Biomechanical Analysis of the Lung: A Feature-Based Approach Using Customized Finite Element Meshes

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Synopsis
We describe a feature-based approach to non-rigid registration of two-dimensional pulmonary MR images. Finite element meshes are constructed to highlight anatomical features evident on a sagittal lung view. Resulting displacements are compared to dense fields extrapolated from manually placed vascular landmarks. Results achieved using customized meshes demonstrate better correspondence to the landmark fields than those acquired using quadrilateral grids. Landmark constraints further improve the solution’s correspondence to the expected result. This work demonstrates the advantages of using feature-based techniques to capture lung deformation, and lays the groundwork for biomechanical modeling of the lung using the finite element method.

Introduction
Quantitation of lung deformation is useful in characterizing changes associated with pulmonary pathology. Diseases such as emphysema change the structural properties of the lung parenchyma, and directly affect its ability to normally expand and contract [4]. It would be helpful to be able to observe and detect such morphologic changes and their effects on normal lung motion using medical imaging techniques. A non-rigid image registration algorithm can be used to compute the deformation between successive magnetic resonance (MR) images of the lung [2,5]. Motion is estimated using the pulmonary vasculature and parenchymal structures as natural sources of spatial markers, without the requirement for explicit correspondence information. MR quantification of pulmonary motion enables in vivo assessment of parenchymal mechanics in order to facilitate disease diagnosis or treatment monitoring [1,3]. One long-term goal is to discover which mechanical characteristics predict the severity of disease and the extent of recovery in affected lungs.

Methods
Five 128x128-pixel sagittal views of the right lung of a healthy male volunteer, acquired with breath-holding at phases between full inhalation and full exhalation, were analyzed [5]. Estimates of pulmonary motion between each sequential pair of images were obtained by optimizing, via the finite element method, the squared intensity difference over the images to identify homologous image locations. The estimated motions correspond to non-rigid deformations of an elastic membrane and reflect to a first order approximation the true physical behavior of lung parenchyma. Two different finite element mesh geometries were used—a regular quadrilateral mesh consisting of 4x4-pixel elements, and an irregular triangular mesh with a higher concentration of elements over the lung and body than over the image background. When using the triangular mesh the background was modeled with a highly flexible material compared to the body, and forces applied to the background were nulled. Resulting motion or displacement fields were compared to dense fields extrapolated from twenty-two manually identified pulmonary vascular landmarks. The landmarks were also used as additional feature constraints to re-solve the registrations using the triangular meshes.

Results
Figures A and B show a pair of consecutive sagittal lung images with the associated triangular mesh overlaid on B. Figure C shows the displacement field resulting from the 32x32-element quadrilateral mesh. Figures D and E show the displacement fields resulting from the triangular mesh in B. The results in E are obtained by also using the pulmonary vascular landmarks to drive the registration. There is a noticeable difference between the results obtained with the quadrilateral mesh in C and the triangular mesh in D—the latter is designed to enhance the structural features of the lung and minimize background distortion. The overall vector endpoint errors between the displacement fields in C and D and the landmark-derived dense displacement fields are 1.43±1.19 and 1.36±1.07 pixels, respectively. Comparison of the vascular displacements in D and E demonstrates the effects of the additional landmark constraints used to achieve the results in E. The mean endpoint error over the body and lung associated with the absence of the landmark constraints (D vs. E) is 1.02±1.75 pixels. The effect of the landmarks is better appreciated by examining regional differences between results obtained with (E) and without (D) the constraints. For each displacement field, the mean endpoint error between the vectors for these two methods within a 10x10-pixel neighborhood around each landmark is 5.53±1.67, 3.73±0.82, 3.65±1.29 and 8.46±2.58 pixels.

Discussion
We present a feature-based approach to the extraction of pulmonary motion via finite element-based non-rigid registration of sagittal lung MR images. The use of meshes constructed to reflect the inherent geometry of the image and reduce the background distortion improves the registration result as compared to the use of elements arranged in regular grids. The difference in the numerical errors for the quadrilateral and triangular meshes is small because the quadrilateral- and landmark-derived fields include background deformation, while the triangle-based results intentionally reduce this motion. Landmarks can also be used to drive the registration to a more optimal solution. When combined with the customized triangular mesh, these additional constraints allow the registration to more effectively capture regional motion within the lung parenchyma. Addition of enhancements such as customized finite element meshes and anatomical landmarks to augment pure intensity-driven approaches lays the foundation for future biomechanical modeling of lung tissue. Unlike more basic image registration methods, this feature-based approach can be used to more effectively capture the deformation of interesting anatomic structures. This is a step towards the ultimate goal of this research—to be able to analyze the effects of disease processes on the motion of the lung parenchyma.

References