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Biomechanical modeling provides more accurate data for neuronavigation than rigid registration

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Abstract

It is possible to improve neuronavigation during image-guided surgery by warping the high-quality preoperative brain images so that they correspond with the current intraoperative configuration of the brain. In this work, the accuracy of registration results obtained using comprehensive biomechanical models is compared to the accuracy of rigid registration, the technology currently available to patients. This comparison allows us to investigate whether biomechanical modeling provides good quality image data for neuronavigation for a larger proportion of patients than rigid registration. Preoperative images for 33 cases of neurosurgery were warped onto their respective intraoperative configurations using both biomechanics-based method and rigid registration. We used a Hausdorff distance-based evaluation process that measures the difference between images to quantify the performance of both methods of registration. A statistical test for difference in proportions was conducted to evaluate the null hypothesis that the proportion of patients for whom improved neuronavigation can be achieved, is the same for rigid and biomechanics-based registration. The null hypothesis was confidently

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5. Disclosure

The authors report no conflict of interest concerning the materials or methods used in the study or findings specified in this paper.

rejected ($p\text{-value} < 10^{-4}$). Even the modified hypothesis that less than 25% of patients would benefit from the use of biomechanics-based registration was rejected at a significance level of 5% ($p\text{-value} = 0.02$). The biomechanics-based method proved particularly effective for cases experiencing large craniotomy-induced brain deformations. The outcome of this analysis suggests that our nonlinear biomechanics-based methods are beneficial to a large proportion of patients and can be considered for use in the operating theatre as one possible method of improving neuronavigation and surgical outcomes.

Keywords

Brain shift; image-guided neurosurgery; nonlinear biomechanical models; nonrigid registration; finite element method

1. Introduction

Complete surgical removal of a cerebral tumor is highly desirable, yet often difficult to achieve. One of the factors that complicate near-complete tumor resection is the craniotomy-induced brain shift that occurs during neurosurgery. It has been established that during craniotomy the brain surface can deform by more than 20 mm²³ and by more than 10 mm in approximately 30% of patients¹⁰. Figure 1 shows the brain deformation experienced upon opening of the skull. As brain shift distorts the anatomy, it diminishes the utility of preoperatively acquired image data^{17,21}. Therefore the efficiency of intraoperative neuronavigation can be significantly improved by fusing high resolution preoperative imaging data with the intraoperative configuration of the patient's brain. This can be achieved by updating the preoperative image to the current intraoperative configuration through a technique known as registration. Although current commercial image-guided navigation systems use rigid registration for this purpose, we are starting to see a shift towards nonrigid registration, which is necessary to capture the nonrigid movement of brain tissue caused by brain shift^{1,4,6,16,18,25}.

Rigid registration is generally carried out in the operating room using neuronavigation systems such as the ExacTrac system available in BrainLab¹² (www.brainlab.com) or the StealthStation neuronavigation system from Medtronic⁹ (www.medtronic.com). In the BrainLab system, the patient is registered to the preoperative image by matching the positions of fiducial markers on the patient and the image. In the Stealth system, registration is performed by matching landmarks identified by a tracked pointer. Although nonrigid registration is believed to provide better data, most current methods^{4,6,16,18,25} are inefficient, that is, cannot provide results in real-time and do not account for the large brain deformations, often observed during surgery^{14,20}. Our biomechanics-based nonrigid registration method overcomes these limitations^{14,20}.

The potential of nonrigid registration has been previously demonstrated and well-documented^{11,13,14,19,31,33}. In brief, we use a biomechanics-based computational model to predict the deformation of the brain, and use this predicted deformation to warp (deform) the preoperative magnetic resonance (MR) imaging data to the current intraoperative position of the brain. We have developed, refined and rigorously tested our methods^{13,14,19,31} to now

achieve this in real-time using a desktop computer during neurosurgery^{14,15}. We are confident that our methods now enable the accurate estimation of brain shift and thus lead to a safer and more efficient surgical approach.

A key advantage of our approach is that it does not require intraoperative MR images and complements existing neuronavigation equipment. The measurement of the position of a number of points on the exposed surface of the brain is sufficient and can be conducted in the operating room using existing neuronavigation technology. The tracking pointer tool available within Medtronic's Stealth neuronavigation system, enables the surgeon to select (by touching) a number of points on the brain surface (technical details regarding the software application are available online at http://www.na-mic.org/Wiki/index.php/Stealthlink_Protocol) and determine their positions in the images using software tools implemented in 3D Slicer^{5,26–28}. This data then serves as an input to our biomechanics-based approach.

In our current work, the advantages of our biomechanics-based approach relative to traditional rigid registration are demonstrated for 33 cases of neurosurgery. To establish the efficacy of our method, a test for difference in proportions³ was performed to evaluate the null hypothesis that the proportion of patients for whom improved neuronavigation can be achieved, is the same for rigid and biomechanics-based registration. The paper is organised as follows: in Section 2, the registration procedures, the methods used to test for accuracy and statistical evaluation methods employed are described; the results for both registration techniques and their statistical analysis are reported in Section 3; and finally, in Section 4, the outcome of the work and clinical applications are discussed.

2. Materials and Methods

2.1 Medical image data

Preoperative and intraoperative medical image datasets of 33 patients with cerebral gliomas were randomly selected from a retrospective database of 859 intracranial tumor cases available at the Children's Hospital in Boston²⁹. The types, locations and sizes of these tumors are presented in Table 1. Imaging was performed using a 0.5T open MR system in the neurosurgical suite. The resolution of the images is $0.85 \times 0.85 \times 2.5 \text{ mm}^3$. Consent was obtained for the use of the anonymized retrospective image database, in accordance with the Institutional Review Board of the Children's Hospital in Boston.

2.2 Biomechanical modeling-based registration

We begin by computing the deformation fields of the brain using a computational model and subsequently use this information to warp (deform) the preoperative images onto their intraoperative configuration (Figure 2). For a detailed description of the numerical modeling approach to predict deformation, the reader is referred to our earlier work^{20,32}. The workflow in clinical situations would be as follows:

Preoperative steps:

- a) The preoperative image is segmented (divided) into the desired structures such as parenchyma, ventricles and tumor (Figure 3).
- b) Based on this segmentation, which can be performed days before the surgery, a patient-specific brain computational model is generated (Figure 3).

Intraoperative steps:

- c) Using only sparse intraoperative data, for example, positional information of the exposed brain acquired using the pointer tool of the StealthStation (Medtronic, Inc.); we apply loading conditions to our computational model.
- d) Once the model is completely defined, we compute the deformation, and then warp the preoperative image so that it now shows the intraoperative configuration of the brain (Figure 2). This final step is performed in real-time during neurosurgery.

2.3 Current technique available to patients: rigid registration

Rigid registration is the standard registration method currently available to patients in MR-equipped operating theatres. In this approach, the preoperative image is aligned with the intraoperative image such that the rigid transform minimizes the mutual information between both images. This technique was described in detail by Wells et al.³⁰ and has been widely adopted by leading intraoperative navigation companies.

2.4 Evaluation of registration accuracy using Hausdorff Distance

Intraoperative MR images acquired using the open 0.5T system were used as the actual configuration (ground truth) to which we compared the results of both rigid and our biomechanics-based registration. We used the Hausdorff Distance (HD) metric to calculate the spatial differences (in millimetres) between two overlaid images. HD was measured by comparing automatically detected feature edges, known as Canny edges². We subsequently evaluated the HD results for both rigid and biomechanics-based registration using intraoperative image data as ground truth, as described in our earlier work⁷. These Canny edges used in evaluation process are shown in Figure 4.

Almost all Canny edges in the warped preoperative image have a corresponding edge in the intraoperative image, that is, they apparently represent the same anatomical feature in both MR images (Figure 4). However, outliers (unusually large HD values) arise when some Canny edges that do not represent the same anatomical feature (hence farther apart), are compared (Figure 4). These outliers (unusually large HD values), confirmed by subsequent visual inspection of the images, were excluded from the final analysis. By reporting the complete HD results over the full percentile (0–100) range, instead of a single quantity at a certain percentile, it is easier to determine the entire range of alignment errors, and also identify potential outliers. In order to report HD values over full percentile range, we used the n^{th} percentile-HD metric that is defined as the HD value that is greater than n percent of the total number of HD values belonging to edges of either image.

2.5 Statistical evaluation using test for difference in proportions

To statistically ascertain whether or not our biomechanics-based approach demonstrates improvements over rigid registration, the test for difference in proportions was conducted³. Our null hypothesis was defined as follows:

Null Hypothesis (H_0)—There will be no statistically significant increase in the proportion of neurosurgery patients for whom accurate data for intraoperative navigation is obtained, when using our biomechanics-based method, as compared to rigid registration (Ability to confidently reject this hypothesis will demonstrate the superiority of our biomechanics-based approach).

The test statistic is a numerical summary of a data set that reduces the data to one value, which can be used to perform a hypothesis test. For the test for difference in proportions, the test statistic follows a normal distribution and depends on the proportion of “Yes” responses (*false null hypothesis*) for both registration methods. In the current study, “Yes” is the response, when the evaluation results show that our biomechanics-based method has at least as good accuracy as rigid registration (therefore, rejects H_0); otherwise the response is “No”. P-value, which is defined as the estimated probability of rejecting the null hypothesis (H_0), when that hypothesis is true^{8,24}, is used to decide the test for difference in proportions between the populations of each group^{3,8,24}. Results with p-value less than 0.05 were considered statistically significant.

3. Results

3.1 Demonstration of the inadequacy of rigid registration using an example case

The overlaid Canny edges for our biomechanics-based method and rigid registration are shown in Figure 5 in both the axial and coronal planes for Case 7. This case experienced large brain shift (10 mm). Here, the misalignments experienced using our biomechanics-based method are less than those found using rigid registration. This observation is also supported by the results from the percentile-HD analysis for Case 7 shown in Figure 6. The misalignment (HD metric) values for rigid registration are higher than those of the biomechanics-based method for all percentiles between 0–100 in both planes. As the accuracy of Canny edge detection is limited by the resolution of the original medical image, an alignment error less than two times the in-plane resolution of the intraoperative image is difficult to avoid²⁹ (1.7 mm in this study). Therefore, edges with misalignment values less than 1.7 mm were considered successfully registered. This choice is consistent with the accuracy of manual neurosurgery, which is reported to be not better than 1.5 mm^{22,29}. Figures 5 and 6 clearly demonstrate the insufficiency of rigid registration for cases with large deformations.

3.2 Biomechanics-based versus rigid registration: statistical results

Small craniotomy-induced deformation, defined as deformation less than 3.3 mm, was observed in 19 cases. For these small deformation cases, there was an insignificant difference between the percentile-HD metric curves, implying that both registration techniques perform similarly. Figure 7 shows this comparable performance using the

percentile-HD results for a typical small deformation case (Case 3). However, in the remaining 14 cases where brain shift exceeded 3.3 mm, our biomechanics-based method proved more accurate.

P-values for the test for difference in proportions—The number of “Yes” responses for our biomechanics-based method and rigid registration were 33 and 19, respectively. P-values for difference in proportions of 0%, 20% and 25% are 0.0000125, 0.00457 and 0.02, respectively. Therefore, there is strong evidence that more than 25% of patients undergoing surgical resection of gliomas would benefit from the application of our biomechanics-based methods.

4. Discussion and Conclusions

The results presented in Section 3 demonstrate that our biomechanics-based method provides improved neuronavigation data for a larger proportion of patients, compared to the commonly-employed rigid registration method. Our method proved particularly effective in cases where the patient experienced a large craniotomy-induced brain shift (>3.3 mm). The probability of less than 25% of patients benefitting from the intraoperative use of computational biomechanics-based brain shift compensation is only 2%; or in other words, the probability of more than 25% of patients benefitting from our approach is 98%. On the basis of our findings, larger scale efficacy testing of our methods is now warranted, with a view to future clinical implementation. Clinical application of this method is further facilitated by the distinct advantage of this new approach, that is, the redundancy of intraoperative MR data. Only the displacements of a limited number of points on the exposed surface of the brain need to be measured using typical neuronavigation systems.

Experience at Brigham and Women’s Hospital²⁹ has demonstrated that intraoperative MR image is immensely useful in ensuring near-complete resection, particularly of low grade tumors. However, this usually comes at the expense of significantly longer operating times, as well as being resource intensive. The use of real-time comprehensive biomechanical computations in the operating theatre could present a viable and economical alternative to an intraoperative MR image. Thus the results presented in this report have the potential to significantly advance the way medical imaging, combined with biomechanical modeling, is used to guide the successful resection of brain tumors.

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Figure 1.

An example of craniotomy-induced brain shift. In the preoperative Magnetic Resonance (MR) image (left), the perimeter of the brain is identified with the green colored spline. Registration of this spline to the intraoperative image, obtained using MR imaging (right), clearly shows the brain shift induced by the surgical procedure. Therefore, surgical planning using preoperative images may result in ineffective procedures.

Figure 2.

Registration process based on our biomechanics-based methods. The flow chart (beginning with the preoperative image) illustrates the various steps used in registering the preoperative images onto their intraoperative configuration. M is the moving image (preoperative image). T is the transform that registers the preoperative image onto the intraoperative configuration of the brain. $T(M)$ is the transformed moving image (warped preoperative image).

Figure 3.

An example (Case 7) of a segmented geometry (left) from preoperative Magnetic Resonance (MR) image and the resulting patient-specific brain mesh (right). An essential engineering-specific detail of the brain mesh (Case 7) is that it consists of 99974 elements and 32023 nodes.

Figure 4.

Evaluation of registration accuracy using Canny edges. Canny edges of a preoperative image warped using our biomechanics-based approach, cropped to the region of interest, and the corresponding intraoperative image. (A) Biomechanics-based warped preoperative image. (B) Canny edges of biomechanics-based warped preoperative image. (C) Corresponding intraoperative image. (D) Canny edges of intraoperative image. By comparing these Canny edges using the Hausdorff Distance method, it was possible to quantify the registration error and the accuracy of each technique.

Figure 5.

Overlaid Canny edges for both registration techniques in two different planes for an example large deformation case (Case 7). (A) Biomechanics-based method in axial plane. (B) Rigid registration in axial plane. (C) Biomechanics-based method in coronal plane. (D) Rigid registration in coronal plane. The green colored portion represents overlapping edges, the blue colored part identifies non-overlapping edges of the warped preoperative image, and the red colored part identifies non-overlapping edges of the intraoperative image.

Figure 6.

Percentile-HD metric curves for axial (left) and coronal (right) plane for an example case of large deformation (Case 7). The horizontal line in the plots represents the minimum expected registration error (1.7 mm).

Figure 7. Percentile-HD metric curves for axial (left) and coronal (right) plane for an example case of small deformation (Case 3). The horizontal line in the plots represents the minimum expected registration error (1.7 mm).

Table 1

The sizes, types and locations of the tumors (cerebral gliomas) for all 33 cases.

Case number	Tumor size (mm)	Type	Location
1	23	Diffuse Astrocytoma	Posterior
2	26	Diffuse Astrocytoma	Lateral
3	11	Diffuse Astrocytoma	Lateral
4	31	Diffuse Astrocytoma	Lateral
5	49	Focal Astrocytoma	Lateral
6	48	Diffuse Astrocytoma	Lateral
7	16	Focal Astrocytoma	Lateral
8	35	Focal Astrocytoma	Posterior-Lateral
9	22	Diffuse Astrocytoma	Anterior-Lateral
10	31	Focal Astrocytoma	Anterior-Lateral
11	25	Focal Astrocytoma	Lateral
12	27	Oligodendroglioma	Anterior
13	28	Diffuse Astrocytoma	Anterior
14	18	Focal Astrocytoma	Anterior
15	11	Diffuse Astrocytoma	Lateral
16	20	Diffuse Astrocytoma	Posterior
17	22	Diffuse Astrocytoma	Posterior
18	23	Diffuse Astrocytoma	Anterior
19	17	Diffuse Astrocytoma	Posterior-Lateral
20	13	Focal Astrocytoma	Anterior-Lateral
21	19	Diffuse Astrocytoma	Lateral
22	15	Diffuse Astrocytoma	Lateral
23	18	Diffuse Astrocytoma	Lateral
24	13	Diffuse Astrocytoma	Posterior-Lateral
25	9	Diffuse Astrocytoma	Posterior-Lateral
26	14	Diffuse Astrocytoma	Anterior
27	18	Diffuse Astrocytoma	Anterior
28	26	Diffuse Astrocytoma	Posterior
29	9	Focal Astrocytoma	Lateral
30	18	Diffuse Astrocytoma	Lateral
31	18	Diffuse Astrocytoma	Anterior-Lateral
32	47	Diffuse Astrocytoma	Posterior
33	20	Diffuse Astrocytoma	Posterior

The tumor size was defined as the length of the longest diagonal of the cuboid that envelopes the tumor. Tumor size was rounded to the nearest millimeter. All the 33 tumors are low-grade gliomas. The location of the tumor was defined in the axial plane.