Radiosurgery/Biology Laboratory

Design and Construction of a Mixed-Reality Lumbar Puncture Simulator

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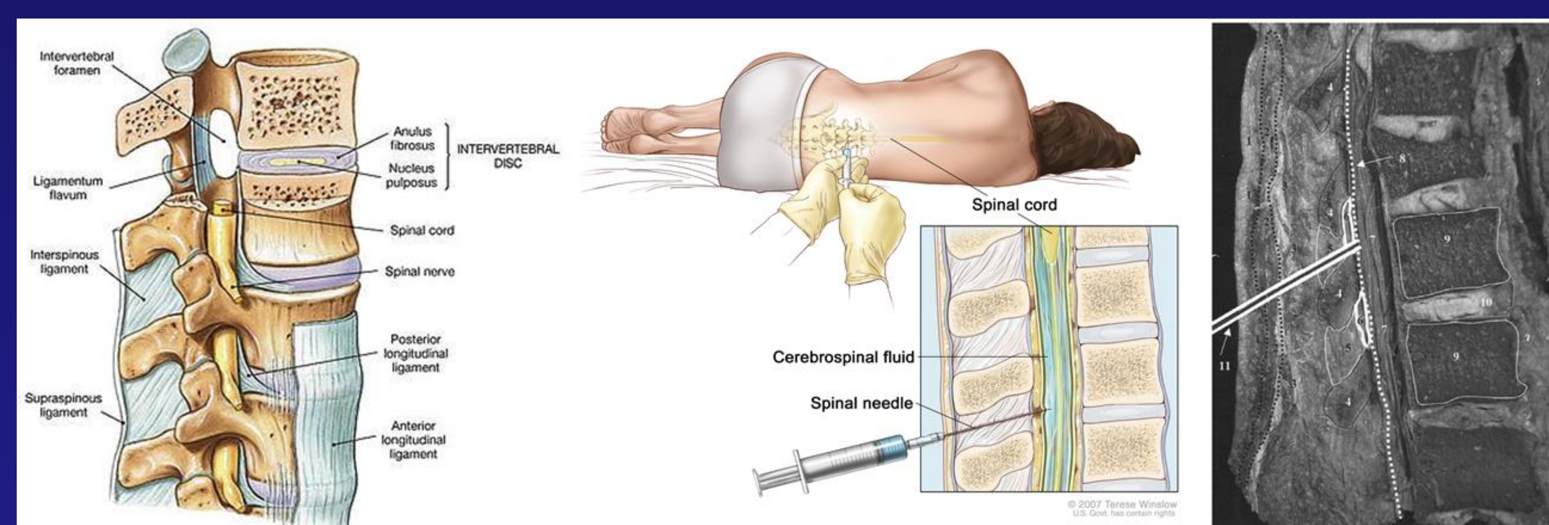
Introduction

In the past two decades alone, simulation training in the health care field has grown exponentially. Simulation-based medical education offers numerous advantages that can change the scope of medical education. The advantages include creating a safe, controlled learning environment, increasing the level of proficiency of performing a specific task, and bridging the gap between traditional and clinical education methods. Historic simulators were created to provide realistic patient feedback, to perform a specific task, or to prompt different clinical cases. Mixed-reality simulation was created at the Radiosurgery and Biology (RSB) lab at the University of Florida (UF). It combines historically created simulators to provide a unique environment with realistic haptic and visual cues that are critical to support decision-making skills necessary for real-world scenarios. A 3-D, patient-specific physical model is created and then connected to a virtual reality platform. The virtual reality platform consists of an image-guided workstation (IGW), a virtual fluoroscopy model, and electromagnetic (EM) tracking system. The 3-D model allows the user to receive the proper tactile feedback while performing the task at hand and the virtual reality platform aids in visual feedback as well as practice with imaging techniques.

In the past, mixed-reality simulators created in the RSB lab have been created for more complex tasks, such as ventriculostomy and treatment of trigeminal neuralgia, that residents and practicing physicians would utilize. This study focuses on the design and construction of a mixed-reality lumbar puncture (LP) simulator that is readily available for medical students. Targeting medical students early in their career will enable them to reach the confidence level needed to perform LPs on their own in real-life scenarios. Realistic haptic and visual cues, practice with imaging techniques, and a scoring rubric for feedback make the mixed-reality platform an all encompassing tool needed to enhance medical education.

The anatomy of the spine is extremely detailed, for the scope of this study only relevant adult anatomy of the lumbar spine was studied (Figure 1.A). For a successfully LP patient positioning plays a crucial role in establishing the correct needle insertion point and patient comfort (Figure 1.B). The proper trajectory of the needle shown in Figure 1.C is needed to correctly place the needle into the subarachnoid space to extract cerebrospinal fluid (CSF) for testing.



A B C

Figure 1. Lumbar Puncture. A) Relevant anatomy. B) Patient positioning. C) Needle trajectory.

Materials and Methods

Anatomic Target Model: The mixed-reality LP simulator combines a 3-D, patient-specific physical model with a virtual reality platform. To create the 3-D, patient-specific physical model, a patient's computed tomography (CT) and fused magnetic resonance imaging (MRI) scan of the lumbar spine including L3, L4, and L5 vertebral bodies, intervertebral discs, sacrum and hip bones was identified. The initial patient did not present any anatomical deformities. The CT scan of the patient was used to contour the structures of interest needed to produce the 3-D, patient-specific model. The structures of interest included the lumbar vertebral bodies (L3, L4, L5), the intervertebral discs, the sacrum, and the hip bones. The patient's fused MRI scan was used to visually evaluate the supraspinous and interspinous ligaments and the dura mater. The contours were exported to our in-house modeling software to create a solid rendered model shown in Figure 2.A. The solid rendered lumbar spine model was printed using a 3-D printer at the Nanoscale Research Facility at UF (Figure 2.B). This 3-D printer is capable of printing multiple materials in a single print job. A hard plastic was used to print the bony structures, shore D hardness 85, while a soft deformable rubber material, shore A hardness 26, was used to print the intervertebral discs. Next, several different materials for the skin, ligaments, dura, and torso phantom were evaluated. Once identified all materials were assembled into a single unit. The hip bones were secured to the lumbar spine model using nylon screws and the supraspinous ligament material was attached to the tip of the spinous process of each vertebral body. The completed anatomic target model is shown in Figure 3. A skin layer was then created by adjusting the fixture of a silicone rubber compound and a flesh-tone pigment was added to make it look realistic, the final skin layer is shown in Figure 4.

A B

Figure 2. Lumbar spine model. A) Solid rendered model. B) 3-D printed lumbar spine model.

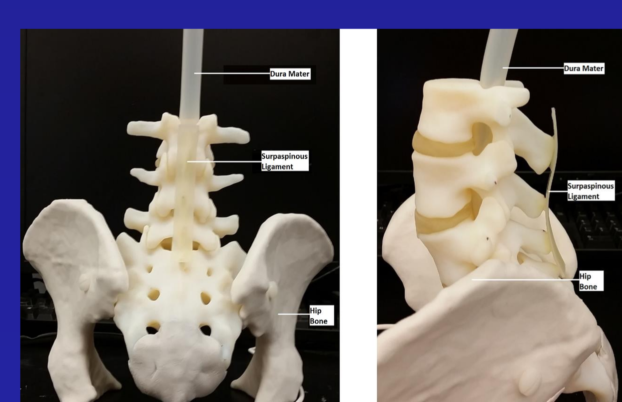


Figure 3. Lumbar spine model with hip bones, ligaments, and dura mater materials attached.

Figure 4. Silicone skin layer

The torso shell shown in Figure 5 was created using the patient's CT to create a contour of the outer body of the patient. The contour was sent to our in-house modeling software to create a solid rendered model and then printed using our 3-D printer. The lumbar spine model was registered to the virtual reality platform using an EM tracking system. An EM sensor was attached to the lumbar spine model so that the virtual reality platform can track the relative positions of the physical model to the virtual x-ray generator. A second sensor was placed inside the needle to track the needle motion. The virtual fluoroscopic images are generated by digitally reconstructing the patient's CT scan into x-ray projections in all directions. Then, as the relationship between the physical model and the virtual fluoroscopy unit changes, the computer selects which x-ray projection is closest to the current configuration. The position of the needle is also recorded and superimposed on the x-ray projection to provide the illusion of its presence within the spine. The virtual fluoroscopic unit allows the user to use common features such as image contrast, spin, and rotation that are available on fluoroscopy units. Figure 6 shows zoomed in images of the virtual fluoroscopy unit and of a virtual fluoroscopic snapshot mimicking the lumbar spine model and needle position. The platform also has the relative position of both target and normal structures. The virtual reality platform enables us to provide the user with feedback metrics to help the user establish correct trajectory or positioning as well as feedback on potential damage to normal structures. For example, when the user punctures the needle through the dura mater the user is notified by an audible signal. While this model can be used to help the student understand the basic anatomy it does not provide the full experience. To more explicitly simulate the procedure the lumbar spine model is positioned inside the torso shell described above. Ballistic gel was melted, dyed using a flesh-tone pigment to match the skin layer, and poured into the shell. The gel was left to cool and the shell was removed exposing the torso phantom shown in Figure 8.

Figure 5. Solid rendered torso shell (top) and 3-D printed torso shell (bottom).

Figure 6. Zoomed in images of the virtual fluoroscopy unit and a virtual fluoroscopic snap shot mimicking the positioning and needle trajectory of the lumbar spine model.

Figure 8. Torso phantom made out of ballistic gel.

Results and Discussion

Validation testing was conducted on the LP mixed-reality simulator to assure proper registration and functions were working adequately. The initial validation was performed with the assistance of several neurosurgery residents who routinely perform LPs. The testing focused on needle positioning. The EM tracking system was used to connect the sensors from the spine model and needle to the IGW. Trial LPs were performed using the needle instrument. Figure 9 shows a virtual fluoroscopy snapshot of the needle approaching the L4-L5 interspace of the physical model. Figure 10 shows the IGW with transaxial, sagittal, coronal, and fluoroscopic views that can be used to assure needle positioning is correct in the physical model.

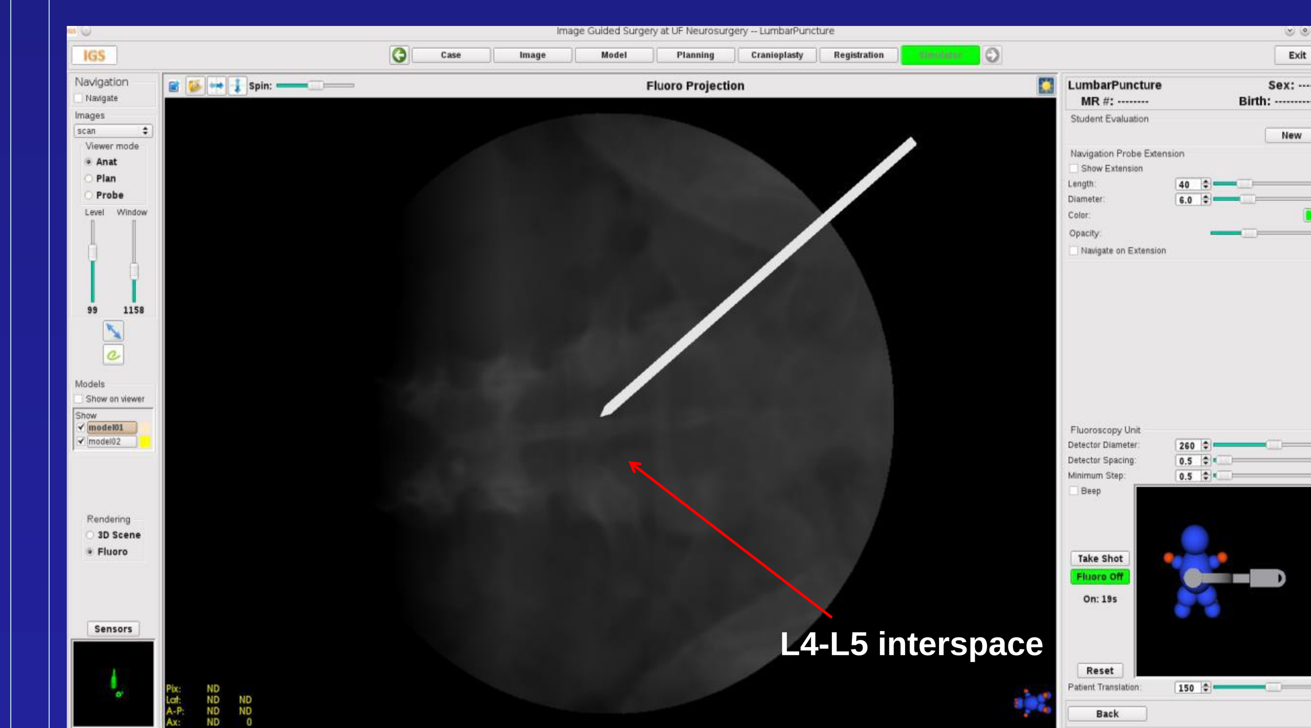


Figure 9. Virtual fluoroscopy snapshot that shows the needle approaching the L4-L5 interspace.

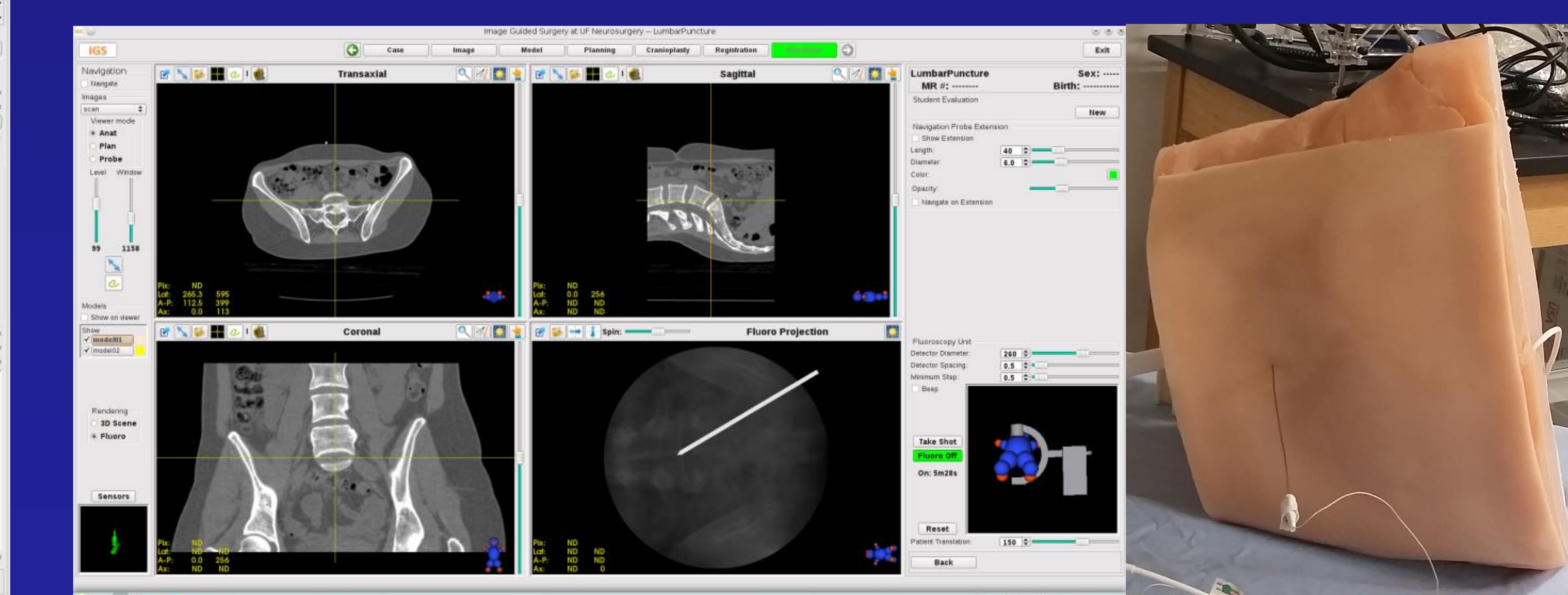


Figure 10. Transaxial, sagittal, coronal and fluoroscopic views shown on the image-guided workstation mimicking the 3-D, patient-specific physical model's position and needle placement.

Future Work

The first generation LP mixed-reality simulator functioned as expected with the haptic and visual feedback necessary for medical students to practice LPs. Future work include creating a second generation model, develop and design a set of pediatric models, and design and conduct a statistical analysis. The second generation model will be redesigned to allow for the normal anatomy to be replaced by different inserts to represent a wide range of anatomical anomalies. Patients with scoliosis, spinal tumors, different body mass indexes (BMI), and spinal hardware can be created for medical students to practice with. The statistical analysis will be designed to both train and evaluate students on the basic skills necessary to perform a LP. The students can be trained using the normal anatomic mixed-reality LP model and subsequent evaluations can be carried out using the variety of models depicting various anatomic variations and BMIs.