A Biomechanical Model of the Human Head for Elastic Registration of MR-Images

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Abstract. The accuracy of image-guided neurosurgery generally suffers from brain deformations due to intraoperative changes, e.g. brain shift or tumor resection. In order to improve the accuracy, we developed a biomechanical model of the human head which can be employed for the correction of preoperative images. By now, the model comprises two different materials while the correction of the preoperative image is driven by a set of given landmark correspondences. Our approach has been tested on synthetic images and yields physically plausible results. Additionally, we carried out registration experiments with a preoperative MR image and a corresponding postoperative image simulating an intraoperative image. We found, that our approach yields good prediction results, even in the case when correspondences are given in a small area of the image only.

Keywords: biomechanical model, inhomogeneous materials, FEM

1 Introduction

The accuracy of image-guided surgery generally suffers from brain deformations due to intraoperative changes like brain shift or tumor resection. To improve the navigation accuracy, we developed a biomechanical model of the human head which allows to predict surgery-induced brain deformations and thus enables to correct preoperative images. Our approach is based on the well-established physical theory of continuum mechanics and uses the finite element method for discretization, which results in a large linear matrix system. Instead of using forces, which are generally difficult to determine from images, we use a set of given correspondences to drive the correction of preoperative images. Different materials were incorporated by spatially varying the material parameters according to the underlying anatomical structure. Prior to our registration experiments with clinical 2D pre- and postoperative tomographic images, we carried out experiments with synthetic 2D images in order to assess the physical plausibility of the deformations predicted by our model.

Previous work on intraoperative image correction, which also addressed the incorporation of different material properties, is based on mass-spring systems [1], a combination of different energy terms [2], or thin-plate splines [3]. However, in comparison to our approach, these models do not incorporate real physical material parameters and hence are only weakly related to the physical behaviour of biological soft tissue.

2 Approach

Our biomechanical model is based on the equations of motion which describe the deformation of a body Ω under externally applied forces. The material properties of Ω are incorporated by substituting the corresponding constitutive equation, which describes the stress/strain relationship of the body, into the equations of motion. Assuming linear elastic materials, i.e. using Hooke's law as constitutive equation, we yield a set of coupled differential equations:

$$\begin{cases} -\mathrm{div}[\lambda(\mathrm{tr}\mathbf{e}(\mathbf{u})) + 2\mu\mathbf{e}(\mathbf{u})] = \mathbf{f} & \text{in } \Omega \\ (\lambda(\mathrm{tr}\mathbf{e}(\mathbf{u}))\mathbf{I} + 2\mu\mathbf{e}(\mathbf{u}))\mathbf{n} = \mathbf{g} & \text{on } \Gamma. \end{cases} \tag{1}$$

Here, λ and μ denote the Lamé constants, $\mathbf{u}$ the unknown displacement vector field, $\mathbf{e}(\mathbf{u})$ Cauchy's infinitesimal strain tensor, $\mathbf{I}$ the identity matrix, $\mathbf{n}$ the unit vector normal to the boundary Γ, $\mathbf{f}$ the applied body forces, and $\mathbf{g}$ the forces acting on Γ. Applying the finite element method, i.e. dividing the body Ω into quadrilateral elements and approximating the unknown continuous function $\mathbf{u}$ by elementwise linear basis functions multiplied with unknown coefficients u_i, yields the linear system

$$\mathbf{Au} = \mathbf{f}, \tag{2}$$

which can be solved for the unknown $\mathbf{u}$. The correspondences for anatomical structures are both computed and incorporated into (2) as described in [4].

3 Material Parameters

So far, our biomechanical model distinguishes two different materials only: brain tissue and skull bone. These materials can be incorporated into the linear equation system (2) by spatially varying the values of the Lamé constants λ and μ according to the underlying anatomical structure. Since we drive the deformation by a set of given correspondences, which are always exactly fulfilled by the model, only the ratios of λ and μ are important for our biomechanical model. A comparison of the calculated ratios found by a comprehensive literature study revealed the interesting fact, that only a small number of different Lamé constant ratios for brain tissue and skull bone exists. Application of these ratios for some initial synthetic experiments showed only slight differences in the resulting deformations. Thus, we conclude that the mean values of the ratios serve as valid estimates for the material parameters. Figure 1 shows the resulting grid deformations and calculated displacement fields using these mean values.

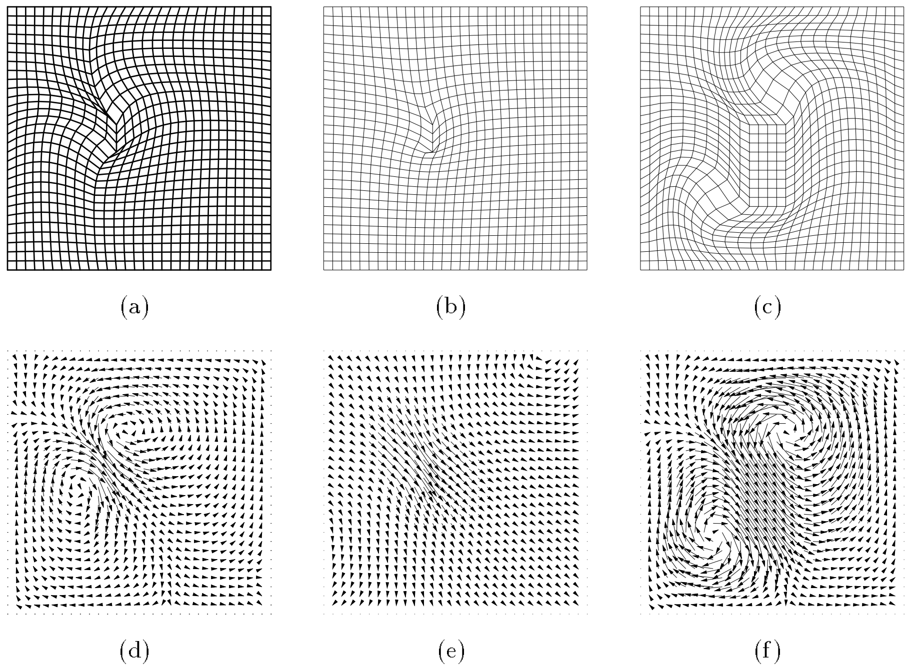
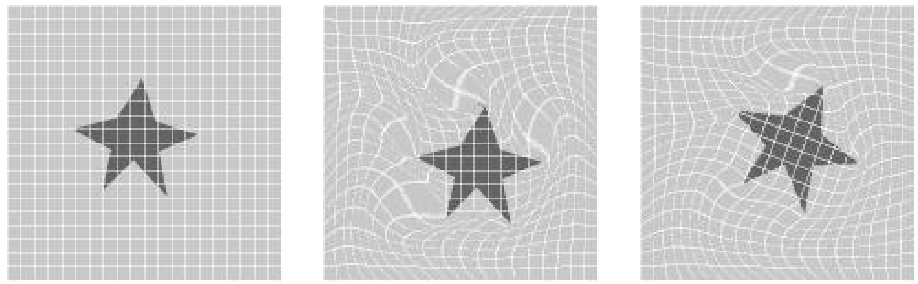


Fig. 1. Resulting grid deformations (top row) and displacement vector fields (bottom row) due to four correspondences acting on the upper left part of the grid. In (a) and (b) homogeneous areas of type brain tissue and skull bone were assumed, respectively. As expected, the assumed skull material results in a much stiffer behaviour. By spatially varying the Lamé constants, we can combine different materials as shown in (c). Here, a (simulated bony) rectangle embedded in simulated brain tissue results in a pure, shape-preserving translation of the rectangle while the surrounding tissue is deformed elastically.

4 Experiments

Our approach has been tested on 2D synthetic images as well as real tomographic datasets. The synthetic experiments comprised different types of movements of a rigid object (e.g., translation, rotation, scaling, and shearing) embedded into an otherwise elastic material. As shown in Figure 2, our approach yields physically plausible results. Problems arise with objects rotated by an angle larger than $45°$. A possible explanation is that the linear elasticity assumption of small displacements is violated in the experiments with large rotation angles.

For the experiments with real data, we used 2D pre- and postoperative MR images which were routinely acquired in conjunction with the planning and therapeutic assessment of a tumor resection. First, the corresponding tumor outlines in both images were manually determined by a medical expert, see Figures 3(a) and (b). Thereafter, the snake algorithm described in [4] has been applied to determine the correspondences for these outlines, which then have



(a) (b) (c)

Fig. 2. Predicted translation of a rigid star embedded into soft material (a) due to two given correspondences (b). In (c), only one correspondence was used, resulting in a translation and rotation of the star.

been used as input for our model to match the pre- with the postoperative image. Assuming only homogeneous soft material for the whole image, Figure 3(d) shows the locally erroneous registration result. In order to improve the registration result, especially in the vicinity of the ventricular system, different materials were incorporated by locally varying the Lamé constants according to the underlying anatomical structures. Therefore, the preoperative image was segmented with an interactive watershed algorithm [5] into four different regions as shown in Figure 3(c): combined skin/skull region (white), brain (dark grey), CSF (light grey), and surrounding air, i.e. image background (black). For brain and skull, the previously determined ratios were used, while CSF and air were roughly approximated as rigid and very soft materials, respectively. The registration result is shown in Figure 3(e). Here, a global translation of the head can be observed which leads to a surprisingly poor result. However, this global effect can be easily suppressed by assuming a rigid image background, i.e. by assigning the Lamé constant values of a rigid body to the image background, see Figure 3(f).

5 Summary and Conclusion

We proposed a biomechanical model of the human head based on linear elasticity theory to predict brain deformations due to surgical interventions. The model is driven by a set of given correspondences and incorporates different material properties. By carrying out experiments using synthetic as well as real medical images, it turns out that the approach yields physically plausible deformation results. We expect that the incorporation of different types of constitutive equations renders possible further improvements of the prediction results.

6 Acknowledgement

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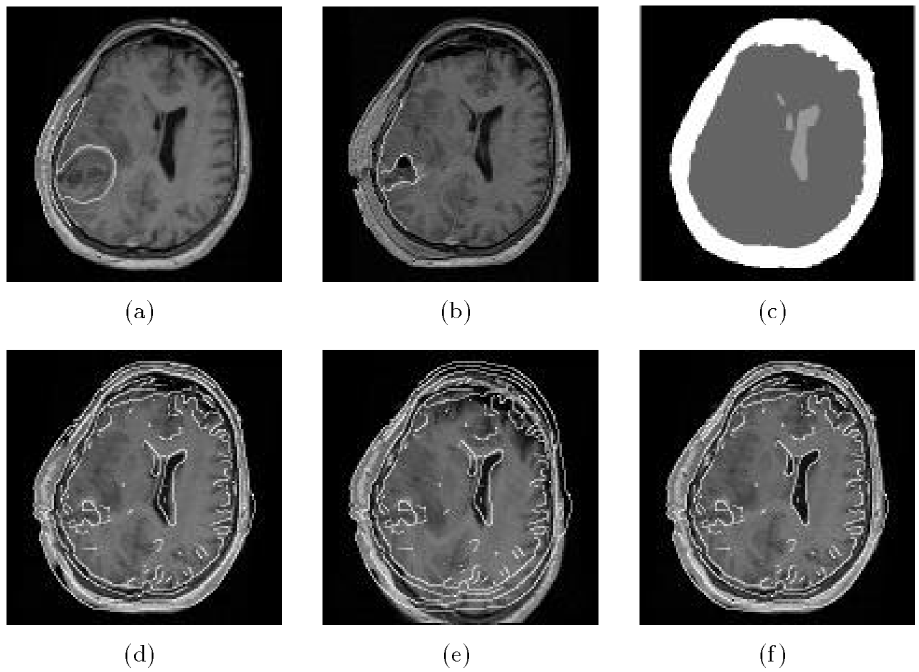

Fig. 3. Manually determined outlines in the pre- (a) and postoperative (b) image. In (c), the segmented regions using an interactive watershed algorithm are depicted. Figure (d) shows the registration result assuming homogeneous soft material properties only (with overlaid Canny edges of the original postoperative image). For the result depicted in (e), inhomogeneous material properties based on the segmentation given in (c) were assumed. The global head translation can be suppressed by assuming an artificial rigid image background, resulting in the overall good registration result of (f).

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