SURGICAL PLANNING FOR PROSTHESIS IMPLANTATION IN THE SHOULDER JOINT BASED ON FREEHAND ULTRASOUND VOLUMES

U. von Jan*, D. Sandkühler**, L. Kirsch***, O. Rühmann*** and H.M. Overhoff**

* Institute of Medical Informatics, Hannover Medical School,
Hannover, Germany
** Medical Engineering Laboratory, University of Applied Sciences Gelsenkirchen,
Gelsenkirchen, Germany
*** Orthopedic Department, Hannover Medical School,
Hannover, Germany

jan.ute.von@mh-hannover.de

Abstract: Diagnostic ultrasound in the shoulder area is nowadays usually limited to two-dimensional (2-D) ultrasound images in predefined, standardized sonogram acquisition orientations. A big limitation for this approach is the small field of view which is thus provided to inspect the joint's three-dimensional (3-D) geometry. Additionally, high demands are placed on the physician's experience concerning the correct acquisition and interpretation of these 2-D images. For utilizing ultrasound imaging in a surgical planning scenario, e.g. for the implantation of the humeral part of a shoulder prosthesis, it is a necessity to be able to determine appropriate 3-D measurements. In this study, we evaluated the feasibility of a purely 3-D ultrasound based approach for the navigated, anatomically optimized implantation of the humeral part of a shoulder prosthesis.

Introduction

Currently, surgical planning for the implantation of a shoulder endoprosthesis is done based on CT, MRI or X-ray imaging. Apart from high costs caused by these modalities, CT and X-ray additionally expose the patient to ionizing radiation.

In contrast, even though it is a cost-effective, non-ionizing modality, sonography in the shoulder area is almost exclusively being used for diagnostic purposes by taking conventional 2-D (B-mode) images in so-called standardized sonogram acquisition orientations [1]. This only opens a small field of view on the joint's three-dimensional geometry. Furthermore, two-dimensional sonography puts high demands on the physician's spatial imagination of the anatomy and his abilities to correctly place the scanhead and to reliably identify the depicted anatomical structures [2].

The inherent problems of ultrasound like blurred images, often accompanied by artifacts (fig. 1), additionally complicate the interpretation of the images.

Important prerequisites for surgical planning, in particular determining the spatial position of certain bony landmarks, cannot be satisfied using only 2-D images. Using ultrasound for surgical planning thus seems only possible if this modality is extended to a 3-D modality and if a computer based, automatic approach is applied for analyzing the resulting image volumes.

In a pilot study, we tested whether it is possible to acquire 3-D ultrasound volumes of the humerus covering all landmarks necessary for determining the parameters for the anatomically optimized implantation of the humeral part of the prosthesis. For this purpose, image volumes were acquired and segmented automatically. A surface model was generated for the bone, which was used as a basis for an interactive, landmarks based prosthesis implantation planning.

Materials and Methods

Manually controlled freehand sweeps of the humeri of 20 healthy volunteers were acquired using a conventional ultrasound imaging system (Nemio™ SSA-550A, Toshiba, Tokyo, Japan); an infrared optical localizer system (Polaris™, Northern Digital Inc., Waterloo, Ontario, Canada) was securely fixed to the ordinary 2-D scanhead (2 (a)). To ensure geometric accuracy for the reconstructed 3-D volumes, a probe calibration as described in [3] was performed to establish the rigid body transformation between the scanhead's image plane and the tracking device. Position data and images were simultaneously recorded on a standard PC (Intel Pentium™ IV, 3.2 GHz, 512MB RAM), which was also used for all following steps [4].

Since ultrasound waves do not penetrate bone and it is therefore impossible to record the whole bone in one go, up to five overlapping sweeps (each consisting of approx. 300 slices), starting in the humeral head area and going down to region of the epicondyles, were recorded for each upper arm to cover as much of the bone's surface as possible (fig. 2 (b)).

For a first visual verification of the completeness (i.e.

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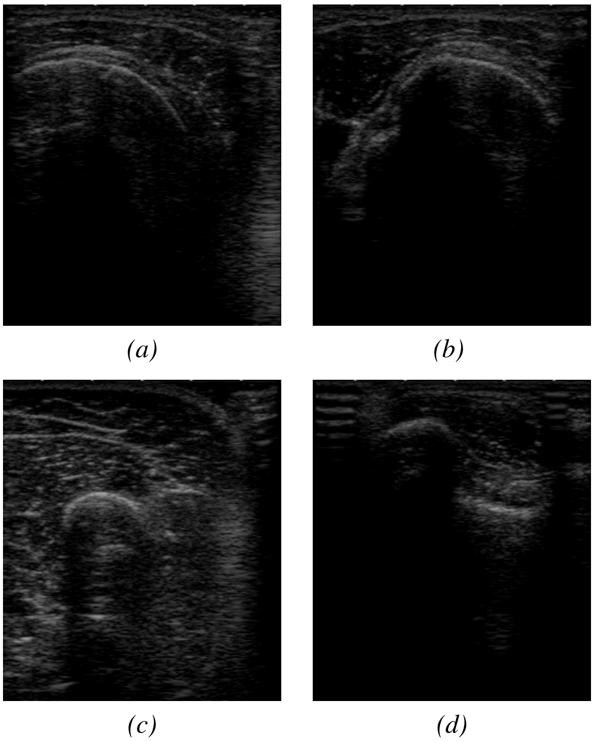
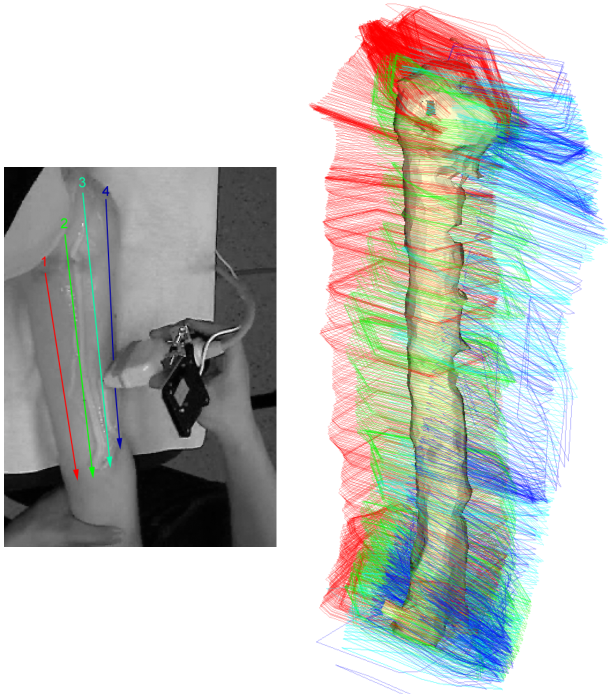


Figure 1: Sonographic images of the humerus in the region of the head *(a, b)*, shaft *(c)* and epicondyles *(d)*. Along with the anatomic structures, artifacts can be seen which can complicate the automatic segmentation process.

coverage of all necessary anatomic structures) and plausibility of the recorded image volumes, freely movable cross sectional planes could be interactively placed into the original reconstructed 3-D image volumes (fig. 3). In this step, all acquired volumes could be confirmed as valid and were passed on for further processing.

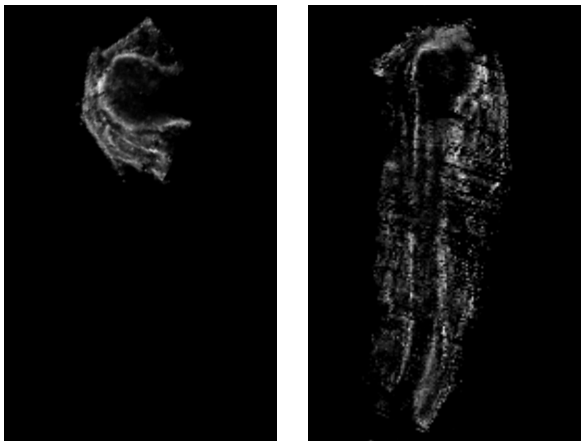
The segmentation of the sub-volumes was done on the original image slices using a locally adaptive, semi-automatic procedure based on methods made available through the Insight Toolkit (ITK [5]) library. After interactive identification of the approximate region of interest (ROI) on a few slices of each sweep, the accurate ROI was automatically identified for all slices and the bony structures in each sub-volume were segmented automatically (fig. 5). During the segmentation process, each slice's spatial position was evaluated to determine the approximate anatomic region it belongs to and thus the expected form of the bony structure in the image. Additionally, the results from neighboring slices were used for fine-tuning. In the rare case of implausible results on a slice, the respective slice was excluded from all further processing steps. Since this only happened in about 5% of the slices and due to the large number of available slices, this did not cause a problem with respect to the completeness of the virtual bone. The segmentation process took less than 5 minutes for a volume of about 1000 slices.

The results for the sub-volumes were then registered



(a) *(b)*

Figure 2: The upper arm is covered using several sweeps *(a)*. The spatial positions of four overlapping sweeps are depicted in *(b)*. For better orientation, the segmented bone's surface is also shown.



(a) *(b)*

Figure 3: Reconstructed cross sectional image planes through the humeral head *(a)* and along the longitudinal axis of the humerus *(b)*, both showing good coverage of the humerus.

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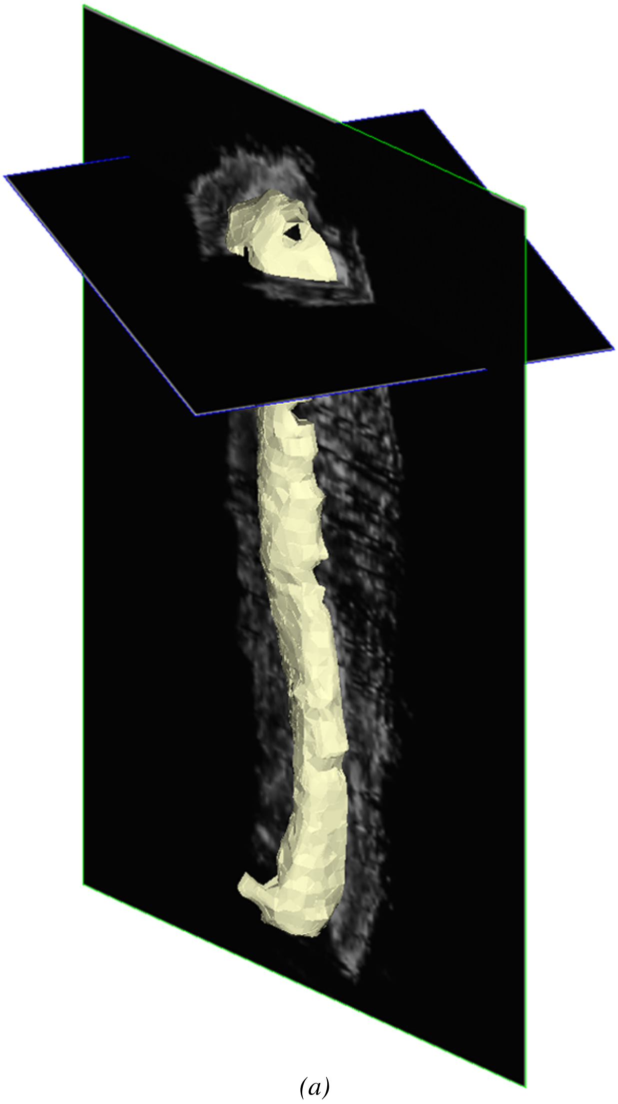
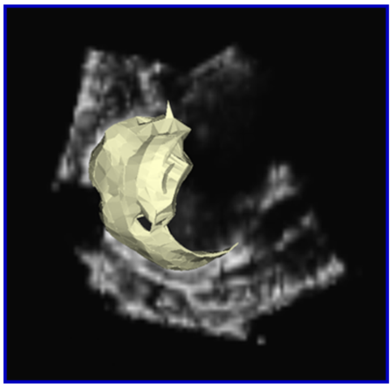


(a)



(b)

(c)

Figure 4: Cross sectional planes in 3D. For better orientation, the bone's reconstructed surface has been overlaid.

to one another to form an almost complete representation of the surface of the humerus. This virtual humerus could in turn be used to automatically determine certain bony landmarks. Furthermore, parameters for a sphere approximating the humeral head and a cylinder approximating the proximal part of the shaft [3] were determined with the help of robust approximation algorithms [6].

In several studies [7, 8, 9], the proximal anatomy of the humeral head has been shown to vary greatly between individuals. Among the factors influencing the ideal implantation of the humeral component of a shoulder prosthesis are e.g. the inclination of the articular surface of the head, the posterior and medial offset as well as the individual's retrotorsion [10].

To define these parameters precisely, additional landmarks on the humerus – an approximation of the collum anatomicum and the intertubercular sulcus – were identified semiautomatically. For this, the physician interactively fine-tuned the primarily automatically determined approximate position of each respective landmark.

Taking all identified landmarks into account, it was then possible to determine the parameters for a local humerus coordinate system – used as a reference – and the necessary parameters for the resection plane used for the humeral head.

For all post-segmentation steps, a Java based visualization tool (VisualMediJa, [11]) based on the algorithms of the Visualization Toolkit (VTK, [12]) was employed. Within VisualMediJa's freely configurable Graphical User Interface (fig. 7), the planning scenario for the prosthesis implantation can be comfortably visualized (fig. 8). The features available in VisualMediJa make it easy to interactively determine the landmarks. To round of the visualization and to simplify verification of the results, any combination of volume data, segmented data – represented either by the original segmentation results or interpolated surface data – or freely placeable cross sectional planes can be used. In addition, geometrical objects representing the determined landmarks or planning parameters important for the implantation of the prosthesis, such as the position of the resection plane for the femoral head, can be overlaid into the scene (fig. 8).

The entire workflow from the 3-D image acquisition over segmentation, landmark determination and planning

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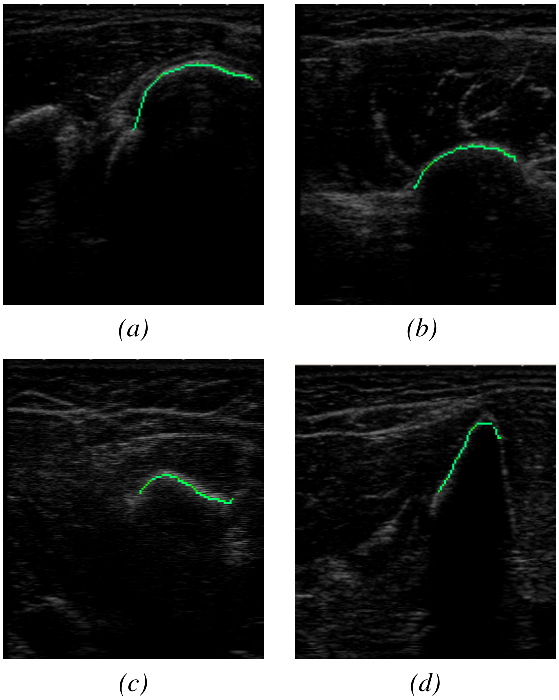

Figure 5: Exemplary results of the automatic segmentation process. In some cases (e.g. *(a)* and *(b)*), parts of the correctly segmented structures are erroneously removed in the process of eliminating improbable results. This does not cause problems due to the large number of available slices.

of a humerus endoprosthesis position to the navigated surgical procedure was exemplary implemented in a cadaver study. Fig. 6) shows the experimental setup.

Results

Many factors, like improper transducer handling or simple artifacts inherent to the ultrasound imaging technique can have a negative influence on the quality of the acquired 3-D ultrasound volumes of the humerus. A reasonable segmentation and reconstruction of the surface of the humerus was possible for all datasets using a semiautomatic segmentation procedure. Due to the large number of available slices, unclear segmentation results for a few slices could be left out without having influence on the final surface representation.

A freely configurable Graphical User Interface which makes it possible to visualize any combination of raw and virtual 2-D images, raw 3-D image volume, segmented volumes and intervention relevant structures like a resection plane and a prosthesis allowed an intuitive surgical planning of the implantation procedure.

Discussion

Ultrasound based surgical planning strongly depends on good ultrasound image bone contrast and proper transducer handling. For all volumes, it was shown that a segmentation of the humerus bone surface was gained. A cadaver study is currently under way to evaluate the validity of the segmentation procedure.

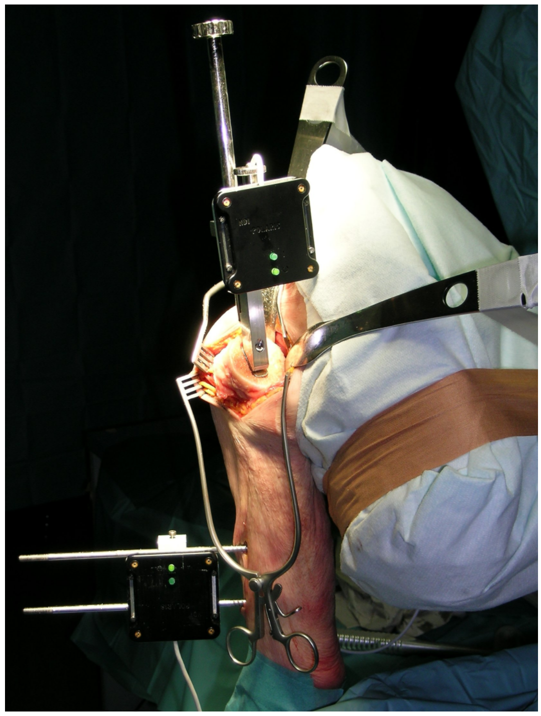

Figure 6: Navigated humerus endoprosthesis implantation. The reamer is also tracked by a LED-system to allow the correct orientation of the instrument. A dynamic reference base has been attached to the humerus to detect movements of the arm during the intervention.

Ongoing work is devoted towards the implementation of a fully automatic identification of all landmarks to make their placement less dependent on the investigator and towards development of a full fledged intraoperative navigation tool.

Conclusions

Robust image segmentation procedures are necessary to enable a purely 3-D ultrasound image based finding and measurement of the humeral part of the shoulder joint even for poor image contrast. A 3-D ultrasound image guided surgical planning scenario for the implantation of the humeral part of a shoulder prosthesis is feasible.

Acknowledgement

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References

[1] W. Konermann and G. Gruber. *Ultraschalldiagnostik der Stütz- und Bewegungsorgane*. Thieme, Stuttgart, New York, 2000.

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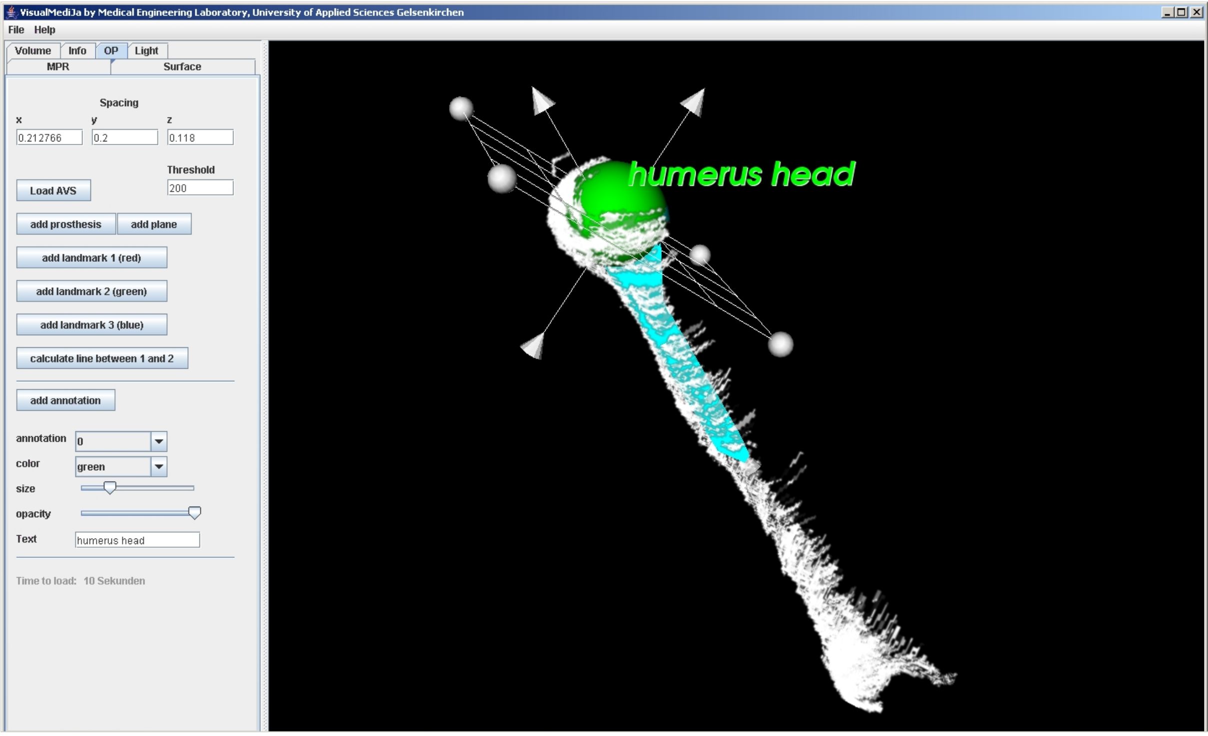

Figure 7: VisualMediJa's interface is freely configurable. In addition to visualizing and interacting with the 3-D scene, VisualMediJa can also be used for documenting findings or surgical plans.

[2] P.J. O'CONNOR, J. RANKINE, W. W. GIBBON, A. RICHARDSON, F. WINTER, and J.H. MILLER. Interobserver variation in sonography of the painful shoulder. *J Clin Ultrasound*, 33(2):53–56, Feb 2005.

[3] U. VON JAN, D. SANDKÜHLER, D. KIRSCH, O. RÜHMANN, and H.M. OVERHOFF. Determining parameters for anatomical landmarks of the humerus from point clouds acquired from the bone's surface. In *IFMBC Proceedings EMBEC '05 "3rd European Medical and Biological Engineering Conference"*, i.p., 2005.

[4] U. VON JAN, D. SANDKÜHLER, L. KIRSCH, and H.M. OVERHOFF. Definition of a humerus coordinate system from semiautomatically segmented 3-d ultrasound volumes. In *Biomedizinische Technik*, volume 49, pages 874–875, Berlin, 2004. Schiele & Schön.

[5] L. IBÁÑEZ, W. SCHROEDER, L. NG, J. CATES, and THE INSIGHT SOFTWARE CONSORTIUM. *The ITK Software Guide*. Kitware, Inc., 2004. http://www.itk.org/ItkSoftwareGuide.pdf.

[6] H.M. OVERHOFF, S. EHRICH, and U. VON JAN. Reliable identification of sphere-shaped femoral heads in 3-d image data. In Kenneth M. Henson, editor, *Medical Imaging 1999: Image Processing*, volume 3661 of *Procs SPIE*, pages 1377–1387, 1999.

[7] U. HARLAND, M. DIEPOLDER, G. GRUBER, and H.-P. KNÖSS. Sonographic determination of the humerus retrotorsion angle. *Z Orthop Ihre Grenzgeb*, 129(1):36–41, 1991.

[8] CH. KUNZ, TH. RIEDER, and R. VIEHWEGER. Can ultrasonography be used to measure torsion angle of the humerus? *Z Orthop Ihre Grenzgeb*, 131:307–312, 1993.

[9] M.L. PEARL and S. KURUTZ. Geometric analysis of commonly used prosthetic systems for proximal humeral replacement. *J Bone Joint Surg Am*, 81-A(5):660–671, May 1999.

[10] U. VON JAN, D. SANDKÜHLER, L. KIRSCH, H.M. OVERHOFF, and O. RÜHMANN. Ultrasound volume based surgical planning for prosthesis implantation in the shoulder joint. In H.P. Meinzer, H. Handels, A. Horsch, and T. Tolxdorff, editors, *Bildverarbeitung für die Medizin 2005*, pages 435–439, Berlin, Heidelberg, New York, 2005. Springer.

[11] S. MAAS and H.M. OVERHOFF. Shared interactive findings on 3-d image volumes. In *Biomedizinische Technik*, volume 49, pages 202–203, Berlin, 2004. Schiele & Schön.

[12] W. SCHROEDER, K. MARTIN, and B. LORENSEN. *The Visualization Toolkit: An Object Oriented Approach to 3D Graphics*. Kitware, Inc., 3rd edition, 2004.

[13] A. FENSTER and D.B. DOWNEY. Three-dimensional ultrasound imaging. *Annu Rev Biomed Eng*, 2:457–75, 2000.

[14] F. LINDSETH, G.A. TANGEN, T. LANG, and J. BANG. Probe calibration for freehand 3-D ultrasound. *Ultrasound Med Biol*, 29(11):1607–23, Nov 2003.

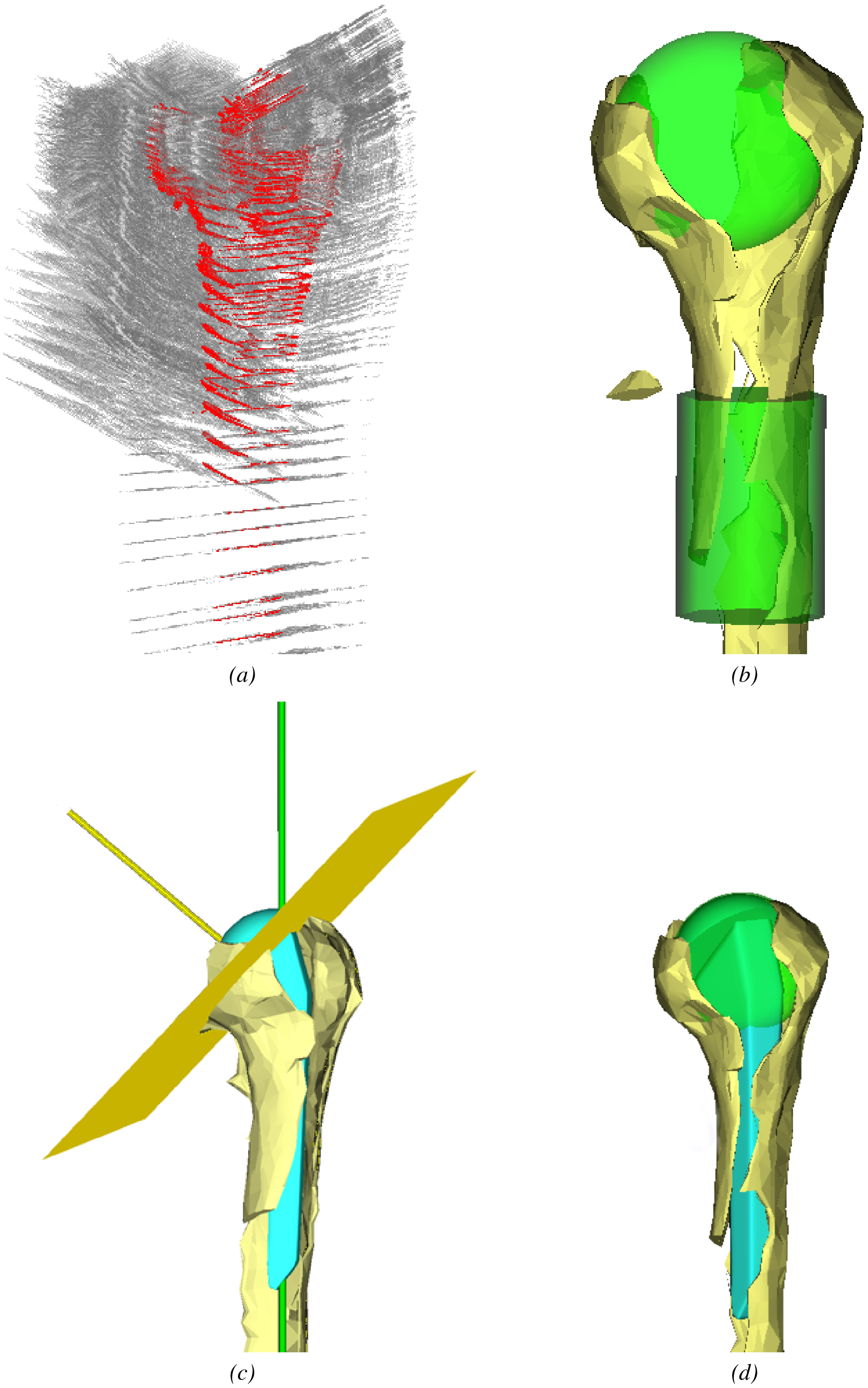

Figure 8: Combinations of different visualizations of the surgical planning process: *(a)* original volume and segmented line data, *(b)* reconstructed surface with sphere approximating the humeral head and cylinder representing the proximal part of the humeral shaft, *(c)* segmented data shown as surface visualization with resection plane and local coordinate system for the humerus and the prosthesis placed according to the interactively defined parameters, *(d)* virtual implantation of the humerus endoprosthesis (blue); the approximating sphere for the humeral head is also shown.

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