Samuel Voß*, Philipp D. Lösel, Sylvia Saalfeld, Philipp Berg, Vincent Heuveline, Friedrich Kallinowski

Automated incisional hernia characterization by non-rigid registration of CT images – a pilot study

Abstract: Incisional hernia repair makes use of prosthetic meshes to re-establish a biomechanically stable abdominal wall. Mesh sizing and fixation have been found to be essential for the clinical outcome. Comparative CT images a) under rest versus b) under Valsalva maneuver (exhalation against closed airways) provide useful information for hernia characterization. However, this process incorporates several manual measurements, which led to observer variability. The present study suggests using an image registration approach of the CT data to reliably and reproducibly extract hernia quantities. The routine is implemented in the software framework MATLAB and works fully automatic. After CT data import, slice by slice undergo non-rigid B-spline grid registration. Local displacement and strain are extracted from the transformation field. The qualitative results correspond to the clinical observation. Maximum displacement of 3.5 cm and maximum strain of 25 % are calculated for one patient's data set. Current approaches do not provide this type of information. Further research will focus on validation and possibilities to include this new kind of knowledge into the design process of prosthetic meshes.

Keywords: Incisional hernia repair, non-rigid registration, computed tomography, Valsalva maneuver.

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***Corresponding author: Samuel Voß:** Forschungscampus *STIMULATE*; Department of Fluid Dynamics and Technical Flows, University of Magdeburg, Universitaetsplatz 2, 39106 Magdeburg, Germany, e-mail: samuel.voss@ovgu.de
Philipp D. Lösel, Vincent Heuveline: Heidelberg Institute for Theoretical Studies, Heidelberg, Germany; Engineering Mathematics and Computing Lab, Interdisciplinary Center for Scientific Computing, Heidelberg, Germany
Sylvia Saalfeld, Philipp Berg: Forschungscampus *STIMULATE*, University of Magdeburg, Magdeburg, Germany
Friedrich Kallinowski: General, Visceral and Transplantation Surgery, University Hospital Heidelberg, Heidelberg, Germany; General and Visceral Surgery, GRN Hospital Eberbach, Eberbach, Germany

1 Introduction

A hernia is an abnormal unstable tissue resulting in a bulge filled with tissue or even organ parts that belong inside the abdominal cavity. As a result, blood flow can be impaired causing discomfort and pain. Hernias can occur in different locations of the body and are of different sizes.

An incisional hernia can develop after major surgery of the abdomen and it is often related with pain and disability. Treatment aims at biomechanical repair of the weakened tissue using a prosthetic mesh, which is placed underneath the abdominal muscles.

One major difficulty is the adjustment of this mesh size, its mechanical properties and fixation to the individual condition of the patient. Since the hernia is less stable than the intact abdominal wall, it deforms higher when exposed to pressure loading during patient's activity. Therefore, accurate mesh sizing and fixation influence the recurrence rate after surgery [1].

CT imaging has been used as an effective method to obtain the required mesh size by differentiating the hernia from the abdominal wall. For each patient, two CT images are taken, one of the abdomen under rest and one with Valsalva maneuver (exhalation against closed airways causing a pressure loading of the abdominal wall including the hernia). Subsequently, the volume change of the abdomen is compared to the volume change of the hernia sac. Two approaches from the literature can be used to quantify the volumes by formulas for simplified geometrical shapes [2–3].

However, the extracted metrics for the hernia are subjected to intra-observer and inter-observer variability, since measurements are taken manually from the CT images. This is in conflict with the high requirements for an accurate mesh size. According to Kallinowski et al. [4], twelve observations are necessary to obtain a variability below 5 %.

The aim of this pilot study is the implementation of an image registration approach in order to extract hernia dimensions in an automated and reproducible manner for improved accuracy during the surgery planning process.

2 Methods

The automatic determination of hernia parameters is implemented in MATLAB 2019b (The MathWorks Inc., Massachusetts, USA). Figure 1 illustrates the workflow from CT data import to the resulting visualization, which is described in the following.

First, the user selects two patient records, the CT scan at rest and the corresponding scan under Valsalva maneuver. In addition, the user can specify registration parameters (for special requirements) and limit the import to a certain range of CT slices. Furthermore, downsampling or cropping of a region of interest can be enabled to speed up the registration process. Afterwards, the native DICOM files are imported slice by slice. The resolution is extracted from the DICOM header for later distance/area calculation.

An optional segmentation and/or masking step can be activated to increase the weighting of local structures.

The non-rigid registration is based on a B-spline grid routine [5]. The CT image from the Valsalva maneuver serves as static image, while the image at rest is the moving image. To minimize an error measure, the moving image is transformed to match the static one. In order to increase performance, the previous transformation grid is used as initial solution for the current slice.

Based on the transformation grid, local displacement is calculated and used to color-code the single CT images. This provides a visual impression indicating regions that undergo large deformation. In addition, the strain field is calculated based on the displacement field representing the relative displacement and excluding rigid body motion.

All single slices are combined into a surface representation of the abdominal wall including the hernia. Interactive windows enable detailed examination of the abdominal wall.

Finally, a statistic of the hernia dimensions (e.g., width, height, area) is exported along with several screenshots for patient information, documentation or surgery planning.

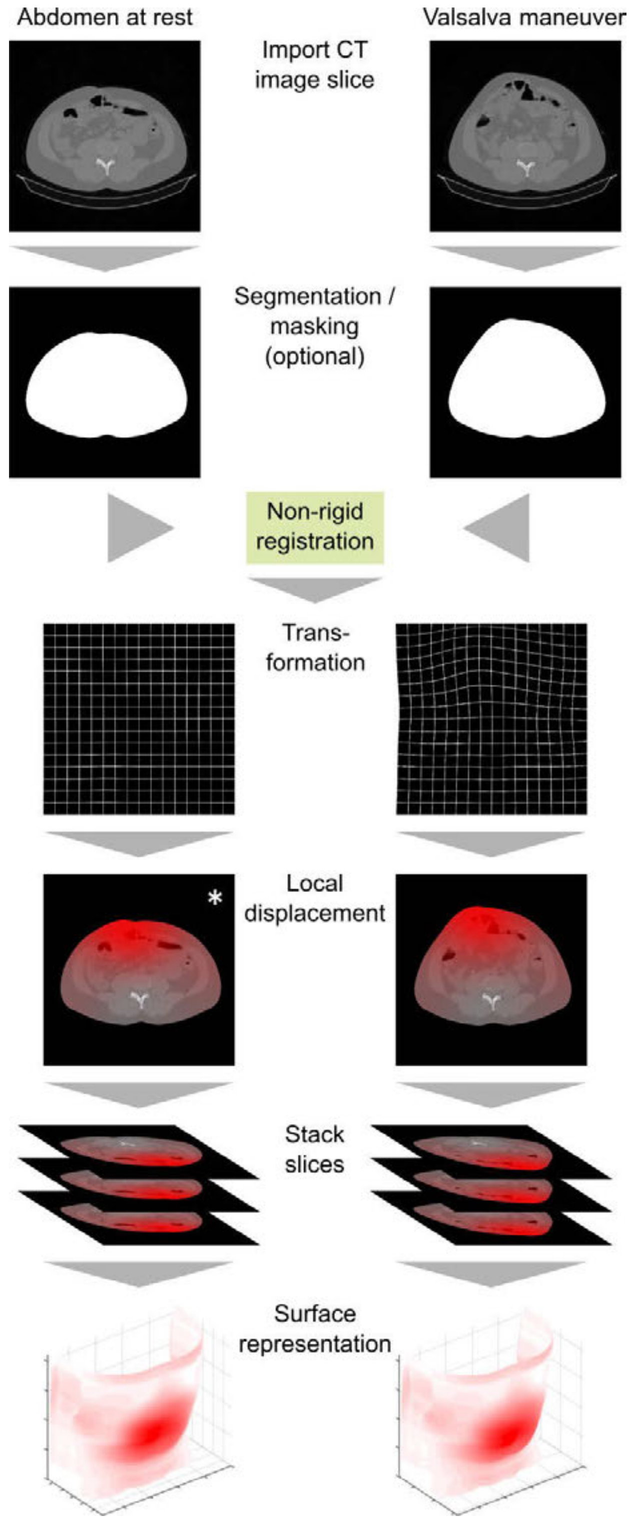

Figure 1: Sequential processing from top to bottom: Import of CT data, optional segmentation/masking, deformation grid from registration, color-coded CT image by local in-plane displacement, stacking to volume model; left column: native image; right column: with Valsalva maneuver. *) Indicates the CT image at rest color-coded with the back projection of the transformation field.

3 Results

The entire procedure for a sample CT data set with 86 slices (resolution of 512 x 512 pixel) requires less than 30 minutes on a standard desktop workstation (Intel Core i7-4770 CPU 4x 3,4 GHz, 32 GB RAM). This corresponds to the processing time of the manual evaluation of hernia dimensions according to internal experiences following the procedure described in Tanaka et al. and Sabbagh et al. [2–3].

Figure 2 shows the local displacement (left) and strain field (right) with respect to the abdominal wall during Valsalva maneuver (top) and on a 2D map (bottom). The displacement distribution is asymmetric with a maximum displacement of 3.5 cm. It occurs on the right abdominal side of the patient next to the navel, which is in agreement with the clinical observation.

The strain field represents the local change in length relative to its neighborhood. Points close to each other, which strongly change their relative position, are locations of high strain. These locations do not necessarily correspond to regions of high displacements, as illustrated in Figure 2. Right and left to the spot of highest displacement, the areas of high strain run from top to bottom. The maximum strain value is 25 %, located even further on the right side of the patient.

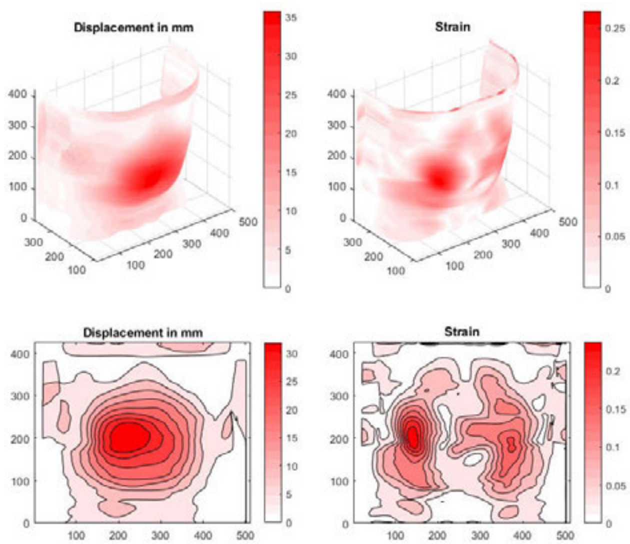

Figure 2: Registration result for the Valsalva configuration, top row: displacement and strain projected on the abdominal wall; bottom row: displacement and strain maps corresponding to the frontal view on the abdominal wall.

4 Discussion

While previous simplified methods have focused on the quantification of hernia volume [2–3], the approach presented in this study enables the acquisition of further hernia characteristics. A detailed map of local displacements is derived from the image registration. This in turn provides information about the local stability of the abdominal wall. Increased compliance of the hernia becomes visible enabling the distinction of the hernia from the abdominal wall. Hernia length, height, area and further measures like morphological parameters can be extracted to enable improved planning and designing of prosthetic meshes.

In addition, the local strain distribution can be used as an indicator for the selection of fixation points. Since regions of high strain undergo larger relative tissue movement, avoiding such regions may result in less complications and discomfort for the patient.

Knowing both, the individual displacement and strain distribution opens up novel possibilities for even more patient-specific treatment. In the future, it may be possible to produce meshes customized to an individual patient based on the local wall behavior under load.

Further advantages of the presented approach are the visualization options, which can be used for patient education, documentation or surgery planning.

The following limitations exist with respect to this pilot study: First, the deformation field is based on the non-rigid registration, which is a mathematical model approximation of the movement between the CT at rest and during the Valsalva maneuver. Although experience shows that this movement is uniform, an approximation comes with errors, which need to be quantified in future studies. This could be achieved by placing markers on the abdominal surface.

Second, due to the 2D (slice by slice) registration, the deformation in the third direction (cranial to caudal) is neglected. Regarding smaller hernias the authors assume that this is a valid simplification. However, especially for very large hernias the deformation of abdomen and hernia is more separated. This clearly limits the applicability of the presented approach.

Third, during the implementation process, the algorithm was tested on a small sample size of patients. Further testing and validation with larger case numbers is needed to evaluate performance and clinical applicability.

In addition to the steps already mentioned regarding validation, future work will focus on a comparison to a) a 3D registration approach and b) the hernia quantification approaches presented in the literature by Tanaka et al. and Sabbagh et al. [2–3].

5 Conclusion

The present study introduces a novel approach for the geometrical characterization of incisional hernias. A non-rigid image registration algorithm is implemented in order to transform an abdominal CT image at rest to one obtained during Valsalva maneuver. The completely automated process enables a considerable reduction of observer variability.

Author Statement

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Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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