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Stereotactic and Functional Neurosurgery

A Noncontacting 3-D Digitizer for Use in Image-Guided Neurosurgery

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Stereopsis · Patient registration · Brain deformation · Brain modeling

Abstract
Current neuronavigational systems face two primary challenges: (1) automatic and robust registration between preoperative images and the operating room space, and (2) compensation for brain deformations that compromise the accuracy of the initial registration. To contend with these difficulties, we firstly estimate the three-dimensional (3-D) structure of the cortical surface using a noncontacting 3-D digitizer. This 3-D structure is then used to establish the initial registration, and to update the preoperative MR volume as the brain deforms. We show that this approach improves the accuracy of registration in a phantom study, and demonstrate the ability to capture cortical motion in six clinical cases.

Introduction

The current approach for patient registration in image-guided neurosurgery is to manually localize skin- or skull-attached fiducials both in the MR volume and in the operating room (OR) after the patient is anesthetized. The transformation matrix that aligns the preoperative images with the OR space is then esti-

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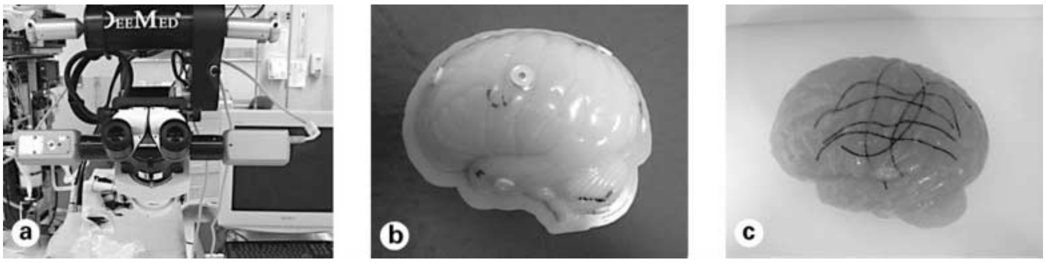

Fig. 1. 3-D digitizer and brain phantom. **a** The operating microscope attached to two CCD cameras. **b** The brain phantom with the conventional fiducials attached to the mold. **c** The brain phantom with the cortical vessels mimicked with electric wires.

mated. As the surgery progresses, the accuracy of this registration deteriorates as a result of soft tissue deformations. There is a need to both automate the initial registration and update the preoperative MR volume to compensate for brain movements.

To avoid scalp-attached fiducials, Nakajima et al. [1] used cortical vessels as registration landmarks. Their approach, however, required extensive manual manipulations. To contend with brain deformations, Skrinjar et al. [2] used two video cameras to model and track cortical surface motion, the results of which were used to update the preoperative MR image volume. Their approach relied on a restrictive Lambertian assumption and employed only a weak calibration.

Building on these basic concepts, we show how an automatic and robust estimation of the three-dimensional (3-D) structure of the cortical surface can be used for initial registration and updating of the preoperative image volume.

Patients and Methods

In this section, we begin with an explanation of how to transform an operating microscope into a 3-D digitizer. We then present the steps involved in patient registration using cortical vessels and the method of estimating cortical motion to update the preoperative image volume.

A 3-D Digitizer via Stereopsis

By attaching two CCD cameras to the binocular optics of the operating microscope (fig. 1a), we can estimate the 3-D structure of the cortical surface. Prior to surgery, this stereo imaging system is calibrated to obtain the extrinsic and intrinsic camera parameters [3]. A stereo image pair is acquired at 15 frames per second. The 3-D coordinates of cortical features, such as vessels, can be estimated in two steps. The first step is stereo matching: for each feature in the right image, the corresponding feature in the left image is found. To accomplish this, we have implemented a number of matching constraints tailored to the cortical image characteristics [see ref. 4 for more details and ref. 5 for a general survey]. The second step is triangulation: the desired 3-D coordinate is computed by combining the estimated correspondences with the camera calibration parameters.

Vessel-Based Registration

The first task for stereopsis is to estimate the 3-D coordinates of cortical vessels and use them, in lieu of the scalp-attached fiducial markers, to register between preoperative images and the OR space. This process can be divided into three steps: (1) segmentation of the vasculature proximal to the surgical focus in the preoperative images and obtaining the coordinates of these vessels in the image volume; (2) localizing the same set of vessels in the OR using stereopsis after craniotomy, and (3) estimating the transformation matrix that relates preoperative images with the patient in the OR – the iterative closest point algorithm [6] is employed for this estimation. Although segmentation of vessels in the MR image volume may involve some manual steps, this process can be completed off-line and prior to the surgery. With the ability to automatically localize the cortical vessels in the OR, we can automate the steps of patient registration performed in the OR.

Compensation for Brain Deformations

The second task for stereopsis is to reconstruct the 3-D coordinates of the exposed cortical surface at the craniotomy site. The motion of the surface can then be estimated over time and used to compensate for brain deformations via finite element method (FEM)-based brain modeling. To begin, the boundary of the cortical surface is manually outlined, and approximately 2,000 uniformly spaced pixels within this region are reconstructed. A parameterized surface is then fit to these estimated 3-D coordinates to combat noise and increase the robustness of the reconstruction. As the brain deforms, a new cortical surface can be reconstructed. The iterative closest point algorithm is again used to track the reconstructed points between surfaces. We are working on using these intraoperative data to update the preoperative image volume.

Results

We are able to estimate the 3-D structure of a surgical scene with an average accuracy of 1.6 mm. Executed on a 1.1-GHz Pentium machine, the 3-D estimation from a stereo pair of 1,024 × 768 images requires approximately 60 s of computation.

Using a brain phantom, shown in figure 1b and c, we compared the accuracy of patient registration using cortical vessels with that using skin-attached fiducials. The fiducial registration error was reduced to 0.26 mm using cortical vessels from 0.99 mm using skin-attached fiducials (table 1).

In our six clinical cases, we used the 3-D digitizer to track the cortical surface. For these six cases, the mean number of features reconstructed to capture the topology of the cortical surface was 2,309, with a minimum of 1,898 and a maxi-

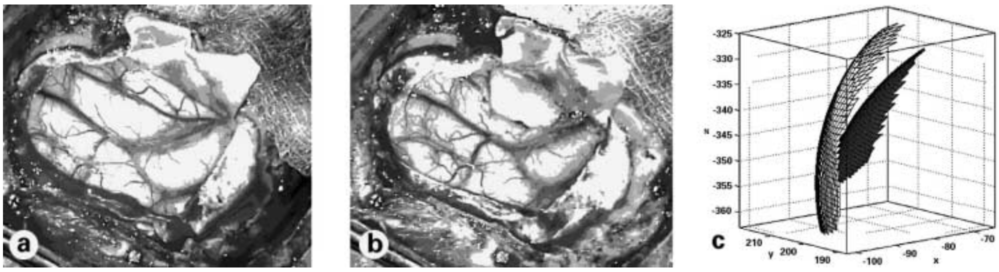

Fig. 2. a, **b** The reconstructed cortical surfaces before (**a**) and after (**b**) a tissue resection. **c** The reconstructed cortical surfaces before (white) and after (gray) resection.

Table 1. Comparison of two registration strategies in a phantom study

	Points	FRE, mm
Using conventional fiducials	7	0.98
Using cortical vessels	57	0.25

FRE = Fiducial registration error.

Table 2. Cortical surface displacements (mm) in six clinical cases

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Minimum displacement	−3.4	−2.1	−1.2	2.1	−3.2	−4.5
Maximum displacement	−12.4	−10.7	−9.9	5.9	4.3	3.9
Mean	−9.5	−6.9	−5.2	3.3	0.7	1.2

mum of 2,857. An example of the reconstructed results is illustrated in figure 2; shown in a and b are microscope images before and after a tissue resection, respectively, and shown in c is the estimated cortical surface. Note the significant shift of the cortical surface postresection. The preliminary results from all six cases, including the minimum, maximum and mean of the estimated displacements, are reported in table 2. A negative value indicates a sagging motion, while a positive value indicates a bulging motion, relative to the closed cranium position. In cases 1, 2 and 3, as a result of cyst drainage or tissue resection, the cortical surfaces sagged. In case 4, the cortical surface bulged as the result of an electrode implantation. In cases 5 and 6, the motions of the cortical surfaces represented combinations of sagging and bulging. The magnitude of these shifts shows the importance of compensating for brain deformations. We can now use these data to guide an FEM-based model for updating the preoperative image volume.

Discussion

We have demonstrated that an operating microscope is capable of digitizing 3-D surfaces with efficient acquisition and image analysis of stereo pairs, without inducing brain deformations. In a phantom study, we used the reconstructed cortical vessels to automatically register the preoperative image volume with the OR space. In six clinical cases, we captured the cortical motions using a noncontacting 3-D digitizer. Our future work includes testing the strategy of using cortical vessels for patient registration in clinical cases and incorporating the motion of the cortical surface into an FEM model to update the preoperative MR volume.

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