Registration of Intraoperative 3D Ultrasound with MR Data for Navigated Surgery

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Abstract. Computer based navigated surgery assists the spatial orientation of the surgeon. Our system registers preoperative data like CT or MR with intraoperative ultrasound data to get the coordinate transformation between the preoperative and the intraoperative data. With a surface volume registration we avoid a difficult surface segmentation in the ultrasound data. To prevent radial exposure and to get more details in the soft tissue the use of MR data for the operation planning is common. Extracting the bone surface in MR data is more difficult than in CT data because MR data has no normalized gray values. To register the ultrasound with the MR data at the knee we detected distinctive anatomic regions in the ultrasound data. We selected an adequate MR sequence in which we could segment the bone surface at the specific region. We evaluate the registration with 1000 random starting positions. 99.2% of the 1000 trails reached the optimum with an error less than 1 mm.

1. Introduction

Due to a trend towards minimal invasive surgery, there is an increasing demand for navigation systems. Image based navigation provides the surgeon a three dimensional orientation where he can control the position of his instruments within preoperative data of the patient.

Many of the commercial navigation systems utilize landmarks as reference for the registration of preoperative data within the coordinate system of the patient. Often these landmarks are difficult to define accurately, which makes them ineffective for procedures requiring a higher grade of accuracy. Using intraoperative imaging for registration yields a much higher accuracy. However, established systems based on intraoperative CT or MR are too expensive for common applications.

Additionally the registration procedure with the above mentioned systems is time-consuming. At this point intraoperative ultrasound is a reasonable alternative. The acquisition of ultrasound data is fast and easy, and leads to comparatively low purchasing and operating costs.

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Because of these advantages the interest in using ultrasound as reference for bone surgery increased during the last years [1,2,3]. We developed an algorithm which is able to register bone structures in CT and ultrasound data [4,5]. Our surface volume registration method enables registration of intraoperative ultrasound with preoperatively acquired CT or MR data avoiding the error-prone task of directly segmenting ultrasound data. Our system showed a high accuracy in phantom data [6] and reliable results in registering patient data of the lumbar spine [7]. In this article, we applied our methods to register osseous structures of the knee. As MR data are frequently used for clinical diagnostics of the knee [8], we focused on the registration of MR and ultrasound data. The use of MR data for diagnostic reason especially at the knee is customary, because of the detail level in soft tissue. Furthermore, there is no radial exposure.

2. Experimental Methods

Our algorithm implements a surface volume registration [4, 5]. The bone surface is preoperatively segmented from a MR or CT dataset. As the scan path of the intraoperative ultrasound scan is defined preoperatively, we are able to eliminate surface points which do not get depicted in the ultrasound data.
A good spatial distribution of the surface points is a prerequisite for achieving good registration results.
Segmentation of bone structures in CT data was done by thresholding as they are represented by defined Hounsfield units. MR is different in this respect, since bone structures do not map to defined gray values. Therefore, we analyzed various MR sequences with respect to bone-tissue contrast. We used T2-weighted MR images for segmentation of bone structures, as this sequence proved to have the highest bone-tissue contrast among those tested (T1, T2, PD).
Several ultrasound datasets of the knee were recorded using various scan paths. All ultrasound datasets were visually inspected to assess if they were suitable for registration. Decision criterion at that point was the existence of clearly visible bone structures. In this respect the region posterior-caudal of the patella proved to be most suitable. The bone surface in the MR-data was extracted using a thresholding approach. Figure 1 shows the MR data of the knee. The surface was extracted by scanning from inside the bone along the rays (see Figure 1). A surface point was defined when the ray reaches a gray value greater than a selected threshold. To reduce the data, only every fourth of the surface points was taken. Thus, the extracted surface consisted of 1447 points.
For this purpose T2-weighted data was particularly suitable as osseous structures and synovial fluid showed a sharp contrast. The ultrasound data was pre-processed with an adaptive time gain correction algorithm to enhance the osseous

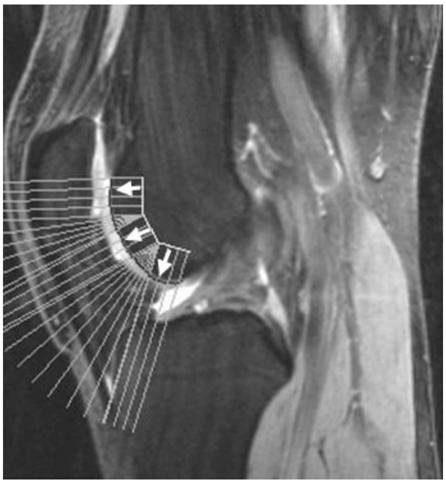

Fig. 1. T2-weighted MR data of a human knee. Extraction of the bone surface by scanning form inside the bone.

surfaces. For registration, the extracted surface was then projected into the ultrasound data.
The sum of gray values in the ultrasound data under the projected surface was used as optimization criterion. We applied a state of the art evolutionary algorithm (covariance matrix adaptation, CMA [9]) to this optimization problem [8].

3. Results and Discussion

For the evaluation a reference registration was defined by first manually pre-registering the surface and the ultrasound data as close to the optimum as possible and afterwards performing multiple local optimizations. The plausibility of the reference registration was verified by visual investigation of fused images of both volumes. The datasets were registered with 1000 different starting positions. The starting positions were generated by independent variation of translation (0 to 10 mm) and rotation (0 to 11 degrees).
To evaluate the registration results, we used the average distance between corresponding points of the registration result and the defined optimum. Within this metric, the starting distances (which were roughly uniformly distributed) ranged from 0 to 10 mm. We considered the registration successful if the average distance between corresponding points was below 1 mm. The results of the registration are shown in Figure 2.
The rate of correct registrations was 99.2%, and the mean precision of successful registrations was 0.096 mm (see Figure 3).Where about 80% of all trails registered with a misalignment of less than 0.01 mm. The average computing time for one registration was 3.7 seconds.

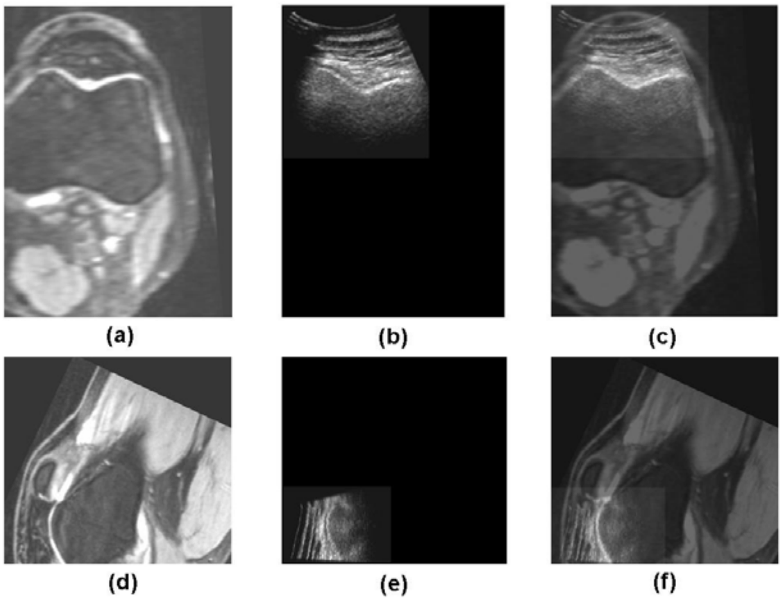

Fig. 2. Ultrasound-MR registration results (a) axial MR slice (b) corresponding axial ultrasound slice (c) axial MR-ultrasound fusion image (d) sagittal MR slice (e) corresponding sagittal ultrasound slice (f) sagittal MR-ultrasound fusion image.

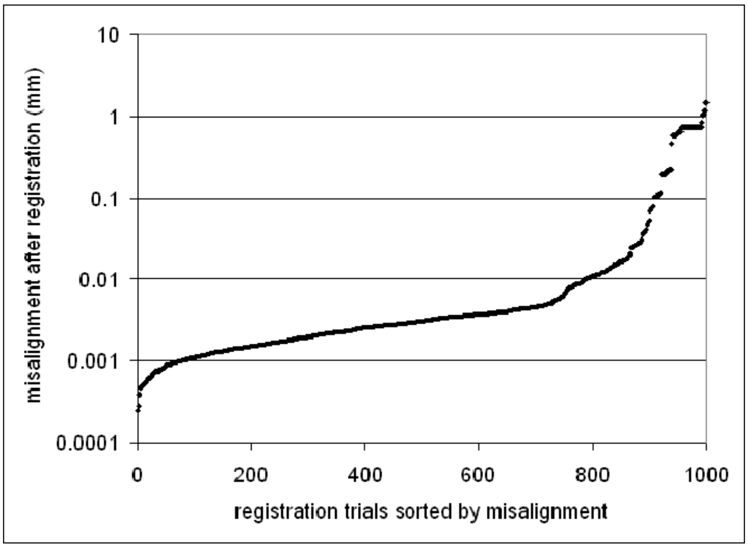

Fig. 3. Misalignment of 1000 registration trails with random starting positions between 0 and 10 mm and 0 and 11°.

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4. Conclusions

The presented algorithm showed good performance registering MR and ultrasound data of the knee. We believe that it is well suited for navigated surgery because of its speed, precision and reliability.
The region posterior-caudal of the patella was particularly appropriate for registration as it featured a good spatial distribution of surface points. The computing time of just a few seconds was acceptable for intraoperative application. The high percentage of successful registrations was very promising and encourages us to carry out further experiments with additional anatomical regions and other MR-sequences.

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