Determination of Surgical Variables for a Brain Shift Correction Pipeline Using an Android Application

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ABSTRACT

Brain shift describes the deformation that the brain undergoes from mechanical and physiological effects typically during a neurosurgical or neurointerventional procedure. With respect to image guidance techniques, brain shift has been shown to compromise the fidelity of these approaches. In recent work, a computational pipeline has been developed to predict "brain shift" based on preoperatively determined surgical variables (such as head orientation), and subsequently correct preoperative images to more closely match the intraoperative state of the brain. However, a clinical workflow difficulty in the execution of this pipeline has been acquiring the surgical variables by the neurosurgeon prior to surgery. In order to simplify and expedite this process, an Android, Java-based application designed for tablets was developed to provide the neurosurgeon with the ability to orient 3D computer graphic models of the patient's head, determine expected location and size of the craniotomy, and provide the trajectory into the tumor. These variables are exported for use as inputs for the biomechanical models of the preoperative computing phase for the brain shift correction pipeline. The accuracy of the application's exported data was determined by comparing it to data acquired from the physical execution of the surgeon's plan on a phantom head. Results indicated good overlap of craniotomy predictions, craniotomy centroid locations, and estimates of patient's head orientation with respect to gravity. However, improvements in the app interface and mock surgical setup are needed to minimize error.

Keywords: Preoperative planning, Android application, brain shift, workflow, tumor, surgery

I. INTRODUCTION

Brain deformation resulting from mechanical and physiological factors present during an operation can pose a considerable challenge to image-guided neurosurgery systems. This deformation, also known as brain shift, can cause misalignments between preoperatively determined target locations and actual target locations intraoperatively (routinely 1 cm or more of the brain cortical surface has been measured [1]). Often referred to as brain sag, the buoyancy forces on the brain are reduced due to cerebrospinal fluid drainage, and the brain deforms under its own weight, i.e. a gravity induced deformation. Quite obviously, this deformation is integrally linked to the head orientation of the patient. In addition, in the case of swelling, it is possible that the craniotomy itself may influence deformation due to the surfaces available for the process. Finally, hyperosmotic drugs such as mannitol are also routinely administered for respective procedures to inhibit swelling as well as a way to reduce the tautness of the brain prior to resection.

In previous work, we have developed a computational approach [2] and pre-/intra-operative pipeline to correct for deformations during surgery [3]. The preoperative computing pipeline was presented in [3] and is dependent on a limited set of surgical variables that need to be estimated prior to the procedure. Briefly, these surgical variables require the surgeon to estimate a head orientation prior to the procedure, an approximate size of craniotomy to achieve the resection goals, and an approximate trajectory into the tumor. However, these variables may not accurately describe surgical conditions during the procedure (for instance, the surgeon may choose to rotate the patient's head by a few more degrees than expected). This variability is accounted for by generating a distribution of possible conditions known as an atlas. The atlas contains sets of boundary conditions that are used to constrain a finite element deformation solution, producing a distribution of possible deformation solutions, known as a "deformation atlas" [3].

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Knowledge of the surgical variables prior to the precomputation phase of the pipeline can help limit the size of the atlas of possible deformation solutions [5]. In order to achieve this, a web interface desktop planner was previously developed to provide the surgeon with the ability to quantitatively determine the surgical variables for a tumor resection procedure by manipulating 3D models of a patient's brain and tumor [3]. However, this method was not amenable to the day to day workflow associated with a practicing neurosurgeon.

As a result, in order to improve the efficiency and simplicity of surgical variable acquisition, an Android application called *Surgical Planner* was developed to provide the neurosurgeon with the ability to interact with 3D models of the patient's head, brain, and tumor on a portable tablet. These 3D models are created using standard tools (e.g. Visualization Toolkit) from preoperative image data, and are exported to *Surgical Planner* as an email attachment. Our Surgical Planner app imports the file and allows the neurosurgeon to plan the expected head orientation, location and area of the craniotomy, and expected trajectory to be taken into the craniotomy location in an easy graphical touch-based interface. Once complete, surgical variables are extracted and exported through the email client back to the planning nodes to complete the preoperative computational pipeline. The purpose of the work presented in this paper is to use *Surgical Planner* to acquire surgical variables from a neurosurgeon's preoperative surgical plan for tumor resection and perform an analysis of the accuracy of the data exported by Surgical Planner.

The novelty of Surgical Planner is that it is designed to be integrated into a computational pipeline that utilizes preoperative and intraoperative data to assist and improve real-time, computer-assisted surgery. Existing preoperative planning mobile applications are limited to providing medical education and calculating medical interactions for specific procedures. Others, such as Brainlab's *TraumaCAD for iOS,* use patient-specific data to guide preoperative plans, but these plans are not integrated into a computational pipeline for computer-assisted surgery.

II. METHODS

(A) Development of Surgical Planner

Surgical Planner was developed using the Android platform, and was written using Java and associated Java libraries. Specifically, the OpenGL-ES-3.0 API (OpenGL for embedded systems) was used to render 3D graphics. In order to render patient graphic models onto the application, a parser was developed to read Legacy-ASCII .vtk files and extract the necessary data for rendering. A Nexus 9 was used during the development of the application, with 2GB RAM and a Dual-core 2.3 GHz 64-bit processor.

With respect to the functionality of *Surgical Planner,* the application was designed to import patient data, provide an intuitive interface for head orientation, provide an intuitive interface for determining craniotomy location and area, provide an intuitive interface for determining trajectory, and export the planned data. *Figure 1* shows the interface, which is explained below.

(1) Control Brain/Head

This button, when selected, allows the neurosurgeon to use touch gestures to freely rotate the patient's head.

(2) Control Camera

This button, when selected, allows the neurosurgeon to use touch gestures to change the view frame and rotate around the operating table to view the patient from different angles.

(3) Plan Craniotomy

Pressing (3) enters the neurosurgeon into "Craniotomy Mode," in which options 4-6 (discussed below) become available in order to plan the craniotomy.

(4) Choose Location

Pressing (4) allows the neurosurgeon to move a target around the head, in order to choose the center of the craniotomy. Once a location has been chosen, a long press of the tablet screen will lock this position (*Figure 2a).*

(5) Change Craniotomy Shape

Pressing (5) allows the neurosurgeon to choose between a circular/elliptical craniotomy or a square/box craniotomy.

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(6) Change Craniotomy Dimensions

Pressing (6) allows the neurosurgeon to move a set of sliders in order to change the size/dimensions of the craniotomy.

(7) Perform Craniotomy

Pressing (7) will run a calculation to determine the points on the surface of the head that will be "removed" as part of the craniotomy procedure. After the calculation is complete, these points turn green to indicate removal (*Figure 2b).*

(8) Set Trajectory

Pressing (8) allows the neurosurgeon to manipulate an arrow representing the trajectory that will be taken into the tumor (*Figure 2c).*

(9) Miscellaneous Controls

These buttons allow the neurosurgeon to choose the color of the head, brain, and tumor, as well as change the opacity of each item using a slider.

(10) Save Data to File

Pressing (10) allows the neurosurgeon to save the data to a file and export the file via an email client.

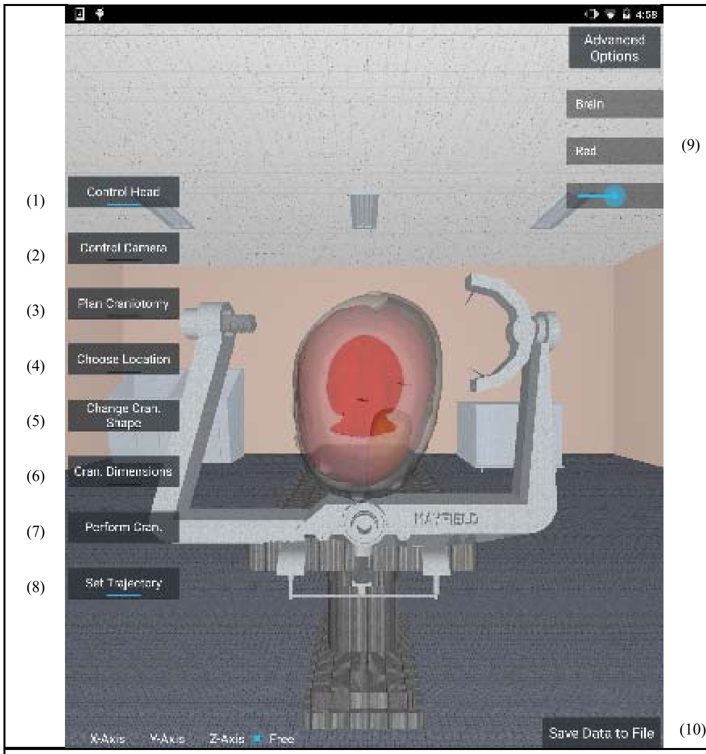

Figure 1: *Surgical Planner* Interface. Controls are described under *Methods.*

The data is reported in a .txt file that contains a vector describing the direction of gravity in the rotated head relative to the original head position. This variable is determined by creating a dynamic rotation matrix that is updated based on touch gestures used to rotate the head, and then applying this matrix to the original gravity unit vector (0,-1,0). In addition, the .txt file includes a point cloud containing the Cartesian coordinates of the craniotomy location. This data is determined by running an algorithm to determine the head surface points that lie within the planned boundary. *Figure 2a* shows an example of the neurosurgeon planning the craniotomy, and *Figure 2b* shows the final craniotomy boundaries after planning is complete. Finally, the trajectory is reported in the .txt file as a unit vector. An example of a planned trajectory is shown in *Figure 2c.*

Figure 2: (a, left) shows the craniotomy planning procedure. (b, center) shows the final craniotomy. (c, right) shows trajectory planning

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(B) Assessing the Accuracy of Surgical Planner Post-Development

After the development of the application was completed, the accuracy of the application's exported data was assessed. A neurosurgeon was asked to plan a surgery for an artificial case using *Surgical Planner* three separate times, and then asked to simulate this surgery on a physical setup of the same case three separate times. Thus, the process of determining the accuracy of *Surgical Planner* can be summarized into two major steps: (1) creation of surgical plan using *Surgical Planner*, (2) and comparison to the execution of that plan on a phantom head system.

(1) Creation of Surgical Plan

Before using *Surgical Planner,* CT-scans of a phantom head were obtained. These scans were used to create a geometric model file of the subject's head. Using a 3D MR Gadolinium enhanced image volume of a real patient, the data was scaled and adjusted to fit with the phantom head model obtained from the CT. This would later be used for the guidance displays in step (2). In addition, surfaces from the head, outer brain, and tumor were extracted to create a geometric model for *Surgical Planner.* This file was exported to *Surgical Planner* via email and loaded by the neurosurgeon. After the files were loaded, the neurosurgeon was presented with the interface shown in *Figure 1* for determining surgical variables. The process of generating a set of surgical variables was explained earlier in this section.

(2) Physical Mock Surgery

The following plan was used to simulate the tumor resection procedure. First, an intraoperative support system was developed for the phantom head that allowed head orientations similar to operating room experiences. This would allow the neurosurgeon to choose a suitable head orientation for the procedure. Image-to-physical registration techniques could then be performed using standard neurosurgical methods to capture this orientation. Based on this registration, a craniotomy area could then be marked with a marker and physical space geometric information could be recorded using digitization technology. Finally, the digitization technology could also be used to estimate trajectory.

On the day of the experiment, the mock surgical setup began with the neurosurgeon analyzing images of the CT-scan of the phantom head to establish a geometric understanding of tumor size and location. Using this knowledge, the neurosurgeon oriented the phantom head in a realistic surgical orientation (*Figure 3a).* After physically orienting the head using a flexible mount, the head was secured in place to remain stationary during the craniotomy planning. An image-to-physical space registration process was performed using a guidance platform (in this case 3D Slicer [4] using the Fiducial Registration Wizard module in the SlicerIGT extension). The point-based registration was performed by selecting the center points of MR-CT-visible markers attached to the phantom head (*Figure 3b*). Physical space fiducial centers were digitized in 3D Slicer using OpenIGTLinkIF and the PLUS toolkit, an application that streams live tracking data to 3D Slicer [4]. All physical space measurements were performed using a Northern Digital Polaris Spectra (NDI, Waterloo, Ontario, Canada). Following registration *(Figure 4a)* the neurosurgeon used the image guidance system setup in 3D Slicer to mark the craniotomy and tumor boundaries and draw the craniotomy contour (*Figure 3b*). After marking the area of the craniotomy, the neurosurgeon was asked to hold the stylus in direction of the planned trajectory. After this was determined, the stylus was used to determine the location of the points along the craniotomy contour. A custom designed tracked laser range scanner was also used to acquire a 3D textured point cloud of the planned craniotomy surface. This would allow for a nice comparison between marked plan in physical space (*Figure 4b)* and the one generated from the Surgical Planner (*Figure 1*).

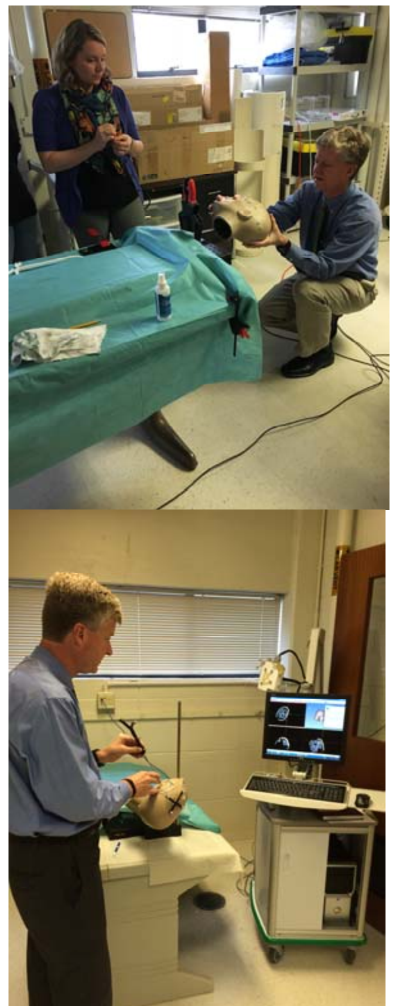

Figure 3:(a, top):Fixation planning. (b, bottom):Craniotomy planning.

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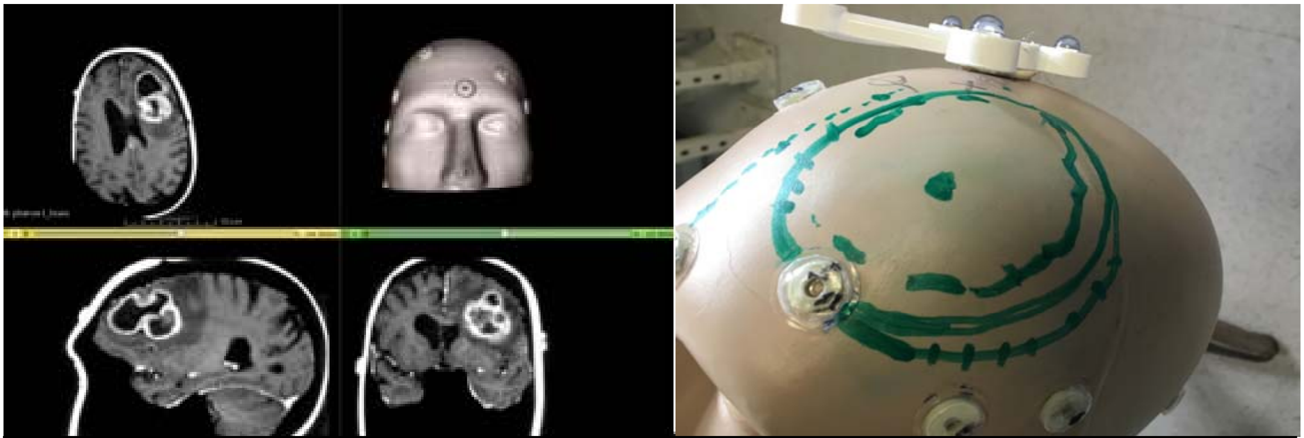

Figure 4: (a,left): Images as displayed on guidance system. (b, right): Tumor boundaries and craniotomy area marked.

III. RESULTS

Data was collected for three trials. Table 1a shows error (in degrees) between the gravity vector designated by *Surgical Planner* and the gravity vector obtained from the mock surgical setup. Table 1b shows error (in degrees) between the gravity vectors designated by *Surgical Planner* in each trial. Table 1c shows error (in degrees) between the gravity vectors designated by the mock surgical setup in each trial. Figure 5a shows the error in head orientation for the 3rd trial, which had the least rotation error. Figure 5b shows the head orientation for each trial as designated by *Surgical Planner,* and figure 5c shows the head orientation for each trial as designated by the mock surgical setup.

For the craniotomy planning procedure, Table 2a shows the centroid location for each trial for the *Surgical Planner* craniotomy and the mock surgical setup craniotomy. It also shows the surface areas of each respective craniotomy in each trial. Table 2b shows the centroid location differences between *Surgical Planner* and the mock surgical setup for each trial, as well as the *Surgical Planner* craniotomy surface area percent error relative to the mock surgical setup craniotomy surface area. Figure 6 shows an overlay of the craniotomy procedure as designated by *Surgical Planner* and by the mock surgical setup, for each trial.

With respect to the trajectory, data was only collected for one trial, and the error between the *Surgical Planner* trajectory and the mock surgical setup trajectory was 40^{o}.

Trial	Rotational Differences (degrees)
1	44.6
2	26.1
3	22.9

a

Differences Among App Trials	Rotational Differences (degrees)
1 to 2	11
1 to 3	14.4
2 to 3	3.7

b

Differences Among Mock Surgery Trials	Rotational Differences (degrees)
1 to 2	8
1 to 3	8.7
2 to 3	3.3

c

Table 1a (left): Error between *Surgical Planner* and mock surgical setup. Table 1b (middle): Error between trials for *Surgical Planner.* Table 1c (right): Error between trials for the mock surgical setup.

Trial	App Crani. Centroid	OR Crani. Centroid	App Crani. Surface Area (mm^2)	OR Crani. Surface Area (mm^2)
1	128.0, 91.6, 116.3	120.3, 100.3, 111.1	1555	4692
2	117.4, 91.2, 119.5	116.8, 108.8, 120.0	1802	4600
3	124.4, 90.3, 119.4	104.8, 113.7, 123.3	1801	4740

a

Trial	Centroid Difference (mm)
1	12.7
2	17.7
3	30.8
Mean	20.4

b

Table 2a (left): Craniotomy planning data for each trial. Table 2b (right): Calculated planning data for each trial.

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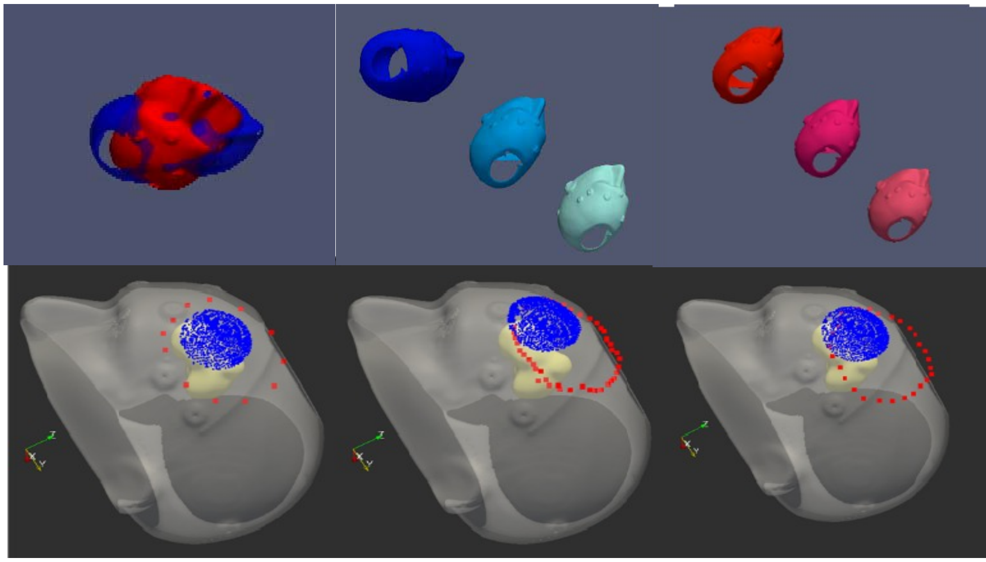

Figure 5a (left): Difference in head orientation between *Surgical Planner* (blue) and mock surgical setup (red). 5b (middle): Rotation as designated by *Surgical Planner* for each trial (in order from left to right). 5c (right): Rotation as designated by the mock surgical setup *Planner* for each trial (in order from left to right).

Figure 6 (left): Overlay of craniotomy point cloud from *Surgical Planner* (blue) and mock surgical setup (red boundary).

IV. DISCUSSION

Analysis of the results indicate significant error in the head orientation vectors designated by *Surgical Planner* and the mock surgical setup. In particular, from Table 1a, the 1st trial had very large error (44°). However, the 2nd and 3rd trials have significantly smaller error (26.1°, 22.9°), and are quite consistent with each other. Indeed, tables 1b and 1c show that there was minimal difference between trials 2 and 3 for both *Surgical Planner* and the mock surgical setup. The error in the 1st trial may be attributed to random error, but cannot be excluded as an outlier without a larger sample size. The improvement in error as more trials were conducted was attributed to the neurosurgeon's improved ability to plan the procedure in each successive trial. In fact, the neurosurgeon stated that as the trials progressed, he gained a better ability in each successive trial to judge the location of the tumor and plan accordingly. Given that no significant training was provided to the surgeon before the experimental trial, the results are nevertheless encouraging.

Even if the error in the 1st trial is excluded, there is still significant error in the head rotation in the 2nd and 3rd trials. After discussions with the neurosurgeon, it was determined that this error was due to the fact that in both *Surgical Planner* and the mock surgical setup, the neurosurgeon's view of the head was not representative of the true OR surgical domain. In *Surgical Planner,* the neurosurgeon desired the ability to be able to "walk" next to the head, as opposed to the simple camera rotation that currently exists. It is believed that providing this functionality in the future will reduce error, based on the craniotomy centroid data in table 2a. The craniotomy centroid data in table 2a for *Surgical Planner* indicates minimal variability in the Y and Z coordinates in each trial, but large variability in the X coordinates (all units in mm). The X-axis is the direction that the neurosurgeon desired to walk along when using *Surgical Planner,* and thus, providing this function in *Surgical Planner* will likely reduce head orientation error. In addition, in the mock surgical setup, the neurosurgeon discussed how the table height in the mock setup was considerably lower than in the OR. As a result, he was forced to crouch when positioning the head. Future improvements for the mock surgical setup may include elevating the table to meet the appropriate OR height. For both *Surgical Planner* and the mock surgical setup, these misrepresentations of the true OR surgical domain are likely the reason for the error.

With regards to the craniotomy plans designated by *Surgical Planner* and the mock surgical setup, there were significant differences in surface area. It is believed that the error in surface area is due to the neurosurgeon's superior ability to plan using the guidance system than to plan with *Surgical Planner.* The neurosurgeon is more familiar with the use of the guidance system to identify structures such as the midline, which are not clearly visible in *Surgical Planner.* A possible way to minimize this error is to load the same image volume used in the guidance system into *Surgical Planner,* so that the neurosurgeon can use the image volume in the app in a similar way to the guidance system and then manipulate the 3D models accordingly on the app. This implementation, while difficult, will be considered for future development. It is interesting to note that while the size of craniotomy was different, the app's simulated craniotomy fell within the confines of the OR counterpart. It should also be noted that in regards to the atlas of the brain shift correction pipeline, the size of the craniotomy is not critical since the size is varied within the precomputation phase. Rather, the centroid of the craniotomy is of more importance, since the size of the craniotomy will be varied relative to the centroid.

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The results indicate that there was some error in craniotomy centroids between *Surgical Planner* and the mock surgical setup (average = 2 cm). There are many possible reasons for this error, including the reason described above for error in surface area. An additional reason for error may include the neurosurgeon's improved ability to plan the procedure in each successive trial, as described earlier. The error could also be attributed to the lack of "walking" functionality in *Surgical Planner* and table height, both of which were also described earlier.

Despite the error in the head orientation and craniotomy procedures, it is important to note that for all three trials, *Surgical Planner* had relatively good precision, and for all three trials, the mock surgical setup also had relatively good precision. Looking at the head orientations, we can see visually in Figure 5b that the *Surgical Planner* head orientations, ignoring trial 1, are quite similar. In addition, in Figure 5c, the mock surgical setup head orientations appear to be very similar. Looking at the craniotomy planning, we see in figure 6 that the *Surgical Planner* point cloud is in a similar location for all 3 trials and the mock surgical setup boundary is similar for all 3 trials. This analysis indicates that there must be some inaccuracy *Surgical Planner's* representation of the OR surgical domain. However, it may also be true that the mock surgical setup is not an entirely accurate representation of the OR surgical domain (for reasons described earlier), so the focus of future development will be to improve the representation of the OR surgical domain in both *Surgical Planner* and the mock surgical setup. We will also have the neurosurgeon familiarize himself with the patient image volume prior to conducting trials, to avoid changes in planning in successive trials based on improved knowledge of the tumor location.

V. CONCLUSIONS

Based on this work, we have found that *Surgical Planner* is a good representation of the surgical domain, since the neurosurgeon was able to successfully generate a set of variables that were reasonably accurate estimates of the simulated mock surgical setup. For each variable, there was significant error due to some inaccuracies in representation of the OR surgical domain in both *Surgical Planner* and the mock surgical setup. Future work will involve developing new controls and functionality for *Surgical Planner* and mechanical changes in mock surgical setup in order to minimize this error. In addition, multiple different cases will be created, and multiple neurosurgeons will be asked to participate in the experiment. A training protocol will also be developed to minimize the chance of error in early trials.

Still, *Surgical Planner* holds promise as a simple, efficient, and timely method of obtaining variables in order to reduce the size of the atlas in the brain shift correction pipeline, as well as the execution time of the preoperative atlas computing phase.

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