In Vivo Evaluation and In Vitro Accuracy Measurements for an Ultrasound-CT Registration Algorithm

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Abstract. An algorithm for the registration of bones in three-dimensional CT- and ultrasound-datasets, based on surface-volume-matching, is tested in vitro with respect to its accuracy. A point-registration based on fiducial markers is used as a reference for the measurements. The comparison of ultrasound- und point-registration shows maximal deviations of up to 1.7 mm for one vertebra. The mean deviation is negligible, indicating that the ultrasound-registration produces no systematic error. Furthermore, the ultrasound-registration is evaluated with in vivo data of patients. This evaluation shows that the proposed, ultrasound-based registration method is suited for different regions of the human body.
Keywords: intraoperative ultrasound, registration, surgical navigation, accuracy, bone

1. Purpose

With surgical navigation a surgeon can place an instrument or an implant minimally invasively, with continuous control of its position. The precise registration of preoperative image datasets in the coordinate system of the navigation system is important for a successful image-based navigated surgery. In many cases, the precise registration of bones is of particular interest (orthopedics, neurosurgery, accident surgery). Conventional methods are based on point-registration, where anatomical landmarks or fiducial markers are used. Such methods have a higher invasivity, since anatomical landmarks have to be dissected and fiducial markers have to be fixed to the bone before the acquisition of preoperative image data.
Intraoperative imaging, which localizes bone through tissue, can solve this problem. The usage of intraoperative CT, 3D C-arm or MR imaging has already been implemented, but these imaging modalities have drawbacks with respect to application, radiation exposure and costs. In this regard, ultrasound has great advantages. The problem of ultrasound however, is the limited imaging of bones, since ultrasound waves are reflected specularly at the tissue-bone interface and are absorbed by bone. These effects signifi-

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cantly reduce the part of the bone surface that can be imaged with echo ultrasound. This has to be considered for the design of an automatic registration algorithm.
Most existing approaches for the registration of bones in CT and ultrasound datasets are based on a segmentation of the bone surfaces in the CT and in the ultrasound images [1-4]. The surfaces are then registered by surface-surface registration methods. The major problem is the segmentation of the ultrasound images, since they are distorted by a high amount of systematic noise (speckle). Furthermore, the bone surface is often not visualized continuously in space.
Thus, the segmentation of in vivo ultrasound data has to deal with two main problems:

- Not all acquired ultrasound images can be segmented, since some of the ultrasound images do not visualize the bone surface with an adequate quality.
- The computation time of the segmentation is relatively long. This is disadvantageous for intraoperative usage.

Our registration approach [5, 6] avoids the segmentation of ultrasound images. Instead, the ultrasound volume data is directly registered with parts of the bone surface, extracted from the CT data (volume-surface registration). The algorithm is very robust and works for different bone structures. On a standard PC, the registration typically takes some seconds.

2. Method

The algorithm was implemented and integrated in a simple custom made navigation system. The accuracy of the algorithm was tested in in vitro experiments. The phantom for the experiments comprised three synthetic vertebras in a water bath (see figure 1). The phantom had a number of drill holes, which were used as reference points for the localization of the phantom with a conventional point-registration.

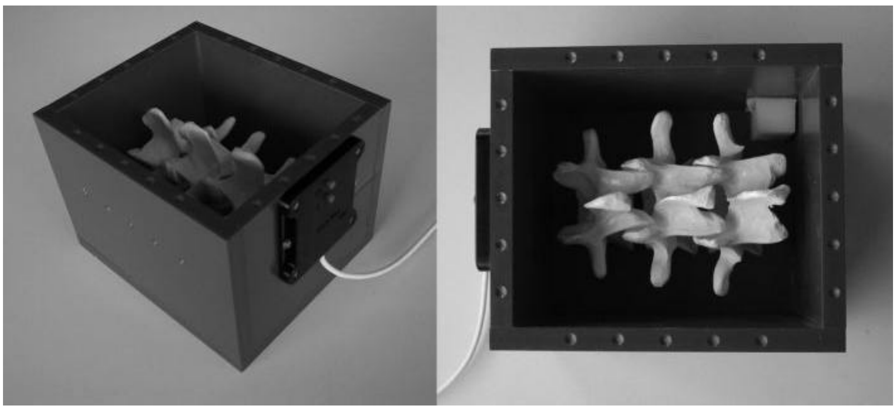

Fig. 1. Phantom for in vitro accuracy measurements. The holes at the rim of the box are the reference points for the point-registration.

CT data was acquired of this phantom. In the CT data, the reference points for the point-registration were marked. For the ultrasound-registration, the parts of the bone surface,

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which are assumed to be visible in the ultrasound data, are estimated in the CT-data. After calibration of the pointer and the ultrasound transducer [7], point- and ultrasound-registration was carried out. Then, the registration results were compared.
Using the transformation matrices of either of the two registration methods, the vertebral bone surface can be transformed from the CT coordinate system to the coordinate system of the navigation system (navigation coordinate system). The maximal distance of the vertebral bone surfaces in the navigation coordinate system is defined to be the error between the two registrations.

3. Results

3.1In vitro accuracy measurements

The calibration and registration procedures were repeated 100 times. For the ultrasound-registration the surface of one vertebra or of three vertebras was used, respectively. The resulting errors are shown in figure 2.

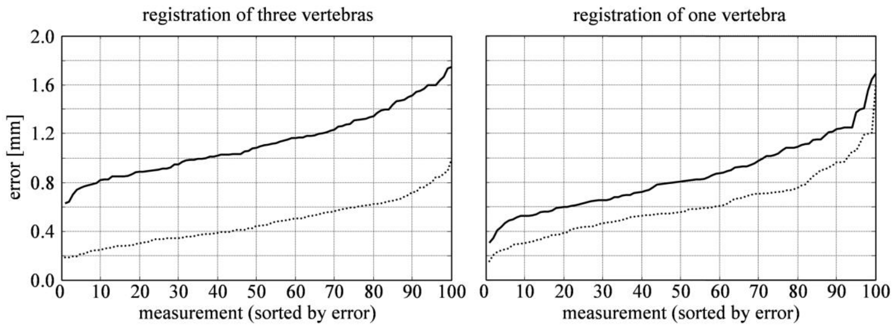

Fig. 2. Deviation between point- and ultrasound-registration. The dotted line shows the error after subtraction of the mean deviation between the both registration methods.

Firstly, the errors plotted with solid lines are considered. Unexpectedly, the errors are larger for the registration of three vertebras than for one vertebra. The error is in all cases smaller than 2 mm, in more than 90 % smaller than 1.5 mm. The RMS is 0.9 mm. It has to be considered that the error is a superposition of the deviations of ultrasound-registration and point-registration. Thus, the largest occurred error is a “constructive” superposition of these deviations.
To get an idea of the systematic error between the both registration methods, the mean distance vector is calculated for a number of points on bone surface. The remaining error (after subtraction of the mean distance vector) is plotted with dotted lines in figure 2. A larger difference with respect to the original error can be seen for the registration of three vertebras. Here, the error is reduced by approx. 0.6 mm. For the registration of one vertebra, this reduction is only 0.2 mm. It is interesting to note that the error after compensation of the mean deviation is now larger for one than for three vertebras. A deformation or translation of the vertebras in the phantom between the acquisitions of the CT-

and ultrasound-data could be a reason for that. Other sources of the systematic error could be:

- Geometric distortions in CT- and ultrasound-images
- Localization errors of the landmarks for point-registration in the CT-dataset
- Systematic errors of the pointer- and transducer-calibration
- Systematic errors of the ultrasound-registration

Considering the very low systematic part of the error for one vertebra, it can be assumed that the systematic error of the ultrasound-registration alone is negligible.

3.2 In vivo evaluation

To verify the possibility to register in vivo data with this algorithm, ultrasound data was acquired from patients, who had a CT exam for diagnostic purposes. For the acquisition of 3D ultrasound data, a Siemens Sonoline Omnia ultrasound system was used, which was equipped with a 3D add-on system (3D Freescan, Echotech). Target regions were the lumbar spine, the tibia and the humerus so far.
In figure 3, the registration result of a lumbar spine is visualized. A sagittal slice of the three dimensional ultrasound dataset in the area of the laminar arc is shown. The gray line illustrates the position of the bone surface, extracted from the CT dataset (left: before registration, right: after registration). By visual inspection, the algorithm registered the ultrasound and CT datasets successfully.
In figure 4, a successful registration result for the tibia can be seen. An axial slice (left) and a sagittal slice (right) of the ultrasound dataset in the area of the tuberositas tibiae are shown. The gray lines mark again the position of the bone surface from CT after registration.
The registration of the humerus is visualized in figure 5. The images represent axial and sagittal ultrasound slices in the area of the sulcus intertubercularis. On the right side, the gray lines illustrate the position of the registered CT bone surface.

4. Conclusion

The proposed algorithm for the registration of CT and ultrasound datasets allows a fast and robust registration of bone structures of different regions of the body. The in vitro accuracy measurements show that the achievable accuracy is adequate for the application in surgical navigation. The applicability of the algorithm was demonstrated at in vivo data of different regions of the body. A measurement of the accuracy in a clinical environment is projected at the moment.

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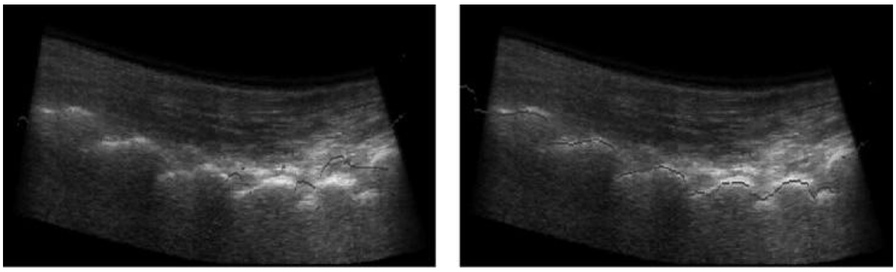

Fig. 3 Registration of an in vivo dataset of a human lumbar spine. Shown are sagittal slices through the three-dimensional ultrasound dataset in the area of the laminar arc. The gray lines indicate the position of the bone surface extracted from the CT-dataset. (left: before registration, right: after registration)

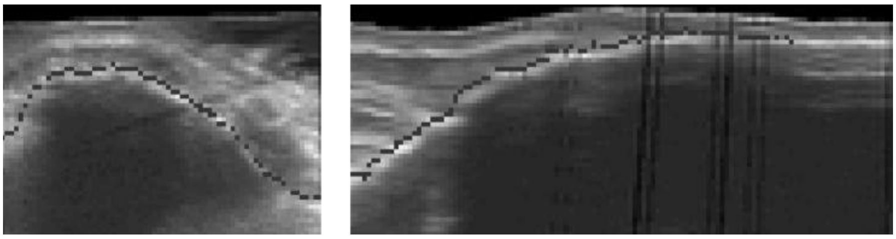

Fig. 4. Registration of an in vivo dataset of a human tibia. Shown are an axial (left) and a sagittal (right) slice through the three-dimensional ultrasound dataset in the area of the tuberositas tibiae. The gray lines indicate the position of the bone surface extracted from the CT-dataset after registration.

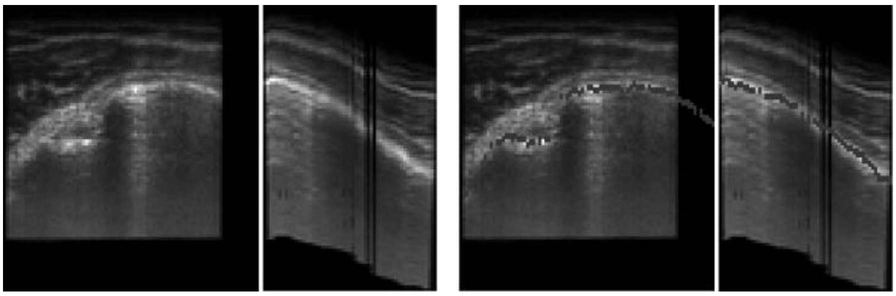

Fig. 5. Registration of an in vivo dataset of a human humerus. Shown are an axial and a sagittal slice through the three-dimensional ultrasound dataset in the area of the sulcus intertubercularis. The gray lines in the images on the right indicate the position of the bone surface extracted from the CT-dataset after registration.

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References

[1] L. Carrat, J. Tonetti, P. Merloz et al. “Percutaneous computer assisted iliosacral screwing: Clinical Validation,” in Proc. MICCAI 2000, pp. 1229-1237.
[2] D. V. Amin, T. Kanade, A M. DiGioia et al. “Ultrasound based registration of the pelvic bone surface for surgical navigation,” presented at CAOS-International 2001, Davos, Switzerland, 2001.
[3] D. M. Muratore, B. M. Dawant and R. L. Galloway, “Vertebral surface extraction from ultrasound images for technology-guided therapy,” in Proc. SPIE Vol. 3661 Medical Imaging, 1999, pp. 1499-1510.
[4] J. Ioppolo, J. Kowal and L. P. Nolte, “Ultrasonic Registration Techniques,” presented at CAOS-International 2002, Santa Fe (NM), USA, 2002.
[5] B. Brendel, S. Winter, A.Rick et al. “Registration of 3D CT and Ultrasound Datasets of the Spine using Bone Structures,” CAS, vol. 7, pp. 146-155, 2002.
[6] S. Winter, B. Brendel, A.Rick et al. “Registration of bone surfaces, extrtacted from CT-datasets, with 3D-ultrasound,” BMT 2002, Berlin, 2004
[7] B.Brendel, S. Winter, H. Ermert, “A Simple and Accurate Calibration Method for 3D Freehand Ultrasound,” BMT 2004, Ilmenau, 2004

In *Proceedings of Computer Assisted Radiology and Surgery (CARS 2005*),
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