Ultrasound based navigation system for minimal invasive surgery at the lumbar spine within OrthoMIT

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Abstract. We present a system to register three-dimensional ultrasound datasets with preoperative CT datasets to support navigated surgery at the lumbar spine, using a registration algorithm based on bone structures. The registration of the coordinates of the patient and the image data is divided into two steps: a rough point-to-point pre-registration and an ultrasound based volume-surface registration. We evaluated three different methods for a pre-registration process in simulation and *in vitro*. The orthogonal *Procrustes* method was compared to the *Downhill Simplex method* with six and four degrees of freedom. The *Downhill Simplex method* with six degrees of freedom provided a precise and robust registration considering misplacements of landmarks on the phantom of up to 56 mm.

1. Introduction

Intraoperative imaging in navigated surgery supports the surgeon's orientation especially during minimally invasive procedures. The position of instruments can be displayed in the preoperative datasets (CT or MRI), and anatomical changes can be visualized during surgery.
Acquiring intraoperative CT or MRI datasets for the registration with preoperative datasets is often associated with high costs, difficult handling, and additional radiation exposure (CT). Due to real time capability and sufficient image quality, ultrasound can be considered as an alternative intraoperative imaging modality for registration.
A system to register three-dimensional ultrasound datasets with preoperative CT datasets to support navigated surgery at the lumbar spine was developed, with the use of a registration algorithm based on bone structures [1]. At first, bone structures are segmented from the preoperative data and fast image processing is applied to the intraoperative ultrasound data. The registration procedure is divided into two steps: a rough point-to-point pre-registration with four landmarks and a precise volume-surface registration (vs-registration) based on image information.
The pre-registration is necessary to find an initial position for the vs-registration, so that the algorithm can work as efficiently as possible. The point-to-point

method has to be performed intraoperatively, so it should be a fast and sufficiently precise process.
The vs-registration is realized by a Covariance Matrix Adaption evolution strategy, which is able to overcome local optima and which shows best results in comparison to other optimization methods [2]. *In vitro* accuracy measurements of the results of the ultrasound based navigation system were carried out by using a phantom consisting of three vertebrae in a water bath (fig. 1). The phantom's drill holes were used as reference points for the localization of the phantom with a conventional and precise point-to-point registration.

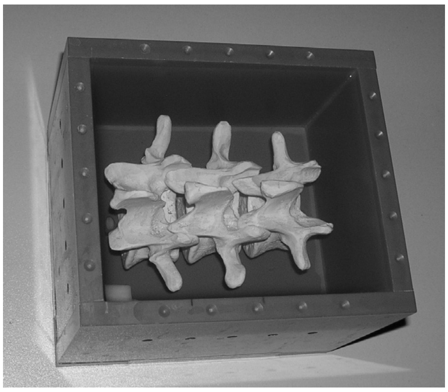

Fig. 1. Phantom for *in vitro* accuracy measurements and pre-registration experiments: three vertebrae in a water bath.

Ultrasound data of the vertebrae was acquired and point-to-point and vs-registrations were carried out. The registration results were compared. The measurements showed, that the registration error is less than 2 mm in all evaluated cases and less than 1.5 mm in 90 % of the cases. The RMSE is 0.9 mm [3].
An *in vivo* evaluation was accomplished by registering CT data of 12 patient vertebrae with the corresponding ultrasound data. For each vertebra the registration was repeated 1000 times with different starting positions. A vs-registration with precision better than 1 mm was considered as correct.
Assuming accuracy of the pre-registration between 0 and 15 mm and a rotation of the surface between 0 and 11°, 98.4% of the trials reached a correct position [2]. In these trials, high precision of the ultrasound registration with a mean error of less than 0.1 mm was measured.
In this paper, we concentrate on applications at the lumbar spine. Three point-to-point registration methods and their ability to provide a precise transformation as a pre-registration for the subsequent vs-registration are compared. In order to simulate a rough intraoperative point-to-point registration, four landmarks were misplaced on the phantom vertebra on purpose. The task for the registration algorithms was to compensate the incorrectly defined landmarks.

2. Experimental Methods

On the bone surface, strong reflection of ultrasound waves occurs. In B-Mode ultrasound the appearance of the bone surface is dependent on the incident angle. Structures below this surface are not visible. Therefore, a vs-registration method is an adequate solution when registering CT with ultrasound datasets. Preprocessing steps have to be carried out for the CT and ultrasound datasets.
Before surgery, the bone surface is extracted from the CT datasets by thresholding. The part of the bone surface visible in the ultrasound data, is estimated considering the restrictions of bone imaging with ultrasound. All surface elements, which are invisible due to specular reflection, are removed [1].
The extracted surface has to be registered intraoperatively with the patient's coordinate system in two steps: a rough point-to-point pre-registration using an infrared optical tracking system (NDI Polaris®) and a vs-registration with ultrasound data. Four landmarks were marked in the preoperative dataset and subsequently in the intraoperative dataset: two at the dorsal process and two on positions that accord with the skin surface above the superior articular processes, as displayed in figure 2.

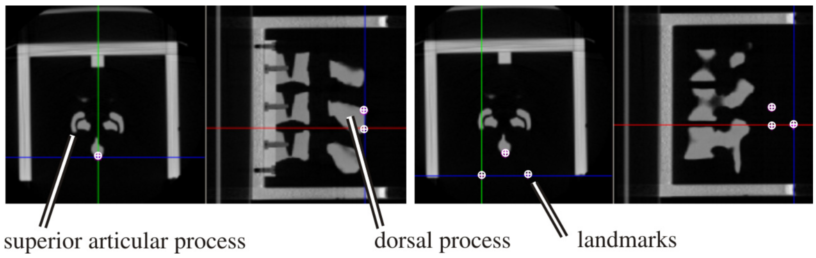

Fig. 2. Four landmarks (displayed white) are marked in the preoperative dataset and on the phantom: two at the dorsal process (left) and two above the superior articular processes (right).

These landmarks would be accessible with a pointer after preparing the patient for the surgery. Especially the landmarks on the dorsal process can be marked intraoperatively with a precision of approximately ± 1 mm. The landmarks on the skin surface have a larger range, since the patient is lying on the back for the CT data acquisition, but is turned around for the spine surgery. Furthermore, the superior articular processes are not visible and the surgeon has to estimate their positions.
Three pre-registration algorithms were evaluated: the orthogonal *Procrustes* method [4], the *Downhill Simplex method* [5] with six degrees of freedom (3 translation directions, 3 rotation angles) and the *Downhill Simplex method* with four degrees of freedom (3 translation directions, 1 rotation angle).
The solution of the orthogonal *Procrustes* problem is described in [4]. This method computes the centroids of two sets of points and overlays them (translation). In a second step, the rotation of one set of points towards the other is minimized, thus defining the transformation.

The *Downhill Simplex method* with six degrees of freedom (*DSm6*) simply searches for the minimum of the sum of the squared distances of the corresponding landmarks [5][6]. In this way, the optimal combination of three translation directions and three rotation angles is found on the basis of minimizing the landmark distances. The *Procrustes* and the *DSm6* algorithm weigh every landmark equally regardless the application.
The *Downhill Simplex method* with four degrees of freedom (*DSm4*) searches for the minimal sum of squared distances by changing one rotation angle and three translation directions. Here, it is assumed, that the two landmarks on the dorsal process are marked first, and with high precision. Thus, the axis between these landmarks defines the rotation axis, so that only one rotation angle is optimized.
A misplacement of some landmarks results in a deformation of the set of points. A perfect match with the landmarks in the preoperative dataset becomes impossible with a rigid transformation. A registration algorithm is only able to find the minimal error as the best fitting of the two sets of points.

Pre-registration experiments were performed. It was assumed, that the position of the two landmarks on the dorsal process can be defined with a pointer with high precision. The two landmarks on the skin surface above the superior articular processes are expected to be defined with a larger error. A misplacement of those landmarks along the anterior-posterior axis is supposable. For that reason, 14 misplacement positions between -13 and 56 mm along the anterior-posterior axis were simulated for the two landmarks on the skin surface. The two landmarks on the dorsal process were kept in their original positions.
This situation was also tested *in vitro* using the phantom in figure 1 and a freehand pointer to define the landmarks. A displacement of approximately ± 1 mm for each landmark is expected. The landmarks on the skin surface above the superior articular processes were defined equivalent to the simulation by 14 misplacement positions between -13 and 56 mm along the anterior-posterior axis
The ultrasound data acquisition was accomplished with a Toshiba Aplio (SSA-770A CV) ultrasound machine and a linear probe (PLT-704 AT) with a center frequency of 7.5 MHz. The tracking system was able to trace the probe's position, so three-dimensional ultrasound datasets for the vs-registration were reconstructed.

3. Results and Discussion

The registration of the ultrasound data with the CT data was considered as correct, if the position of the surface was transformed to the corresponding position in the ultrasound dataset. This was verified by a visual inspection. The pre-registration algorithms minimize the translation and the rotation, the vs-registration has to accomplish, in order to register the surface with the three-dimensional ultrasound data.
Figure 3 shows the results of the simulation: the translation and the rotation, the vs-registration has to accomplish after pre-registration. With no misplacement of the two landmarks on the skin surface, each algorithm delivers a perfect transformation. The vs-registration does not have to translate or rotate the surface in the ultrasound dataset. That is only possible for a correct definition of each

landmark, a situation that does not appear during surgery but during simulation. With a misplacement of the two landmarks on the skin surface, the pre-registration algorithms can only find the minimal error between the two sets of points.

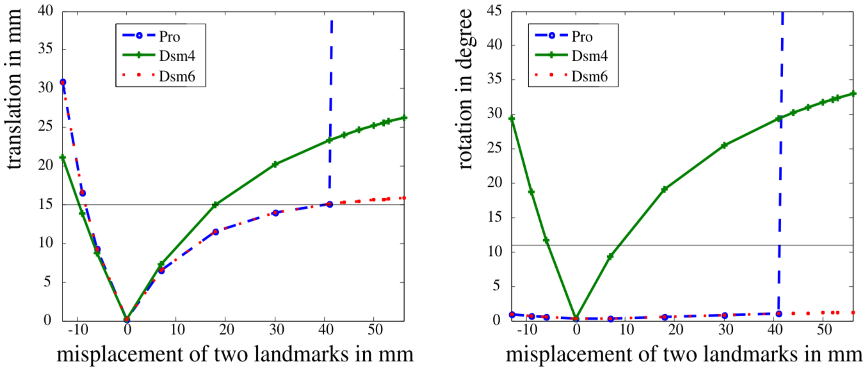

Fig. 3. The different pre-registration algorithms (*Procrustes* (Pro), *Downhill Simplex* with four degrees of freedom (*DSm4*) or *Downhill Simplex* with six degrees of freedom (*DSm6*)) provide different starting positions for the vs-registration. The vs-registration has to overcome a certain translation (left) and rotation (right) to reach the correct position of the surface within the ultrasound volume.

The orthogonal *Procrustes* method delivered the same transformation as the *DSm6* until a misplacement of the two landmarks on the skin surface above 40 mm. For larger misplacements, the vs-registration would have had to translate the set of points over more than 160 mm and rotate it more than 170° in order to carry out the registration.

The *Downhill Simplex methods* provided a robust transformation for landmark misplacements up to 56 mm. Since they search for the minimum error of the sum of the squared distances of the corresponding landmarks, every pre-registration provided a transformation, that demanded a translation less than 32 mm and a rotation less than 34° towards a correct registration. As expected, *DSm6* achieved a more precise pre-registration than *DSm4* in most cases.

In order to evaluate the success of each algorithm, a pre-registration and a vs-registration was carried out. The evolutionary vs-registration can overcome some local minima. The computing time decreases, if the pre-registration provides a starting position close to the correct position. The vs-registration was successful in combination with *DSm6* up to a 56 mm misplacement of two landmarks, with *DSm4* up to 50 mm and for the *Procrustes* method up to 41 mm.

In the *in vitro* tests on the phantom with the freehand pointer, the RMSE of marking the landmarks on the dorsal process was 0.58 mm. Still, *DSm4* and *DSm6* provided a robust pre-registration up to a misplacement of the two landmarks on the skin surface of 56 mm. The vs-registration was successful for the *DSm6* up to 56 mm misplacement, for *DSm4* up to 52 mm and for the *Procrustes* method up to 43 mm. The computation time for the *Procrustes* method was $0.188 \cdot 10^{-3}$ s, the *Downhill Simplex methods* needed 0.281 s for *DSm6* and 0.0781 s for *DSm4*.

4. Conclusions

Regarding results of prior *in vivo* evaluation, the vs-registration algorithm could find the correct surface position in an ultrasound volume data in 98.4% of all cases, if the initial translation does not exceed 15 mm and the initial rotation does not exceed 11°. Thus, the *DSm6* algorithm can provide a sufficiently precise pre-registration, even if the landmarks on the skin surface were misplaced between -6 and 40 mm along the anterior-posterior axis (vertical line in fig. 3).
Despite the fact, that the *Procrustes* method is a fast algorithm to find a transformation between two sets of points, it fails if the misplacement of some landmarks is too large. For the *Procrustes* point-to-point registration, this is the case, if two landmarks are misplaced more than 40 mm. A robust pre-registration algorithm should be preferred, since the computation time of these transformation algorithms can be ignored. This way, the precise *DSm6* should be implemented for the pre-registration.
The developed system for the registration of CT and ultrasound datasets allows a fast and robust registration of bone structures of the human lumbar spine. The easy handling and the *in vivo* accuracy measurements show that the achievable accuracy of the system is adequate for the application in surgical navigation.

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