Patient specific virtual reality for simulation of spine surgical Procedures: A fast highly automated system for VR based image guided therapy, and education.

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INTRODUCTION: Advanced 3D interaction and simulations based on medical imaging data has previously been demonstrated as having utility for surgical education and treatment planning[1]. Physicians use multi-modal medical imaging for pre-operative planning, intra-procedure guidance, and even post-procedural assessment primarily by inspection of 2D slices of imaging volumes. Surgeons typically form a mental 3D representation of the target, drawing from magnetic resonance imaging (MRI) and computed tomography (CT) scans and their existing anatomical knowledge. This task is demanding, and despite years of training, a degree of uncertainty persists even for seasoned professionals. Virtual reality (VR) is ideally positioned to enhance comprehension of individual anatomy, using patient-specific 3D organ models derived from MRI or CT scans. However, the use of 3D models by physicians is limited because the end-to-end process to go from imaging data to a patient specific 3D model that can be used by physicians for treatment planning or education is time consuming, often requiring a significant number of hours, multiple software packages as well as engineering and artistic expertise. This process is currently too expensive and time-consuming to be used routinely for surgical planning or education. To address these limitations, within this investigation we built a specialized image analysis pipeline that uses state of the art methods for image registration, segmentation, and evaluated interaction with the model in a virtual reality platform. The study focused on spine decompression surgical procedures. Spinal decompression surgery is used to treat spinal stenosis which is narrowing of the spinal canal leading to compression of neural elements (spinal cord, spinal nerves). The broad research questions addressed by this study are in 3 broad areas: 1) medical image analysis, 2) surgical simulation in VR, and 3) integration into education and treatment planning. Two objectives achieved by this study are creation of medical image analysis pipelines for the automatic creation of patient specific models for simulating spine surgery and creation of high-fidelity simulation of surgical spine procedures integrated into a virtual reality application.

METHODS: A semi-automated image analysis pipeline (Figure 1) was developed that uses diagnostic medical imaging data (CT and MRI) to create 3D models of the spine that include individual vertebrae, intervertebral discs, neural elements contained within the dura mater (spinal cord, cerebral spinal fluid, nerve roots, cauda equina), ligamentum flavum, and tumour involvement if present. The pipeline begins with segmentation of vertebrae in 3D computed tomography (CT)[2] using an existing deep learning model trained by our group (DSC = 0.904 ± 0.056). This is followed by segmentation of vertebrae 3D MRI images. In MRI for the lumbar spine, we trained a nnU-Net[3] deep learning model to segment the lumbar spine using an open dataset[4,6]. In MRI of the cervical and thoracic spine neurological (CSF, spinal cord, nerve root) and musculoskeletal structures (bone, ligament flavum, intervertebral discs) were segmented using the based on Spinal Cord Toolbox[5], specifically automatic spinal cord segmentation (DSC: 0.95 ± 0.02) followed by automatic registration to the PAM50 template. The next pipeline stage was registration (affine and deformable) of CT and MRI images using a novel perturbed continuous optimization approach developed by our group. 3D models were saved in DICOM Seg format (3D Slicer 5.3.0). 3D models and associated imaging were loaded into a custom spine surgery simulation module within the SieVRt VR DICOM viewing platform. The spine surgery simulation module allowed users to simulate a spinal decompression procedure with created patient specific models. Performance of the image analysis pipeline was done using hausdorff distance (HD) and dice similarity coefficient (DSC) to evaluate volumetric agreement. The pipeline was evaluated with retrospective clinical data of 9 patients (5 lumbar, 1 cervical, 2 cervicothoracic and 1 thoracic) undergoing spinal decompression procedures at Sunnybrook Health Sciences Centre following approval from the institution's research ethics board. The training and evaluation of pipeline was done using 4 NVidia A100 GPUs (40 GB memory) on Compute Canada resources (https://docs.alliancecan.ca/wiki/Narval/en). Semi-structured interviews of staff surgeons and trainees were used to assess the qualitative value of the patient specific surgical simulation of spinal decompression surgeries.

RESULTS: High fidelity patient specific models were created quickly with the average time to generate the 3D models about 2 minutes. The spine tissues were accurately segmented, including those within the MRI, vertebral bone (DSC = 0.92 ± 0.05, intervertebral discs (DSC= 0.86 ± 0.09) and the neural elements (DSC: 0.92 ± 0.03). CT and MRI were registered with good spatial accuracy (vertebral level [HD = 1.20 ± 0.18 mm] and spinal cord [DSC > 0.9, HD 1.284 ± 0.512 mm]. Users suggested that VR can be beneficial for surgeons and surgical trainees. Trainees specifically reported the value of being able to practice a procedures multiple times, to better understand the steps of the procedure. In terms of better understanding the surgical strategy and goals, the most value was seen in the lateral recess and foramen, where the ability to fuse their understanding of anatomy with the patient specific medical imaging was enlightening. The ability to better visualize and understand the decompression required of the nerve roots within the foramen and lateral recess was identified as particularly helpful for trainees. The visualization of the foramen that is possible in the VR based system was consistent with what can be achieved in the OR with a surgical microscope. Participants thought the platform was a powerful surgical education and planning tool and could result in procedures with quicker results and fewer complications. Additionally, it is believed that the platform can expedite hands on learning by providing simulated ORs to increase case volume.

DISCUSSION: We developed a fast and robust pipeline which creates a patient specific 3D model based on CT and MRI. The model was then imported on a virtual reality module to simulate the spinal decompression procedure using surgical instruments in a virtual surgical environment. Feedback from the staff surgeons and trainees suggested that this technology helps in understanding spinal stenosis, neuroanatomy, and concepts of performing spinal decompression. One of the challenging parts of this study was segmentation of nerve roots and ligamentum flavum, future work will focus on better visualization and imaging parameters that can best delineate their 3D shape.

SIGNIFICANCE/CLINICAL RELEVANCE: Immersive VR based simulation brings the possibility of treatment planning in a 3D environment that can allow surgical strategies to be determined and investigated with a greater level of depth than is currently possible with 2D review of medical images, leading to better treatment planning. Surgery is a 3D intervention; the technology developed as part of this study is useful for surgical education and will enable planning in 3D, lower intra-operative risks, and lead to better surgical outcomes.

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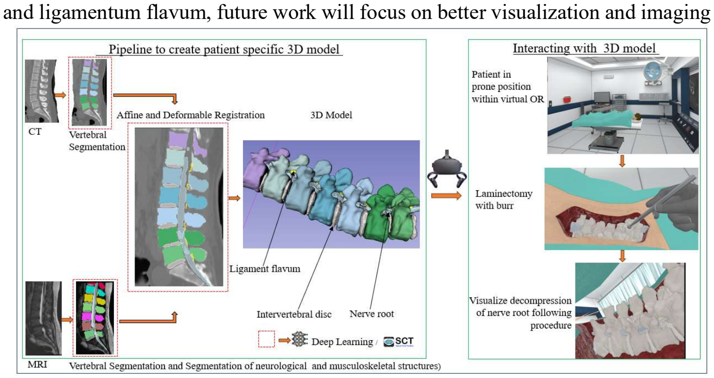

Figure 1. Workflow of Patient Specific Virtual Reality for Simulation of Spine Procedures

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