REGISTRATION OF 3D CT- AND ULTRASOUND-DATASETS OF THE SPINE USING BONE STRUCTURES

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INTRODUCTION

An important prerequisite of minimally invasive computer assisted surgery is the precise registration of preoperative datasets (mostly CT or MR) within the coordinate system of the navigation system.

Many different methods exist for the registration of preoperative images with the patient coordinate system during surgery. The majority of these methods is based on landmarks, which can be anatomical landmarks or fiducial markers. The accuracy of these registration methods depends on the number of points and on the ability of these points to move with respect to the structure of interest (the bones). For a precise registration, a large number of anatomical landmarks on the bone surface is required and consequently tagged in the CT dataset. Alternatively a smaller number of fiducial markers (mostly screws) that are fixed to the bone preoperatively can be used. Intraoperatively, all these points must be accessible to be referenced with a pointing device of the navigation system. These procedures are time consuming and increase the invasiveness. Furthermore, changes in the anatomy during the surgical procedure cannot be visualized.

To overcome these disadvantages, intraoperative imaging modalities are utilized. In this case, complete anatomical structures can be used for registration (mostly surfaces) to increase the accuracy. Additionally, intraoperative changes of the anatomy can be considered. Some CT or MR based systems are implemented but have major disadvantages with respect to the costs, application difficulties and radiation exposure (CT). Regarding these drawbacks, intraoperative ultrasound could be a solution.

During the surgical procedure, a 3D ultrasound-dataset is acquired with a transducer that is tracked by the navigation system. Ultrasound registration can easily be repeated intraoperatively to account for relative motion between bones.

The major problem of intraoperative ultrasound is its low imaging quality. The acquired data is very noisy due to speckle. In addition, ultrasound images show only a small part of the bone surface due to the reflection properties of ultrasound waves at the tissue-bone interface. Nearly the complete ultrasound wave is reflected at the interface, so no imaging is possible beyond it. Furthermore, the reflection is almost completely specular. Hence interfaces that are not orthogonal to the direction of sound propagation deliver a weak or no image at all.

METHOD

An algorithm for the registration of 3D CT- and ultrasound-datasets must take into account the problems and restrictions of ultrasound imaging. Hence we propose as a first step an estimation of the surface that is expected to be visible in the ultrasound images, based on the CT-data.

As mentioned above, the visibility of bone surfaces depends on the direction of ultrasound propagation. So the surgeon should preoperatively indicate in the CT-dataset the way he wants to move the transducer. It is assumed that the imaging plane is approximately orthogonal to the skin surface and the scanning path, so that a reasonable volume-dataset can be recorded. Knowing the scanning path and the transducer geometry, it is possible to estimate a bone surface in the CT-dataset that would be visible in an ultrasound-dataset.

The estimation procedure comprises three steps. First, the complete bone surface is determined by simple thresholding in the CT-dataset. Then, each element of the surface is tested on its visibility for the transducer. This visibility check considers that the ultrasound wave is completely reflected at the first tissue-bone interface. In the next step, the angles between the normal vectors of the visible surface elements and the direction of ultrasound propagation are calculated. If any of these angles exceed a defined threshold, it is assumed that the associated surface elements cannot be imaged because of the specular reflection of the ultrasound wave.

The bone surface is the only anatomical structure that can be used for the precise registration of a bone, since all other anatomical structures can move relatively to it. Thus, the estimated surface should be enough input information for the registration algorithm from the CT-dataset.

A robust segmentation of the ultrasound-dataset would be very difficult and for a whole 3D dataset very time-consuming. Thus the best way for the registration seems to be a surface-volume registration, which tries to find the correct position of the estimated surface in the ultrasound-dataset.

Therefore a criterion has to be defined that gives evidence of the correctness for the chosen position of the estimated surface in the ultrasound-dataset. Since the tissue-bone interface is imaged as a bright curve with ultrasound, a local criterion is the average gray value of all voxels that are covered by the surface. This criterion has the advantage that the averaging of a large number of voxels eliminates the noisy character of the ultrasound-data. Furthermore, the complete surface is evaluated in the criterion, avoiding disturbing influences of other bright structures with different shapes.

It is assumed, that the average gray value is maximal at the correct position of the surface. Thus, the registration procedure can be formulated as an optimization problem: rotation and translation parameters for the surface have to be optimized to find the maximum of the average gray value. The resulting values of the parameters describe, how the CT-dataset must be transformed to fit with the ultrasound-dataset. The initialization of the registration can be based on the ultrasound scanning path indicated on the preoperative dataset.

EXPERIMENTS / RESULTS

The described registration algorithm was implemented and evaluated using CT- and ultrasound-datasets, acquired from an ex-vivo preparation of a human lumbar spine with surrounding tissue.

The first step was the surface estimation in the CT-data. Comparison of surfaces and corresponding ultrasound images showed that the estimation accurately predicts the bone surface visualization with ultrasound. The surface and the acquired ultrasound volume were the input for the registration algorithm. The optimization of the average gray value was initially realized by a deepest descent method.

The calculation time for the registration of the whole lumbar spine, assuming that the vertebras cannot move relative to each other, was 50-100 seconds. For a single vertebra the registration took 5-15 seconds. The computation time depends on the position of the two datasets before the registration. This result was achieved on a 650 MHz Processor, excluding the computation time for the surface, since this can be done preoperatively. The program was realized in Matlab and C and was not optimized for speed.

Since the ultrasound-data is not preprocessed in this case, the registration result is only affected by the surface estimation. The two main parameters of the surface estimation are the threshold for the extraction of the bone surface in the CT-dataset and the assumed direction of ultrasound propagation. The impact of these parameters was investigated.

To test the sensitivity of the algorithm with respect to the threshold, this parameter was varied between 100 and 400 Hounsfield units (HU). The registration with 200 HU was deemed to be a reference. Overall, a maximal rotational deviation of 0.625° and a maximal translational deviation of 0.5 mm (which is equal to the resolution) confirm that the algorithm is not very sensitive with respect to the chosen threshold.

The influence of the assumed direction of ultrasound propagation was tested by varying the angle of incidence within a range of 20 degree around different axes. Most crucial is an alteration of the angle around the longitudinal axis, since the position of the transducer relative to the spinous process has a great impact on the visibility of the lamina in the ultrasound image. The reference registration is defined as a registration, where the assumed direction of ultrasound propagation for the surface estimation was validated by the registration; i.e. the calculated position of the ultrasound-dataset relative to the CT-dataset verified the expected angles of incidence. The results show that a difference of 10 degrees between assumed and real incidence angle entails an acceptable maximal deviation of 0.5 mm and 0.375°. For larger differences in angle, deviations of up to 1° and 2 mm seem to be too large. In these cases, a new estimation of the surface has to be done intraoperatively to correct the misalignments. Thus, the impact of the assumed incidence angle on the registration result is small and can be corrected.

Another item of interest is the scope of the registration, i.e. the misalignments that can be determined by the algorithm. The initially realized deepest-descent method can lead to wrong registration results due to local maxima.

The surface of a single vertebra was rotated around different axes, starting from the registered position. Afterwards, the optimal translation was searched for this rotated surface to avoid effects due to the choice of the rotation center. The average gray value has no further optima with respect to rotations of up to 20° around the medio-lateral and anterior-posterior axes. A rotation around the longitudinal axis with a deviation of more then 12° cannot be detected correctly by the deepest descent method, since local maxima appear. Nevertheless, the absolute maximum is non-ambiguous, and a different optimization strategy could find the correct position. So the optimization criterion permits a registration scope for rotational misalignments of at least 20°.

To test the convergence behavior of the algorithm with respect to translational misalignments, the estimated surface of a vertebra was displaced from its registered position in various directions, and the average gray value was calculated. Local maxima appear at displacements of about 30 mm in each direction. Again, these local maxima can mislead a deepest descent method, but a more sophisticated optimization algorithm should have no problems to find the correct optimum. The scope of the algorithm, which can be indicated by these results, is approximately 15 mm with the currently used deepest descent method. The optimization criterion allows a correct identification of translational misalignments up to 40 mm.

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