simulation may also have a place as specialized classes. The rotation and transparency of the vertebrae were then implemented as a specialized class of separator which would contain all of the logic to perform the actions of rotation and transparency changes. This becomes a building block to basic animation libraries, such as the pedicle screw animation which was also created with interpolators. This also represented a start to the creation of other classes which may eventually be used in scripts to orchestrate the actions that occur in a surgery. These scripts could eventually be used to randomize complications that occur during the course of a module to help test the knowledge of residents in emergency scenarios.

Figure 26. Screenshot of spatial memory and orientation module while vertebrae is semi-transparent and rotating

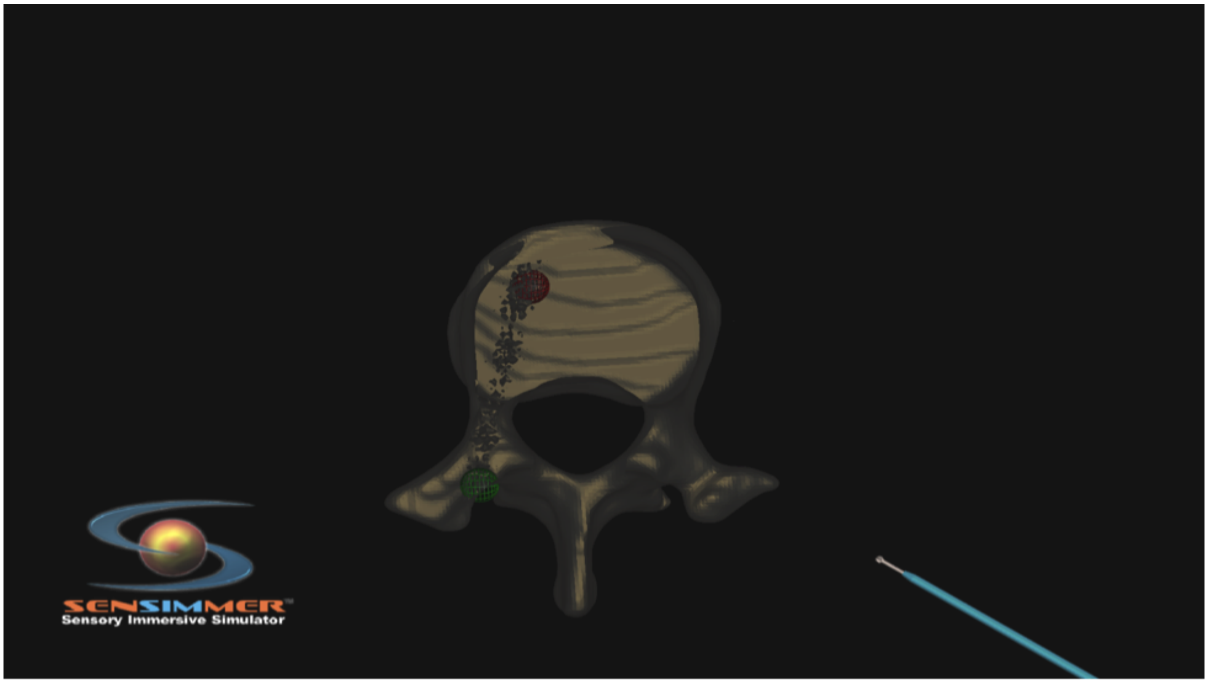

Figure 27. Screenshot of spatial memory and orientation module showing trajectory taken by the instrument

4.3.4 Results

The spatial memory and orientation module was one of three applications used in the previously mentioned study of 55 applicants to a neurosurgery residency. 36 out of the 55 applicants, performed the Spatial Memory and Orientation task referred to as "Trajectory Planning".

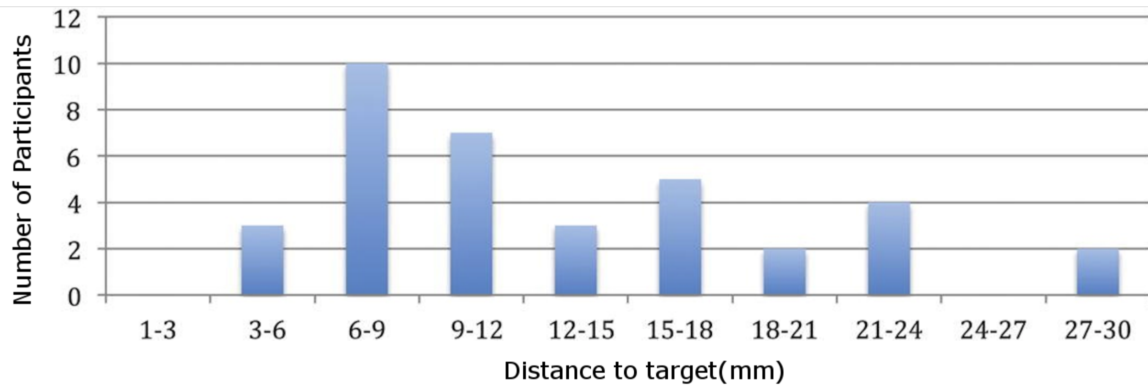

Figure 28. Spatial Memory and Orientation results (16)

The X-axis shows results for the distance to the target in millimeters. The Y-axis shows the number of participants in that score range.

In Figure 28 the spatial memory and orientation scoring roughly follows a normal distribution, with 25 out of 36 participants scoring within the 6 to 18 millimeter range and forming the center of the normal distribution, while the rest of the participants were outliers on the tail sections.

While tools that aid in training spatial memory and orientation exist, most of this software consists of 3D objects rendered on a 2D screen. The spatial memory and orientation module is one of the first augmented virtual reality evaluations of a person's spatial memory and orientation, utilizing haptics for tactile feedback. This 3D workspace provides an objective assessment of the participants' taken trajectory, and would not be possible without virtual reality simulators. Investigating the relationship between manual motor skills and spatial memory would not be possible without touch feedback which creates an immersive experience. This module therefore shows a novel use of the ImmersiveTouch® simulator to study spatial memory and orientation that is objective and easily reproducible. This would not be possible using manikins or any other traditional technologies, presenting the utility that virtual reality can provide to research.

4.3.5 Future Work

As part of future enhancements to the module, advanced statistics could be computed utilizing data recorded from the users exact trajectory, path deviations, movement accelerations and other information with regards to how the objective is approached. Removing any indications of a medical objective may be beneficial to create an abstract objective in which the spatial memory and orientation skills could be tested in different populations such as trained surgeons, residents, medical students, and the general population. Tools such as the ImmersiveTouch® platform could also be used to study how spatial memory and orientation abilities develop in children, or how they deteriorate in individuals with neurological disorders.

The use of video games to research the performance effects on tasks such as laparoscopic, endovascular, and endoscopic techniques has been previously studied, however, these studies mostly involve games in which users move around a 3D space on a 2D screen. Most studies noted a correlation between initial performance that became insignificant as the complexity of the task increased. Studies suggest that this link is causal and not due to the inclination of individuals with natural visuospatial skills to both enjoy playing video games and be proficient at surgery. (46)

Future research could be performed in determining how tasks in a virtual 3D space with perspective tracking and haptics compare to training on traditional video games on a 2D screen with regards to an individuals performance increase in motor skills. For individuals with no traditional video game experience it may be more intuitive to map their movements in a fully 3D environment and similar or better increases in performance may be observed when compared to the performance gains from traditional video games. Investigating these links may prove useful in developing the next array of tests and modules to evaluate and develop ones general sensory-motor and cognitive abilities.

CHAPTER 5

CONCLUSION

This thesis presents a broad spectrum of modules designed for the ImmersiveTouch® Simulator using the Sensimmer SDK™ with the objective of quantitatively evaluating both motor-sensory skills and cognitive abilities, and also simulating clinical procedures in an attempt to improve clinical performance using haptics and augmented reality. Several of the modules were also utilized in studies consisting of motor-sensory skills testing, as well as evaluation of a residents performance in a clinical procedure. These studies showcased how the ImmersiveTouch® Simulator could be used as both a training and research platform as well as providing ideas for interesting research questions. Even though the ImmersiveTouch® Simulator was mainly designed to be used for medical applications, it is clearly also a viable research tool in many areas including sensory-motors areas such as stereognosis, dexterity, and spatial visualization. The combination of augmented virtual reality as well as sensations of perspective and touch allow the ImmersiveTouch® Simulator to serve as a truly immersive platform. Currently developed modules have only scratched the surface of possible software developed for this platform in both medical applications as well as applications in other fields.

5.1 Future Work

As previously discussed, virtual reality simulation is poised to eventually become a standardized platform in which we can objectively evaluate future successes both of residency candidates as wells as residency graduates. It is also important to mention the role which virtual reality may have in helping improve the quality of medical education while reducing patient risk. These modules serve as a technical demonstration of the ability to develop a wide range of procedures for the ImmersiveTouch® Simulator to be used both in resident training, evaluation, and research studies. All facets of the technology have room to improve; levels of immersion and realism will improve as well as techniques for automating the process of preparing patient data for simulators. While medical education and research clearly stand to gain from the use of virtual reality simulators, another often mentioned "holy grail" of medical virtual reality simulations is the possibility to rehearse a procedure using actual patient data before working on the real patient. Rehearsing procedures may help even highly skilled surgeons to better plan their approach and determine possible complications.

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Education *Bachelor of Science – Bioengineering; Minor in Mathematics*
University of Illinois at Chicago, Illinois, 2011

Master of Science – Industrial Engineering
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Professional Experience

6/13-Present **Kranze Technology Solutions**, Prospect Heights, IL
Software Engineer

- Lead developer on multiple projects
- Development of testing tools and simulators for avionics bus
- Development of PLC software for Motion Table and Gantry and corresponding client side control architecture
- Development of infrared countermeasures system integration lab
- Secure Networking for Digital Interoperability
- RFID for Tactical Operations

10/11-6/13 **ImmersiveTouch**, Chicago, IL
Software Developer

- Development of augmented reality surgical simulations with haptic feedback
- Lead developer on multiple projects
- Development of updates to Sensimmer API(including implementation of Dual Haptics)
- Technical demonstrations to medical personnel

5/10-12/11 **K-Plus Computer Services,** Chicago, IL
IT Consultant

- IT Support for multiple Small-Medium Businesses
- Microsoft Server, Active Directory, MS Exchange, Symantec Backup Exec
- Network Security (Cisco/Sonicwall Firewalls)
- Server Virtualization (VMware ESXi)

5/11-8/11 **Iowa State University,** Ames, IA
REU Student Researcher

- Performed chemical synthesis and analysis of Quantum Dots
- Trained in use of Spectrophotometer and Fluorometer
- Trained in basic lab safety, use of Bio-Hood, and Glovebox
- Performed data analysis and experiments independently

Honors Graduated B.S. Magna Cum Laude
Sara Smith Wilson Scholarship
Steven J. Hampton Merit Scholarship
Caterpillar Scholar Award

Teaching

2010 **Honors College,** Chicago, IL
Tutor
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Professional Memberships

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UIC Honors College

Journal Publications

Jaime Gasco, Achal Patel, Juan Ortega-Barnett, Daniel Branch, Sohum Desai, Yong Fan Kuo, Cristian Luciano, Silvio Rizzi, Patrick Kania, Martin Matuyauskas, Pat Banerjee, and Ben Z. Roitberg. *"Virtual reality spine surgery simulation: an empirical study of its usefulness."* Neurological Research. 2014

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Conference Publications

Dan Branch, Juan R. Ortega-Barnett, Yong-Fan Kuo, Thomas Jefferson Holbrook, Achal Patel, Sohum K. Desai, Adrian Mzee Smith, Cristian Luciano, Silvio Rizzi, Patrick Kania, Martin Matulyauskas, P. Pat Banerjee, Ben Z. Roitberg, Jaime Gasco-Tamarit, "*Virtual Reality Spine Surgery Simulation: An Empirical Study of its Impact on Technical Performance",* Congress of Neurological Surgeons Annual Meeting, San Francisco, California, October 2013

Thomas Jefferson Holbrook, Nick Koshy, Juan R. Ortega-Barnett, Hoi Chan, Yong-Fan Kuo, Achal Patel, Sohum K. Desai, Dan Branch, Adrian Mzee Smith, Cristian Luciano, Silvio Rizzi, Martin Matulyauskas, Patrick Kania, P. Pat Banerjee, Ben Z. Roitberg, Jaime Gasco-Tamarit, "*Neurosurgical Tactile Discrimination Training with Haptic-based Virtual Reality Simulation*", Congress of Neurological Surgeons Annual Meeting, San Francisco, California, October 2013