Validation of Non-Rigid Registration of Contrast-Enhanced MR Mammography using Finite Element Methods

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Abstract. This paper presents a validation study for non-rigid registration of 3D contrast enhanced magnetic resonance mammography images. We compare the performance of two non-rigid registration algorithms based on single- and multi-level free-form deformations using B-splines and normalized mutual information. To assess the registration performance, we employ a biomechanical deformation simulator of patient motion likely to occur *in vivo*.

1 Introduction

Contrast enhanced magnetic resonance (CE-MR) mammography imaging is an emerging imaging technique for the detection and diagnosis of breast cancer. It requires the acquisition of a 3D MR scan prior to the injection of a contrast agent like Gadolinium DTPA, followed by a dynamic sequence of 3D MR scans. Contrast uptake curves derived from the subtraction between pre- and post-contrast images can be used to detect cancerous lesions, and to distinguish between malignant and benign disease. To facilitate this analysis, image registration [1, 2] is needed to correct for any patient motion occurred between scans induced by breathing motion, patient reaction to contrast injection, contraction and relaxation of the pectoral muscles, and movement against the scanner RF coil. A number of registration algorithms have been developed in recent years to correct for these particular motion artefacts in CE-MR images, taking the non-rigid nature of the tissue motion and deformation into account [3–5]. Prior to clinical use, it is necessary to validate any such registration technique in order to maintain clinical usefulness of the data. Validation of non-rigid registration is limited however by the lack of knowledge as to if, how much, and where patient movement has occurred. We have recently presented a methodology for validation of non-rigid registration using finite element methods (FEMs) [6] where we generate biomechanical, physically plausible deformations to simulate a gold standard deformation vector field. In this paper, we apply this validation strategy to compare the performance of Rueckert's registration method [5] to our extended generalized registration framework [7].

2 Method

From a large CE-MR mammography database, four patient cases were selected, which, unlike the great majority of cases in the database, showed little motion between image acquisitions. For these, we have constructed finite element models of tetrahedral structural solids with quadratic displacement behaviour using ANSYS [8]. We have assigned linear, isotropic material properties to the mesh elements using Young's moduli of 88kPa (skin surface), 1kPa (fat), 10kPa (fibroglandular tissue), and 16.5kPa (tumorous carcinoma), and a Poisson's ratio of 0.495 for near-incompressibility [9, 10]. We have applied different surface displacements, including regional displacements, point punctures simulating breast biopsies, as well as one- and two-sided plate contacts, simulating movement against the RF coil and fixation of the breast, respectively. The models were solved using ANSYS, and the original post-contrast images were warped using the generated deformation vector fields to simulate patient motion between pre- and post-contrast image acquisition. Figure 1 shows example slices of an image pair and a model for one patient before and after motion simulation.

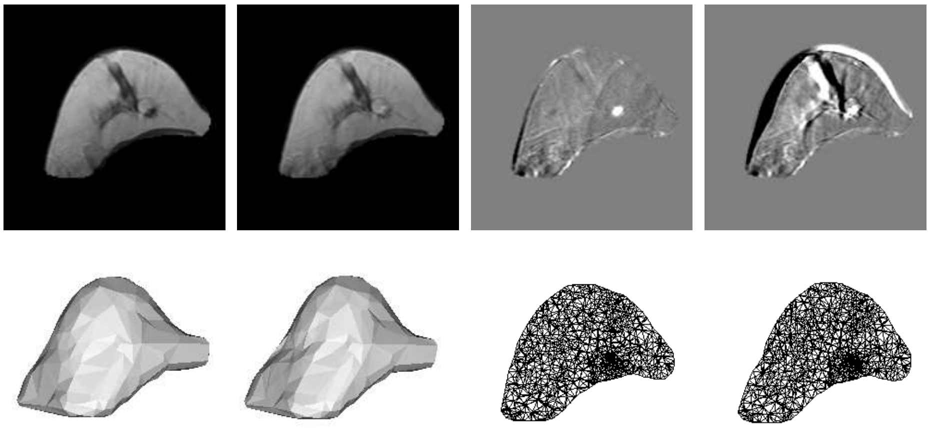

Fig. 1. Top, from left to right: example slices through pre- and post-contrast images of a patient, original subtraction showing tumour enhancement, and subtraction after simulated regional surface displacement showing bright motion artefacts. Bottom, from left to right: undeformed and deformed finite element model shown as 3D surface rendering and 2D wire-frame cut.

In this work, we have investigated the registration performance of two non-rigid registration techniques. The first one is the combined global and local motion model by Rueckert et al. [5] which uses single-level free-form deformations (FFDs) based on B-splines and normalized mutual information as a voxel-based similarity measure. The second technique is our new generalized non-rigid registration framework [7], which extends the technique by Rueckert to multi-level free-form deformations and non-uniform control point resolution. In this work, we are comparing the effect of varying the control point resolution in both techniques.

3 Results

We have used Rueckert's single-level FFD method at a range of different B-spline control point resolutions of 20mm, 15mm, 10mm, and 5mm, and our new framework with the same set of resolutions, but in a hierarchical manner. Fig. 2 shows example registration results for the patient and FEM simulation shown in Fig. 1. Visual assessment of subtraction images can be used to rank the performance for the two methods and chosen control point resolutions. However, here we are able to assess the registration accuracy quantitatively by computing the target registration error (TRE) [11] over the image voxel positions with respect to our generated gold standard deformations.

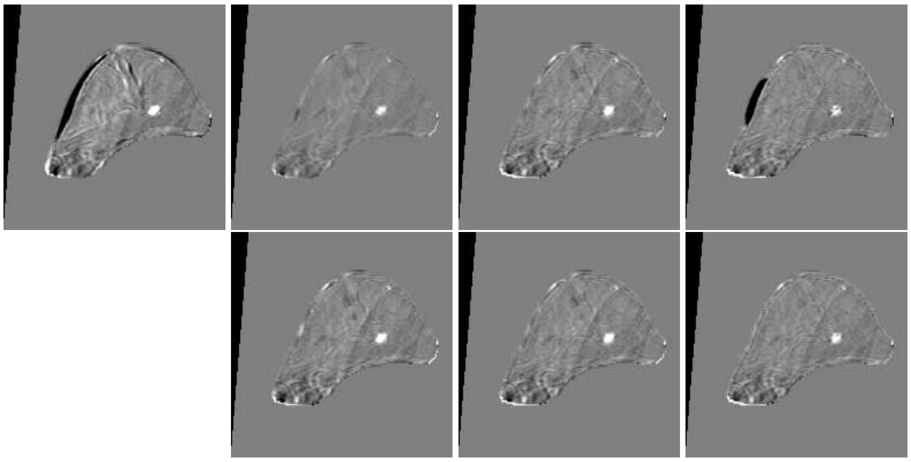

Fig. 2. Example slice through the subtraction volumes for the patient and simulation shown in Fig. 1 for different registration methods. Top, from left to right: affine registration, single-level FFD using 20mm, 10mm and 5mm control point spacing. Bottom, from left to right: Multi-level FFD using 20mm and 15mm; 20mm, 15mm and 10mm; and 20mm, 15mm, 10mm, and 5mm control point spacing. The affine registration was the starting estimate for the 20mm single FFD, which in turn was the starting estimate for the 20mm to 15mm multi-level FFD. Note the registration failure for the 5mm single-level FFD, and the success for the 20mm down to 5mm multi-level FFD registration.

We have found both non-rigid registration methods to double the accuracy after affine registration in terms of the median TRE, which was 0.4mm for the registration of the original post-contrast to the FEM-deformed post-contrast images, and 1mm for the more realistic experiment of registering the original pre-contrast to the FEM-deformed post-contrast images. At high FFD resolutions, the single-level FFD method was found to fail for large localized deformations, leading to physically implausible folding of the deformation vector field or to localized registration failure (an example of the latter can be seen in Fig. 2). An improved performance was found with the multi-level FFD registration, where a set of large to small deformations is recovered, leading to a numerically improved accuracy and robustness of the registration.

4 Conclusion

We have presented a non-rigid registration validation study for CE-MR mammography using finite element methods as a biomechanical gold standard, and have successfully validated two FFD-based non-rigid registration algorithms for different control-point resolutions. This study is an important step towards making the registration techniques applicable for clinical routine use. We are currently investigating the effect of the residual, albeit very small patient motion between the original image pairs, and the effect which the contrast enhancement present in one but not the other set of images may have on the chosen voxel similarity measure and on the local preservation of volume.

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