Surface-based preoperative CT/MRI to intraoperative face scan registration: a clinical study

R. R. Shamir[1], M. Freiman[1], L. Joskowicz[1], E. Zehavi[2], S. Spektor[2], Y. Shoshan[3]

[1]*School of Engineering and Computer Science, The Hebrew Univ. of Jerusalem, Israel.*
[2]*Mazor Surgical Technologies, Caesarea, Israel.*
[3]*Dept. of Neurosurgery, School of Medicine, Hadassah University Hospital, Israel.*

Abstract. We present a clinical study of surface-based registration between a preoperative CT/MRI of a patient head and an intraoperative surface scan of his face. The study was conducted on 14 patients that underwent neurosurgery with standard neuronavigation based on preoperative CT/MRI datasets. Intraoperatively, before the surgery started, surface scans of the patient faces were acquired with a surface scanner. After extracting face surface points in the upper region of the face from both datasets, the resulting point sets were aligned with a robust two-step rigid registration algorithm. The mean face registration error was 0.9mm (std=0.35mm). The mean estimated target registration errors at 60, 105, 150mm from the face surface were 2.0mm, 3,2mm, 4.5mm. These results indicate that surface-based face registration is clinically viable.

Keywords: surface-based rigid registration, neurosurgery, registration error

1. Introduction

A key step in Image Guided Surgery (IGS) is the accurate intraoperative alignment between preoperative CT/MRI images and the intraoperative patient situation and position. Currently, three registration approaches are available to achieve this alignment: 1) landmark-based; 2) image-based, and; 3) surface-based registration. Landmark-based registration consists of correlating geometric and/or anatomical landmarks present in both the preoperative image and the patient's head. Patients are preoperatively imaged with a few markers affixed to their skin or bones, which are then localized in the images together with additional anatomical landmarks. Intraoperatively, the surgeon touches the markers and landmarks with a tracked probe and pairs them to those in the images. The transformation that aligns the point pairs is then computed, and the CT/MRI image is registered to the intraoperative coordinate system. The drawbacks of this method are: 1) it assumes that the markers remain on the patient skin between the imaging and surgery time; 2) it assumes that the markers and landmarks are reachable intraoperatively; 3) it requires an additional time-consuming and error-prone intraoperative manual procedure, and; 4) its accuracy depends on the surgeon's ability to localize the markers and landmarks. Despite these drawbacks, it is the method of choice in commercial neurosurgery, ENT, and orthopaedics IGS systems.

Image-based registration uses intraoperative images to establish the correspondence between the preoperative CT/MRI and the intraoperative situation. With X-ray fluoroscopy or ultrasound, the images must be processed to eliminate noise and distortions, the imaging device must be calibrated, and the imaging views must be co-registered [1,2]. This requires tracking of the imaging device, or imaging a registration object alongside the anatomy. While the method does not require preoperative marking and is percutaneous, it is not always robust and accurate. Interventional CT/MRI imaging does not require registration but it is expensive and not always available [3].

Surface-based registration uses intraoperative surface data from the patient anatomy to compute the alignment. The data is acquired with a tracked laser probe or with a 3D surface scanner [4–8]. The tracked probe measures the distance from the probe to a point on the surface with a beam laser. A few hundreds of points can be acquired by moving the probe around the region of interest. Surface scanners acquire in a few seconds a cloud of hundreds of thousands of points in a single scan. The method is applicable when the anatomy is visible, such as in neurosurgery (face scan) and in total knee replacement (exposed distal femur and proximal tibia). Its advantages are that: 1) it is marker-free; 2) it is fast, intuitive and easy to use; 3) it has no manual localization errors, and; 4) its accuracy is surgeon-independent and is averaged over many points.

Despite its potential, only a few clinical accuracy studies have been conducted, both for the z-touch probe [9,10] and for surface scanners [5–7]. The studies include few cases and report the registration error at the fiducials area or at the scanned surface points, which falls short of providing the desired clinical target registration error.

2. Materials and methods

We conducted a clinical study of surface-based registration between a preoperative CT/MRI of the patient head and an intraoperative surface scan of his/her face. The study is part of an ongoing project on image-guided precise targeting in keyhole neurosurgery with a miniature robot [8]. Its conclusions are relevant to all surface-based IGS systems.

To assess the clinical accuracy of the surface-based CT/MRI to face scan registration, we measure the RMS distance between the outer face surface points automatically extracted from the intraoperative facial scan and their closest corresponding points in the CT/MRI. This provides the Face Registration Error (FRE) which serves as the Fiducial Registration Error, for the accuracy measure for targets on the face surface used as fiducials. Since the registration error of targets inside the brain cannot be measured directly, we estimate the Target Registration Error (TRE) of virtual inner target points at increasing distance from the face surface center of mass.

In the period of 6-10/2006, 14 patients who underwent various neuronavigation-based surgical procedures were randomly selected. For each patient, we obtained the preoperative CT/MRI image data sets with customary acquisition parameters that were used in the surgery. The images were typically acquired a day before the surgery.

After the surgeon elaborated the preoperative plan with the navigation system software, we automatically segmented and extracted the outer surface of the head from the image data set, as described in [8]. Intraoperatively, after patient anesthesia, intubation, an insertion of nasogastric tube (no eyes covering) and positioning and before skin preparation for surgery, several scans of the patient faces were obtained with a commercial surface scanner. We then applied noise reduction and semi-automatic face segmentation on each scan with the scanner software to extract the face surface in the upper face region (forefront, eyes, and nose). Next we applied a robust two-step rigid registration algorithm on both cloud of points to align the datasets. The first step establishes a coarse correspondence based on four eye and nose bridge landmarks automatically extracted from both the CT/MRI and the face scan. The final transformation was then obtained with a robust Iterative Closest Point registration [11]. Afterwards, we computed in our laboratory the actual FRE as the mean Euclidean distance between the two registered surfaces, and an estimate of the TRE at increasing distances from the surface scan center of mass with the formula in [13].

In addition, we studied the sensitivity of the error to the scanning conditions, which depends on the surface scanner internal parameters, the patient anatomical properties, and the environment parameters. Scanner parameters include the intensity of the projected structured light and the expected object brightness. Patient parameters include the skin color and the presence of facial hair. Environmental parameters include the operating room illumination, the distance and orientation of the surface scanner with respect to the patient, and the surrounding tools, tubes, and other equipment around.

3. Experimental results

We scanned the 14 patients in the actual operating room clinical setup. Two patients were omitted, as their MRI images were too noisy due to patient motion during the scan. Of the remaining 12, one was a CT scan and the rest were MRI scans. The MRI scans are $256 \times 256 \times 200$ voxels with voxel size of $0.93 \times 0.93 \times 1mm^3$ from which 73-115K face surface points were automatically extracted [8]. The CT scan is $512 \times 512 \times 100$ voxels with similar voxel size from which 64K face surface points were extracted with the ITK-SNAP toolkit [12]. The surface scans were acquired with the faceSCAN II (Breuckmann, Germany), whose RMS accuracy is 0.3mm (std=0.2mm). The surface points were automatically computed from the segmented images with custom software. Intraoperatively, we acquired a total of 34 scans of the 12 patients (7 on supine and 5 on lateral position). For each patient, several scans were acquired with different scanning, patient, and environmental setups. The registration time was < 1min on a standard PC.

We computed the actual FRE and the estimated TRE after registration at 10 targets of increasing distance from the face surface center of mass. Based on this, we derived the following indications to obtain optimal results. The surface scanner should be above the patient head and at a distance of 0.9-1.2m. The scanner internal parameters for light intensity should be 75-100 units and the expected scanned object parameter set to "dark". The patient skin color and facial hair do not affect the registration accuracy.

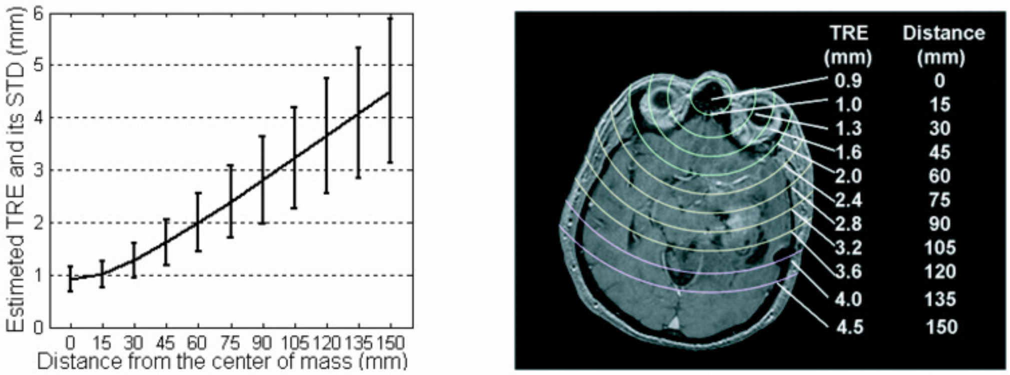
4. Discussion

Our results show a surface registration RMS error of 0.91mm (std=0.35mm, max=2.0mm). These are excellent results, comparable to those obtained by contact-based registration, with a CT/MRI resolution of about 1mm and variability in the patient's anatomy and surgical conditions. Fig 1. shows the results. As expected, the estimated mean TRE and its standard deviation increase as the target locations are further from the face scan center of mass.

The clinical relevance of these results can be visualized by superimposing the estimated TRE error on the patient's MRI iso-lines. The iso-lines show the error estimations and allow the surgeon to evaluate the viability of the surface scanning method for a specific patient and surgical application. For example, applications requiring an accuracy of 2mm can be performed for targets in the frontal area, at an average depth of at most 60mm. More forgiving applications, requiring an accuracy of 4mm can be performed for deeper targets, at average depth of 135mm. In addition, for specific patients, the accuracy also varies. For example, the estimated TRE at depth 150mm of two patients was 6.0mm versus 3.0mm, while their FRE was the same.

5. Conclusion

We have presented a clinical study of surface-based registration between a preoperative CT/MRI of the patient head and an intraoperative surface scan of his/her face. Our results on 12 patients in various clinical conditions show that the surface registration error is comparable to that obtained by contact-based registration with skin-applied



(a) Mean (range) of estimated TRE (b) Estimated TRE iso-lines on MRI slice

Figure 1: Estimated Target Registration Error (TRE) as a function of its distance from the face surface center of mass.

markers in commercially available optical-based neuronavigation systems. Moreover, the study quantifies the estimated target registration error inside the brain, showing what specific accuracy can be predicted in each region of the brain. This provides a valuable tool to support the surgeon's decision on how to proceed.

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