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Bone registration with 3D CT and ultrasound data sets

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Abstract

For many navigated surgical procedures, the precise registration of preoperative data sets with bones of the patient is an important requisite. Conventional navigation systems use paired point registration based on anatomical landmarks or fiducial markers. This approach increases the invasiveness, since landmarks must be exposed and fiducial markers must be connected to the bone.

Intraoperative imaging modalities can overcome this disadvantage. Ultrasound seems to be ideal because of the easy data acquisition. The problem, however, is the low imaging quality regarding bones.

The proposed algorithm for the registration of CT and ultrasound data sets considers the ultrasound imaging properties. That part of the bone surface, which should be visible in the ultrasound data is estimated from the CT data. The ultrasound data is preprocessed to emphasize bone surfaces. Thus, the ultrasound data contains a bright shape that is formed like the surface estimated from the CT data. A surface–volume registration tries to correlate the estimated surface with this bright shape.

The algorithm was validated using an ex vivo preparation of a human lumbar spine. The algorithm was shown to cope with initial misalignments of about 30 mm and 15°.

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Successful registration of in vivo data of lumbar spine, tibia and shoulder indicate the feasibility of the approach.

Keywords: Registration; Intraoperative imaging; Ultrasound; Bone; Surgical navigation

1. Introduction

Navigational procedures have become extremely important in modern surgery. During the last years, navigation systems based on preoperatively obtained radiologic data (mostly CT and MRI) have given additional safety to minimal invasive procedures. The precise registration of preoperative data sets within the coordinate system of the navigation system is an important basis for a successful navigated procedure. In many surgical disciplines (orthopedics, neurosurgery, traumatology, etc.), the accurate registration of bones is of main interest.

1.1. Conventional registration

Common methods are based on paired point registration using anatomical landmarks or fiducia1 markers. To ensure an accurate registration, a large number of landmarks must be marked in the preoperative data set. Alternatively, a smaller number of fiducial markers (mostly screws) can be used, which must be fixed to the bone. These methods are time consuming and increase the invasiveness of the surgery.

1.2. Intraoperative imaging

Registered intraoperative imaging modalities, which can localize the bone through tissue, can overcome the disadvantages of conventional registration. In this case, complete anatomical structures can be used for registration (mostly surfaces), thus increasing the accuracy. The usage of intraoperative CT or MRI has been proposed and implemented [1,2], but these systems have major drawbacks with respect to intraoperative applicability, costs and radiation exposure (CT).

Regarding these drawbacks, intraoperative ultrasound seems to be an ideal intra-operative imaging modality. The easy-to-perform, non-ionizing, real-time data acquisition could lead to a fast and accurate transcutaneous (non-invasive) registration of the preoperative data.

The problem of ultrasound, however, is its comparatively low imaging quality, especially regarding bones. The low imaging quality is due to physical interactions of ultrasound waves with tissue [3]. Ultrasound images show only a small part of the bone surface due to the reflection of ultrasound waves at the tissue–bone interface. Almost 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 roughly orthogonal to the direction of sound propagation deliver a weak echo or no echo at all. These properties must be considered for the development of an automatic registration algorithm.

Existing approaches for the registration of bone structures in CT and ultrasound data sets address long bones [4], pelvis [5,6] and spine [7–9]. Since the imaging of the anatomy is very different with CT and ultrasound, volume–volume registration methods based on similarity measurements will not work. Thus, all these approaches use surface–surface registration methods. The major problem and disadvantage of these approaches is the segmentation of the ultrasound data set to extract the bone surface. This segmentation leads to a time consuming intraoperative ultrasound data acquisition and processing. At the spine, the above-mentioned approaches are tested only with bone models without surrounding tissue. This leads to ultrasound images which can be segmented much easier than in vivo data.

2. Methods

We propose an algorithm for the registration of 3D CT and 3D ultrasound data sets based on bone structures, which takes into account that ultrasound produces very noisy images (speckle) and visualizes only parts of the bone surface. The 3D ultrasound data set is acquired by tracking the movement of a calibrated ultrasound transducer with the navigation system and by combining the recorded images to a volume. The registration algorithm can be divided into the preprocessing of preoperative CT data, the preprocessing of intraoperative ultrasound data and the registration of the preprocessed data sets.

2.1. CT preprocessing

The preprocessing of the CT data is not time critical, since it can be done preoperatively. First, the complete bone surface is extracted from the CT data by thresholding. Then, the part of the bone surface, which should be visible in the ultrasound data, is estimated considering the restrictions of bone imaging with ultrasound. All surface elements are removed, which are invisible due to total or specular reflection. Since the visibility depends highly on the position of the ultrasound transducer during the acquisition, the scan path of the ultrasound transducer must roughly be known for this estimation. It could be indicated in the CT data by the surgeon preoperatively. An example for the surface estimation at the tibia is given in Fig. 1.

2.2. Ultrasound preprocessing

Unlike other approaches, this approach avoids a segmentation of bone surfaces in the ultrasound data, since it is difficult to implement the segmentation in a robust way and since the segmentation is very time consuming. Thus, the preprocessing step for the ultrasound data consists only of an adaptive depth gain compensation (DGC) to emphasize bone surfaces and suppress overlaying tissue. Fig. 2 illustrates the effect of the adaptive DGC at the example of the tibia.

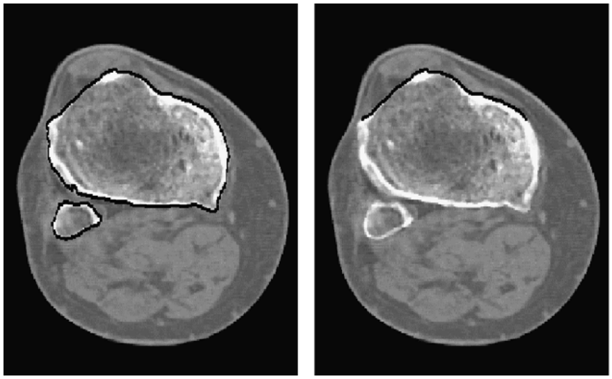

Fig. 1. Surface estimation in the CT-data. Left: axial slice of the tibia. The black line marks the complete extracted bone surface. Right: the black line now marks the bone surface after removing surface elements that are invisible for ultrasound. The assumed ultrasound propagation direction is from the top to the bottom of the image.

2.3. Registration

The preprocessed ultrasound data and the estimated surface from the CT data are the input for the registration algorithm. For the registration, a criterion has to be defined that assesses the correctness of the chosen position of the estimated bone surface in the ultrasound dataset. Since the bone surfaces are imaged as bright voxels in the ultrasound data, the ultrasound volume should contain a bright shape that is formed like the estimated surface. To find this shape, the estimated surface is positioned in the ultrasound volume, and the gray values of all voxels, which are covered by the surface, are summed. To account for the fact that only parts of the estimated surface may fall into the acquired

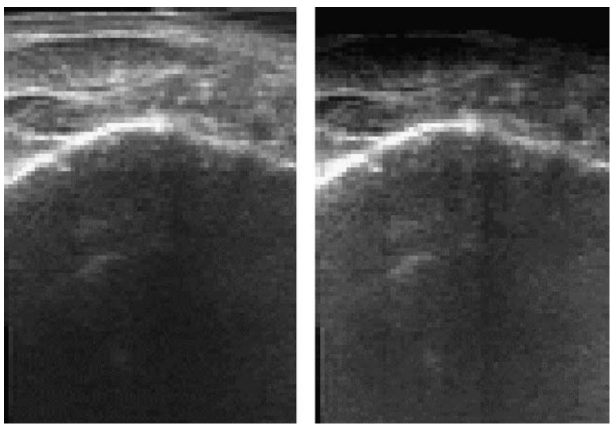

Fig. 2. Adaptive DGC to emphasize bone surfaces. Left: axial ultrasound slice of the tibia before application of the adaptive DGC. Right: same image after application of the adaptive DGC.

ultrasound volume, the sum is divided by the number of surface elements in this part. This "average gray value" should be maximal, if the estimated surface is positioned correctly in the ultrasound data. This criterion has the advantage that the summation of a large number of voxels eliminates the noisy character of the ultrasound data. Furthermore, the complete estimated surface is evaluated in the criterion, reducing disturbing influences of other bright structures with different shapes.

Thus, the registration process is an optimization of the average gray value, depending on the transformation parameters (rotation, translation). For this optimization, any of the classical optimization algorithms can be used. Due to the noise-reducing character of the average gray value, the optimization function is quite smooth, and a deepest descent method is sufficient for small misalignments of the two data sets after initialization. For the initialization, the ultrasound scan path indicated on the preoperative data set, and the tracked scan path of the transducer can be used.

Since the criterion is only the sum of the gray values of voxels that are covered by the estimated surface, the resulting computation time for the registration should be acceptable for intraoperative application.

3. Results

The algorithm was implemented and validated using an ex vivo preparation of a human lumbar spine with surrounding muscle tissue.

3.1. Data acquisition

CT data was acquired using a Siemens Somatom plus 4. 3D ultrasound data was acquired using a Siemens SONOLINE Elegra with a 3.5 MHz curved array, which was mounted to a 2-axis computer controlled positioning system to obtain a highly accurate data set. Thus, it was possible to evaluate the algorithm without disturbing errors of the tracking system and the calibration.

3.2. Preprocessing and registration

A comparison of the estimated surface from the CT data with the ultrasound data (Fig. 3) shows that the estimation is a very good prediction of the visible bone surface in the ultrasound data.

The registration of the data sets took about one minute for the whole lumbar spine and about 10–15 s for a single vertebra on a 650-MHz PC. The optimization algorithm used was a deepest descent method. The algorithm was shown to converge for initial misalignments of about 30 mm and 15°. A visualization of the registration process is given in Fig. 4.

The registration algorithm was analyzed with respect to the influence of adjustable parameters The threshold for the surface extraction from CT was varied from 100 to 400 Hounsfield units (HU), and the assumed direction of the ultrasound transducer was varied about 10° around the correct direction. The rotation and translation parameters for the

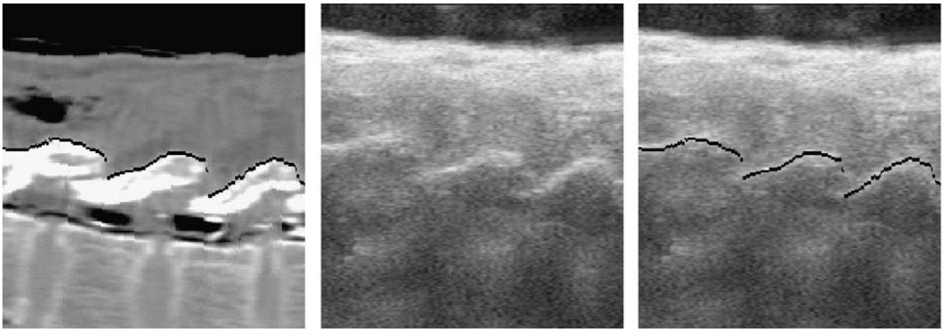

Fig. 3. Estimated surface and corresponding ultrasound data. Left: sagittal CT slice of the laminar arc (human lumbar spine). The black line marks the estimated surface. Middle: corresponding ultrasound slice. Right: overlay of estimated surface and ultrasound slice.

registration of the whole lumbar spine and of a single vertebra deviated about 0.5° and 0.5 mm, indicating that the algorithm is robust with respect to these parameter variations [10].

3.3. In vivo results

Additionally, in vivo CT and ultrasound data of the lumbar spine, the tibia and the shoulder were acquired using a commercial 3D add-on system (Easy 3D, 3D Echotech, General Electric) for a conventional 2D ultrasound system (Siemens SONOLINE Omnia). Since this system is based on a magnetic tracking system (pcBird, Ascension) with a quite low accuracy compared to optical tracking systems, these data sets were only used to verify the convergence of the algorithm and to visually control the success of the registration so far. The result was that the data sets of all regions can be registered with the proposed registration algorithm, indicating the feasibility of the approach for different applications.

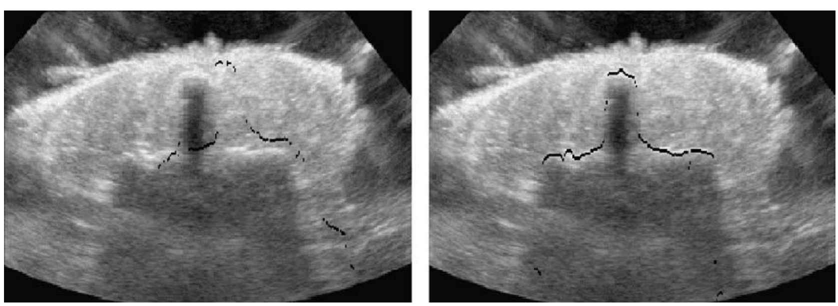

Fig. 4. Registration Process. Left: before registration. Right: after registration. The black line marks the position of the estimated surface in the ultrasound data.

4. Discussion

A robust algorithm for the registration of 3D CT and ultrasound data sets is presented. The computation time seems to be acceptable for intraoperative usage. The algorithm is robust with respect to parameter variations. First, in vivo acquisitions showed the feasibility of the approach. Further studies are needed to determine the precision in a clinical environment for different applications.

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