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EXTENDED REALITY TOOLS FOR DEEP BRAIN STIMULATION: A FRAMEWORK AND DESIGN CONCEPTS FOR PROCEDURAL PLANNING

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ABSTRACT

Extended reality tools have been theorized to revolutionize medicine. Many tools on the market today fail to provide value in a clinical setting. Extended reality tools must emulate existing clinical workflows to add value to a doctor's process. A framework is created to capture the clinical workflow by defining user tasks, graphical user interface functionalities and backend software functionalities. Two extended reality tool designs are presented based on the workflow captured in the framework. The first extended reality tool is designed for communication and collaboration, while the second tool is designed with a full immersive experience.

Keywords: extended reality, framework, deep brain stimulation, design concepts.

NOMENCLATURE

2D	Two dimensions
3D	Three dimensions
DBS	Deep Brain Stimulation
DICOM	Digital Imaging and Communications in Medicine
XR	Extended Reality

1 INTRODUCTION

Advances in computing technology suggests opportunities to use extended reality (XR) technologies to enhance medical procedures, improve patient outcomes, and advance medical device designs. Computing technology is already revolutionizing the medical industry through next generation genome sequencing [1], automated in-depth analyses of magnetic resonance images (MRI) [2], and personalized precision medicine [3], among others.

The neurosurgery space has been theorized to be impacted by XR tools. Dozens of XR-based tools are available in the neuro space for anatomical education, surgical simulations, and procedural planning [4]. The development of XR tools has outpaced evidence showing positive impact to patient-centered outcomes and the results of existing studies are mixed when compared to conventional methods [4]. More evidence is needed to show improvement in surgical performance due to the use of XR tools [5]. Evidence based studies to quantify improvement require a control for comparison with the new XR tool. Therefore, the goal of this article is to contextualize our development of two XR tools within a boarder objective of designing tools based on a specific medical workflow framework. The existing medical workflow then serves as the control when evaluating the XR tools.

Deep brain stimulation (DBS) therapy provides symptom relief for individuals suffering with Parkinson's disease, essential tremors and dystonia [6]. A pulse generator is implanted into the patient's brain to electronically stimulate the brain fiber tracks to reduce symptoms [7]. Anatomical atlases from cadavers guide surgeons during the DBS planning process [8]. Accurate placement of DBS electrodes is critical for stimulating the correct target region of the brain [8]. Most targets are less than 10 mm in diameter [9] and multiple electrodes passing through the brain increases the risk of a hemorrhage [9]. Many large studies report hemorrhage rates from 0% to 9.5% [10] and the occurrence of misplaced leads ranges from 3.8% to 12.5% [11].

One advanced planning process uses segmented seven tesla (7T) MRI scans instead of the anatomical atlases to identify the patient's target regions [12]. The 7T monoscopic images, plus medical experience, assist with the placement of the electrodes within a millimeter of accuracy [9]. The procedural planning for DBS relies on a spatial relationship evaluation between the device and the anatomy to select the best electrode placement.

2 METHODS

Two issues of current three-dimensional (3D) visualization techniques for DBS procedural planning is 1) the lack of vasculature data available when selecting the patient specific electrode location and 2) the siloed steps in the planning process to confirm the electrode placement. For example, after the target location (three degrees of freedom) is selected the doctor reviews a series of two-dimensional (2D) DICOM images of the patient's brain to select the electrode trajectory (three degrees of freedom). The second part of the process requires the doctor to reconstruct the orientation of the electrode within their mental model of the patient's brain, an orientation which transverses at an oblique angle to the 2D DICOM images.

The spatial affordances of XR tools could improve the placement planning process for DBS electrodes by further analyzing the 3D relationship between the electrode and the patient's brain. User studies provide evidence of improved performance by comparing task performance against a control task. Therefore, XR tools must follow conventional methods, which were established based on evidence.

Requirements. Before developing a comprehensive XR tool for DBS, the conceptual requirements of the system must be defined. Based on interdisciplinary discussions with DBS domain experts and a literature review of the state of the art; tasks are defined as the doctor: 1) selects registration points in the patient's anatomy to orient the brain with the DBS frame, 2) confirms the anatomical orientation, 3) selects the electrode target location, 4) selects the electrode trajectory orientation, 5) analyzes the BenGun electrode variations, and 6) reviews the microelectrode readings and electrical field simulation volumes.

Anatomical Models. The patient specific anatomical model was acquired from datasets available at the Center for Magnetic Resonance Research, Department of Radiology at the University of Minnesota. All sub-regions of the deep brain stimulated by DBS therapies were manually segmented. The regions include the caudate, GPe (external globus pallidus), GPi (internal globus pallidus), putamen, RN (red nuclei), SN (substantia nigra), STN (subthalamic nucleus), and thalamus, along with the brain matter, skull, vasculature, anterior commissure (AC) point and posterior commissure (PC) point. Multiple regions were segmented to test multiple use cases of the XR tools with only one patient's dataset.

Stereotactic Frame Models. The DBS stereotactic frame model was reverse engineered from two available frames; a Coswell-Robert-Wells (CRW) frame (Figure 1) [13] and 2) Leksell frame (Figure 1) [14]. Each component was measured and modeled in SolidWorks (Waltham, Massachusetts, USA).

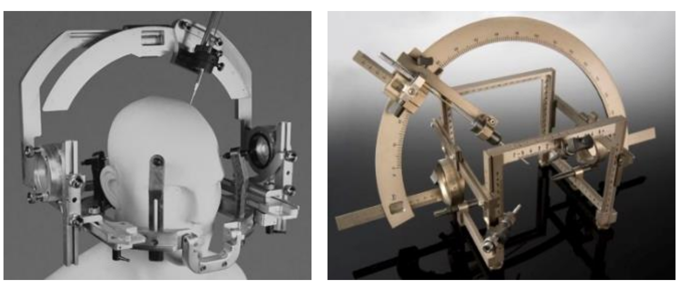

FIGURE 1: CRW STEREOTACTIC FRAME (LEFT) [13] AND LEKSELL STEREOTACTIC FRAME (RIGHT) [14].

Visualization Techniques. The anatomical models were saved as stereolithography (.stl) models, colored in Meshmixer (San Rafael, California, USA) and saved as object (.obj) and material (.mtl) files. The deep brain regions were colored in blue and purple colors, the vasculature in a red color, the brain matter in an off-white color and the skull/skin model in a medium skin tone. The models and stereotactic frame were imported into Unity (San Francisco, California), which is a platform to rapidly design and develop XR tools .

3 RESULTS

The final results are a framework of features for DBS procedural planning XR tools and two XR tool designs based on the framework; the first design presented on a stereoscopic display with touch screen and tracked interactions and the second design presented in a head-mounted-display (HMD) with handheld controllers.

3.1 FRAMEWORK

A workflow framework defines the functionality available in a XR tool (Figure 2). The features available replicate the procedural planning process for a specific medical profession. Specific functionalities are necessary to replicate the procedural planning process with a XR tool and create a point of comparison between new and existing technologies.

The workflow for DBS electrode procedural planning begins by importing a patient's dataset into the software. The XR tools are design independent of the dataset, therefore any patient's data can be used for the electrode placement process. The doctor identifies the AC point, PC point and three points along the brain's midline to register the patient's brain to the stereotactic frame. The doctor confirms the orientation of the patient's brain and begins the planning process.

First, the doctor aligns the distal end of the electrode model with a region of the patient's brain, using cartesian coordinates. The distal location impacts the quality of the patient's therapy. Second, the doctor orients the electrode trajectory using polar coordinates, while considering other regions of the brain and vasculature. Conventional methods use 2D DICOM images to orient the electrode at an oblique angle through the DICOM images. The mental workload to review anatomy presented in 2D is higher compared to 3D visualizations of anatomical structures when completing a task [15].

Third, a five port BenGun attached to the stereotactic frame assists with guiding the electrode into the patient's brain. A port is selected based on microelectrode readings captured during the procedure to confirm the distal tip location within the brain. The center port is used during the planning process, but adjustments made during the procedure resulted in over 1mm error in 24% of electrode placements [16]. The inaccuracies are due to the electrodes assumed location based on the microelectrode readings [16]. A visual inspection of the BenGun options could be done with a XR tool during the planning process.

Microelectrode readings used during the procedure confirm the electrode location. The electrode's electrical fields provide therapy to the patient and the therapy quality depends on the electrode location. The electrode location can be reverse engineered from the microelectrode readings and electrical field data. Incorporating multiple types of electrode data in one tool encourages cooperative work between doctors, radiologists, scientists, and engineers to improve surgical planning outcomes for complex anatomical structures [17].

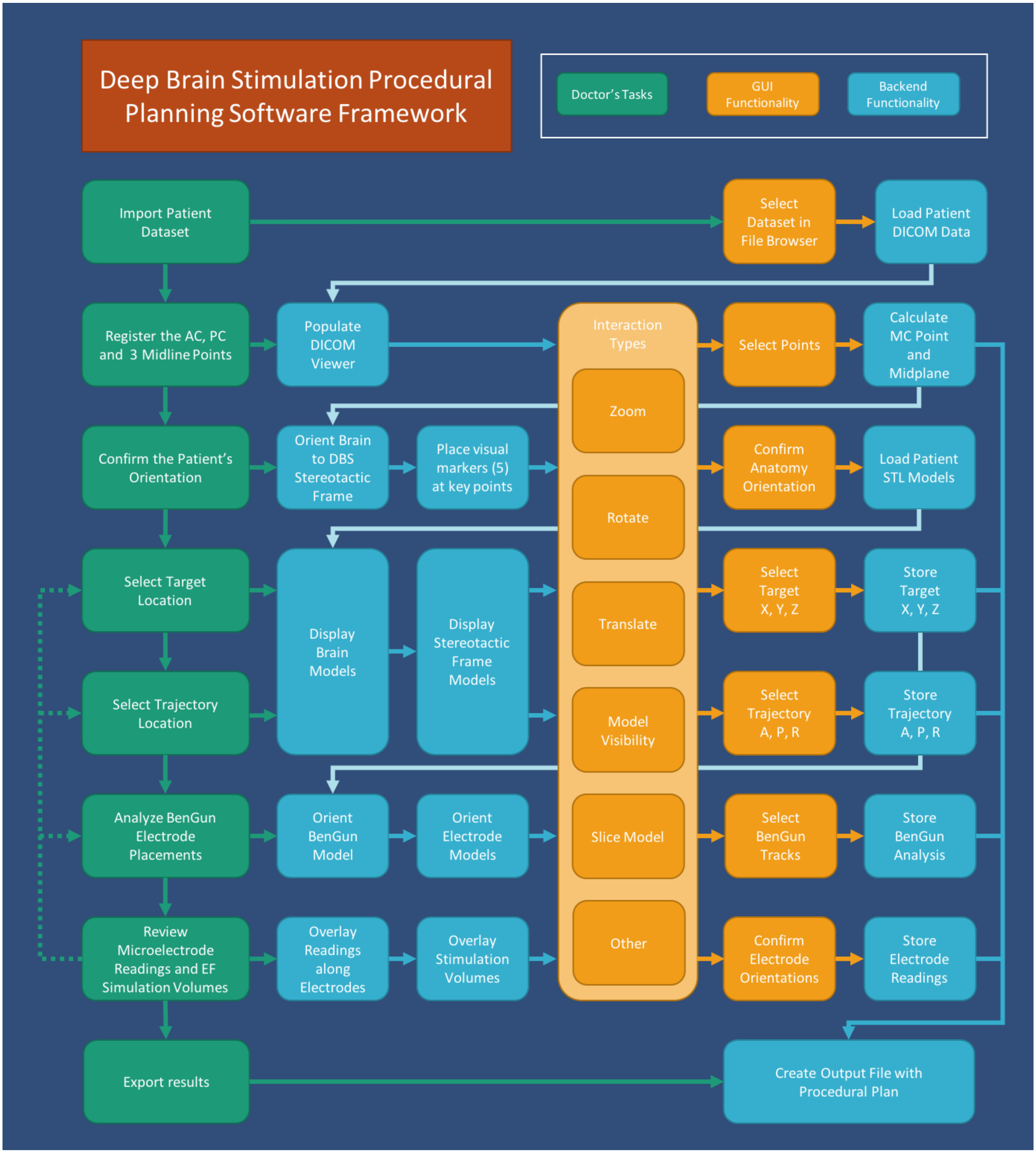

FIGURE 2: FRAMEWORK OF FEATURES NEEDED FOR A VIRTUAL REALITY TOOL TO MATCH THE DEEP BRAIN STIMULATION PROCEDURAL PLANNING WORKFLOW. TASKS THE DOCTOR MUST COMPLETED ARE INCLUDED IN GREEN. COMPUTATIONAL FUNCTIONALITY OF THE SOFTWARE IS DEFINED IN BLUE, WHILE FEATURES OF SOFTWARE USABILITY ARE DEFINED IN YELLOW. THE COLOR-CODED ARROWS SHOW THE FLOW OF DATA THROUGHOUT THE WORKFLOW PROCESS.

Implanting an electrode into a patient's brain is a complex procedure with many variables to consider. Centralizing a checklist for complex neurointerventional procedures has been shown to improve communication and reduce the number of adverse events during a procedure [18].

3.2 DESIGN ONE: STEREOSCOPIC DISPLAY WITH TOUCH INTERACTION

The first XR tool is designed for collaboration and communication. Medicine requires collaboration between many medical specialties and communication with medical support staff. The adage of 'if a picture is worth a thousand words then a model is worth a thousand pictures' holds true in medicine. A screen displayed XR-based model creates a multi-person shared experience, where care team members can participate and/or observe the planning process. Improving methods of communication between staff members directly improves the safety of patient procedures [18].

The system is designed with a 75" screen with stereoscopic capability, 24" interactive touchscreen and spatial tracking to interact with the model (Figure 3). The primary participant can rotate, translate, zoom and complete macro manipulations in the tracked space. Micro manipulations are adjusted on the touch screen (Figure 4). The touch screen has three sections; left justified tabs, centered anatomical model, and right justified tabs. The left justified tabs include task-specific controls used by the doctor during the planning process and presented in chronological order from top to bottom. Although, the tasks can be completed in any order to suit the doctor's needs.

FIGURE 3: THE FIRST VIRTUAL REALITY TOOL DESIGN FOR DEEP BRAIN STIMULATION PROCEDURAL PLANNING USING A STEREOSCOPIC DISPLAY (LEFT) AND TOUCH SCREEN (RIGHT).

The center of the touch screen shows the anatomical models and the stereotactic frame. The center model mimics previous methods to plan DBS procedures. Multiple presentations of the data within a tool improve data accessibility and creates a bridge between new and existing XR tools.

The right justified menu is populated with model interaction controls. The view tab includes; resetting the model, resetting the camera, a complete system reset and exiting the simulation. The visibility of each model is toggled in the models tab. Slicing through the models reveals features of the anatomy hidden by other models.

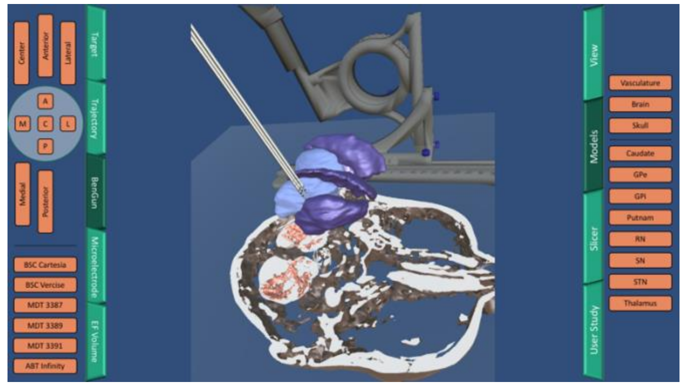

FIGURE 4: THE GRAPHICAL USER INTERFACE FOR THE FIRST VIRTUAL REALITY TOOL DESIGN, AS PRESENTED ON THE TOUCH SCREEN.

4.3 DESIGN TWO: HEAD MOUNTED DISPLAY

The second XR tool is designed for an immersive experience with a head-mounted-display (HMD). The device immerses a participant in the virtual environment with a full field of view. Research has shown high-immersive experiences improve spatial understanding, reduce information clutter during task completion and may increase a participant's bandwidth to perceive complex datasets [19].

FIGURE 5: THE SECOND VIRTUAL REALITY TOOL DESIGN FOR DEEP BRAIN STIMULATION PROCEDURAL PLANNING USING A HEAD MOUNT DISPLAY (RIGHT).

An HTC Vive Pro is used for the implementation. (Figure 5). Participants move their bodies to adjust the model view or rotate the model with the controller. The functions are organized by task completion and model interaction. The dominate hand controller is coded with task-specific controls, while the non-dominate hand controller is coded with model interactions. Two floating GUIs provide additional controls.

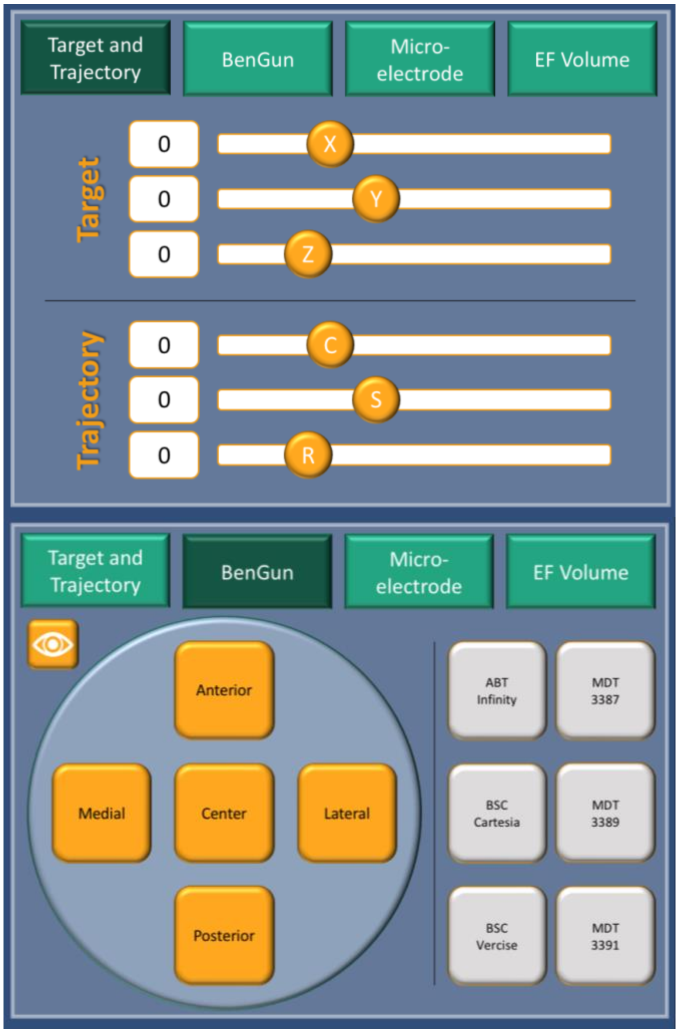

FIGURE 6. CONTROLS TO COMPLETE MICRO ADJUSTMENTS OF THE ELECTRODE TARGET AND TRAJECTORY (TOP). CONTROLS TO ANALYZE THE BENGUN CONFIRGURATION OPTIONS (BOTTOM).

Task-specific controls follow the doctor's workflow for the planning process (green tasks) and include; selecting a target location and a trajectory orientation, analyzing the electrode placement variations based on the BenGun port options, and confirming the placement with microelectrode readings and simulated electrical field volumes (Figure 6). Participants use their dominate hand controller for finer scale operations and task completion [20], for example, to adjusting the electrode target within millimeter accuracy.

Model interaction controls (yellow interaction types) include; manipulating the model through rotation, translation, scaling, model visibilities and slicing through the model (Figure 7). Participants prefer to use their non-dominate hand when starting tasks, macro scale operations and defining the frame of reference [20], for example adjusting the view and visibility of the models throughout the procedural planning process.

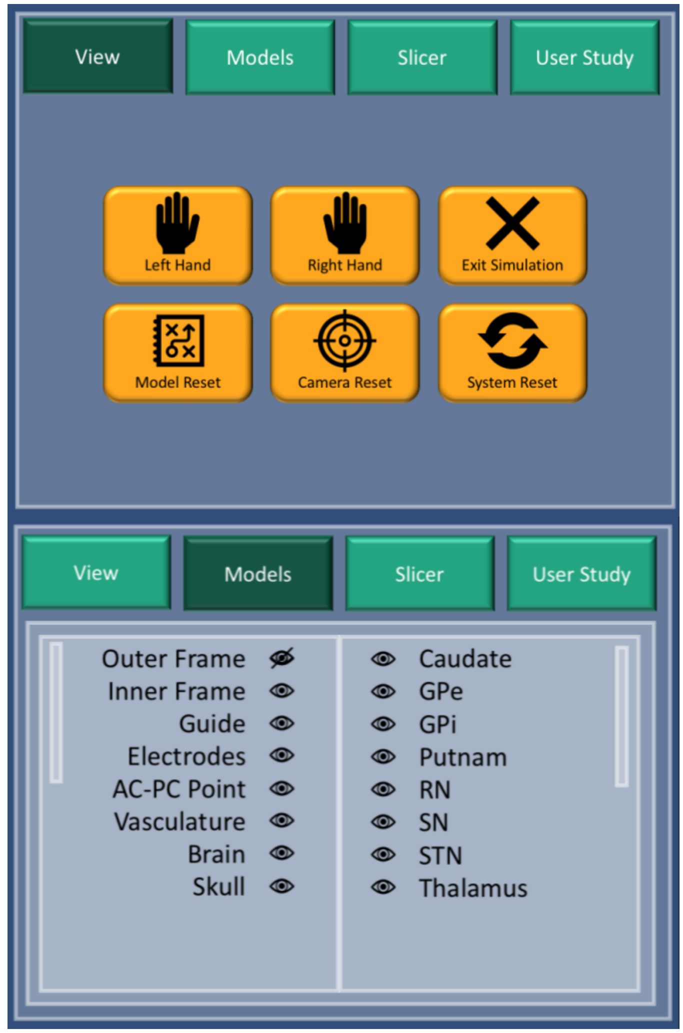

FIGURE 7. MODEL INTERACTION CONTROLS TO CHANGE THE SYSTEM SETTINGS (TOP). MODEL VISBILITY TOGGLES OF SIMULATION MODELS (BOTTOM).

4 CONCLUSIONS

A framework places the design of a XR tool within the context of an existing medical workflow. Medical workflows are developed based on evidence to ensure patient safety during procedures with numerous variables. Previous research shows evidence of XR-based tools improving doctors' knowledge of the relationship between the patient's anatomy and the procedure or device [21]. The XR tool workflow should fit within the medical workflow to either simplify the procedural steps, improve procedural knowledge, or advance existing methods. Various extended reality-based technologies, for example, stereoscopic display, CAVE, head-mounted-display, augmented reality etc., are available to create different user experiences. The design of XR tools has implications on the usability and acceptance of a solution. Studying the usability of XR tools within the intended medical workflow creates the evidence to determine if the solution improves outcomes, diminishes performance or is not statistically significant. Designing XR tools based on a workflow framework is critical to ensure tools meet the clinical needs and improve patient outcomes.

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