Ultrasound Volume Guided Navigated Implantation of the Humeral Part of a Shoulder Prosthesis

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Abstract. Diagnostic ultrasound in the shoulder area is nowadays usually limited to conventional, two-dimensional (2-D) ultrasound images taken in predefined, standardized sonogram acquisition orientations. This only provides limited insights into the joint's three-dimensional (3-D) geometry. In contrast, 3-D freehand acquired ultrasound volumes can cover the anatomic structures necessary e.g. for planning the implantation of the humeral part of a shoulder prosthesis. In a pilot study, such landmarks were determined from the semiautomatically segmented volumes. A first verification of the approach was performed using an experimental prototype for surgical planning and navigation in a cadaver study.

1 Introduction

At present, preliminary diagnostics as well as the planning process for surgical interventions in the shoulder area, e.g. the placement of the humeral part of a prosthesis, are mostly based on X-ray, X-ray CT or MRI imaging. But X-ray imaging exposes patients and medical staff to ionizing radiation, and all mentioned modalities cause organizational efforts and high costs.

On the other hand, ultrasound imaging – which is a non-ionizing and comparatively cheap modality – only plays a minor role in intervention planning and realization of the surgical procedure and is primarily being used in diagnostics using 2-D images acquired in standardized acquisition positions [1]. Additionally, two-dimensional sonography places high demands on the physician's spatial imagination of the joint's three-dimensional anatomy and his ability to correctly place the scanhead and identify the depicted anatomical structures. The approach neither gives the possibility to determine their spatial coordinates nor to derive precise topographic measures, which is essential for implementing an ultrasound based surgical planning and navigation process. Problems inherent to ultrasound imaging, e.g. blurred images, often accompanied by artifacts, additionally complicate the interpretation of the data. Thus, the use of ultrasound as an imaging modality for this purpose only seems possible if it is extended to three dimensions and if a computer based, automatic approach is applied for analyzing the resulting volumes and calculating the necessary measures.

2 Materials and Methods

Using a conventional ultrasound system (Nemio^{TM} SSA-550A, Toshiba, Tokyo, Japan) with an infrared optical localizer system (Polaris^{TM}, Northern Digital Inc., Waterloo, Ontario, Canada) attached to the transducer, the surfaces of the humeri of $N = 20$ healthy volunteers were acquired in up to four overlapping, manually controlled freehand sweeps. Each sweep contained about 300-500 2-D slices. Position data and corresponding images were simultaneously recorded on a standard PC, which was also used for all further steps [2].

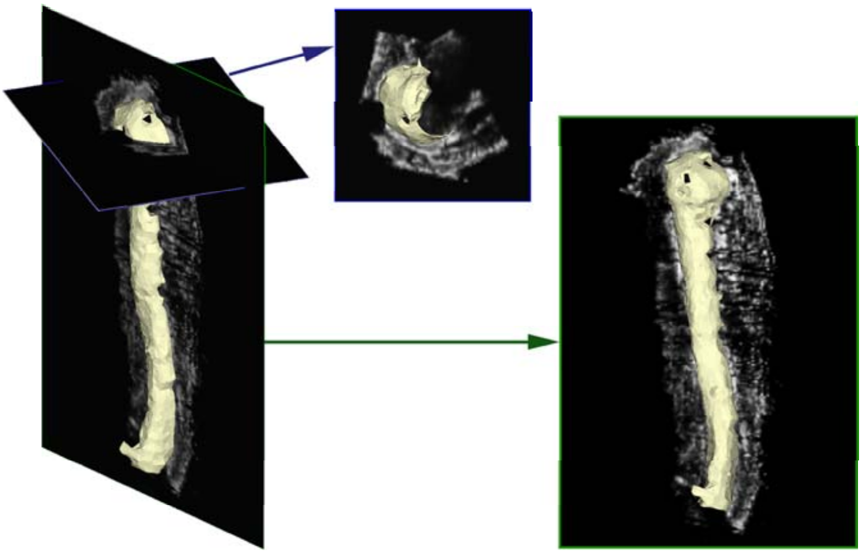
Each ultrasound volume was reconstructed using the 2-D images and their spatial position. To ensure the geometric accuracy of the volumes, a calibration was performed to establish the rigid body transformation for the tracking device versus the transducer's image plane [3]. Using freely placeable cross sectional planes, an interactive, visual verification of the image volumes was performed to determine their completeness (i.e. coverage of all expected anatomical structures) and plausibility (fig. 1). All volumes passed this verification process and could therefore be passed on to the following processing steps.

The segmentation was performed slice-wise using a locally adaptive, semi-automatic procedure. Since each slice's spatial position – and therefore the approximate anatomic region it belongs to, i.e. head, shaft or epicondyles – is known, a slice specific region of interest (ROI) ideally only containing the desired structure could be easily calculated after interactive specification of a few (usually up to 10) points roughly defining the approximated center axis of the humerus and known size ranges for each anatomic region. Within each slice's ROI, the depicted anatomic structure was then automatically delineated. The results from neighboring slices were used for fine-tuning. In the case of implausible results, the results of the respective slice were excluded from all further processing. Since this only occurred in a small number of slices ($< 5\%$), there was no problem with respect to the completeness and accuracy of the bony surface reconstructed from the segmentation results.

The reconstructed virtual humerus could in turn be used for reliable identification of parameters for certain anatomic landmarks (fig. 2), such as a sphere approximating the humeral head or a cylinder approximating the proximal humeral shaft. These parameters were calculated with the help of robust approximation algorithms [3].

Several other parameters – such as the inclination of the articular surface of the humeral head, the posterior and medial offset as well as the individual's retrotorsion angle – also influence the ideal position for implantation of the pros-

Fig. 1. Cross sectional planes in 3D showing good coverage of the humerus in the acquired 3-D ultrasound volume. The reconstructed bone's surface has been overlaid for better orientation.

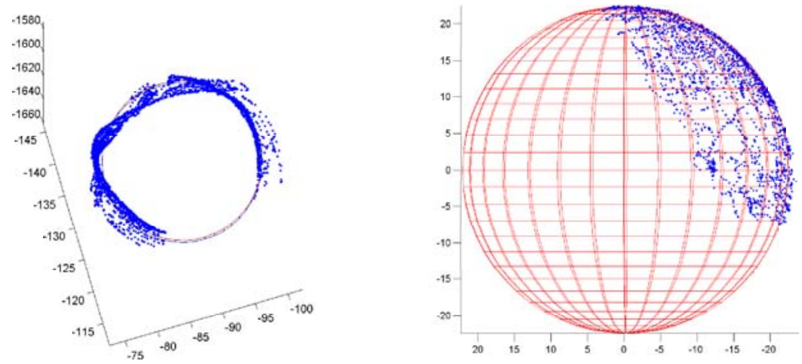


thesis. For their precise definition, additional landmarks must be determined. For this, the initial approximation of the collum anatomicum and the intertubercular sulcus was calculated automatically; the physician could interactively fine-tune the position of these landmarks. Taking all identified landmark parameters into account, a local coordinate system (LCS) for the humerus [4] – to be used as a reference for all planning steps – and the necessary parameters for the resection plane for the humeral head could then be calculated.

Various prosthesis types offer different methods [5] for adjusting the position of the humeral cap part with respect to the position of the implanted shaft, i.e. by varying the values for inclination of the head, the retrotorsion angle, the medial offset etc. Depending on the chosen model, the necessary parameters were always calculated such as to ideally reconstruct the joint.

An interactive, Java-based tool (VisualMediJa, [6]), based on the algorithms of the Visualization Toolkit (VTK, [7]), was used for all post-segmentation steps. Within its flexible interface, the planning scenario could be comfortably visualized. During all steps, any combination of original and segmented data, the bone's surface reconstruction as well as geometric objects representing the positions for the determined landmarks or other planning parameters could be shown in the scene. For validation purposes, the entire workflow – from 3-D volume acquisition, over segmentation, landmark determination and planning of the prosthesis position to the execution of a navigated surgical procedure according to the planned parameters was exemplary carried out in a cadaver study.

Fig. 2. Approximation results for two anatomical landmarks: segmented data points vs. (a) the cylinder approximating the proximal humeral shaft (top view) and (b) the sphere approximating the humeral head (side view). The 90% quantile of the absolute approximation errors is less than $2mm$ for both landmarks.



(a) (b)

3 Results

Although many factors, like improper transducer handling or problems inherent to ultrasound imaging, i.e. artifacts, influence the quality of the acquired image volumes, a reasonable segmentation and reconstruction of the bone's surface was possible for all volumes. As shown for two exemplary landmark calculations in fig. 2, the approximation errors for the determined landmark parameters were within acceptable ranges.

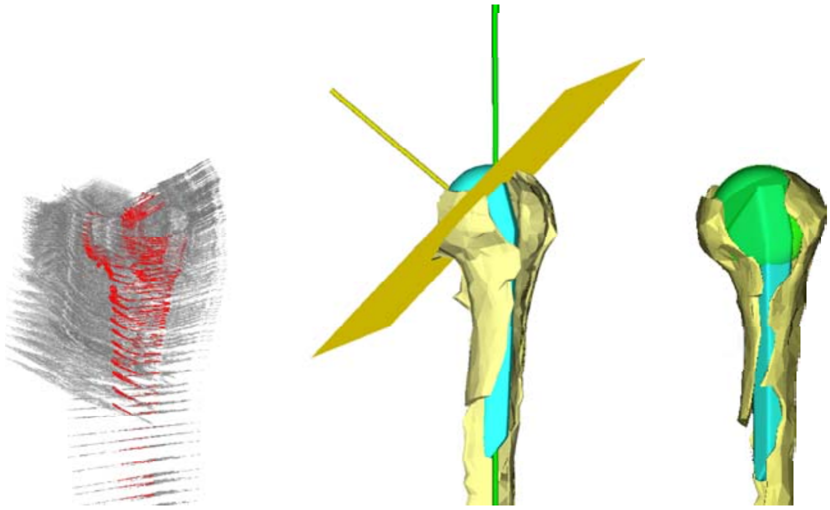
By offering a variety of visualization and interaction possibilities, VisualMediJa's freely configurable graphical user interface allowed an intuitive surgical planning process for the prosthesis implantation (fig. 3). In the cadaver study, the planned parameters could then be easily transferred to the navigation setup used for the implantation of the prosthesis in the cadaver's humerus [2].

4 Discussion

Ultrasound based surgical planning strongly depends on proper image acquisition techniques, not least of all proper transducer handling or good image bone contrast. For all acquired volumes, a satisfactory surface representation of the humerus and all parameters for the anatomically optimized placement of the prosthesis could be determined.

Ongoing work is dedicated towards a fully automatic determination of all required landmarks and planning parameters to make the planning process less dependent on the individual physician and towards developing a full fledged intra-operative navigation tool.

Fig. 3. Different visualizations of the surgical planning process: (a) original volume and segmented data, (b) surface reconstruction of the segmented data with resection plane, local coordinate system and a prosthesis placed according to the determined parameters, (c) virtual implantation of the humerus endoprosthesis; the sphere approximating the humeral head is also shown



(a) (b) (c)

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