An Optimized Surgical Planning Environment for Complex Proximal Humerus Fractures

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Abstract. The precise restoration of a joint’s mobility after fractures can only be successful, if the original anatomical relationships are reproduced as closely as possible. Precise estimates about the morphology of the bony components are therefore of paramount importance both for reconstructive surgery by ostheosynthesis as well as for partial or total joint replacement by arthroplasty. In case of the shoulder joint, only the proper reassembly of the fragments provides sufficient information about the original anatomical relationships of a fractured humerus, due to high individual variability and lateral asymmetry. To support the precise planning of the interventions, this paper presents an enhanced environment facilitating both underlying processing steps: fragment segmentation and bone reassembly. This includes an intuitive interface for correcting pre-processed volumetric CT data as well as a visuo-haptic, virtual environment for physically-based simulation of interactive reassembly. The planning system has been successfully tested in a pilot study on four clinical cases.

1 Introduction

Complex shoulder fractures are usually the result of severe traffic accidents, often involving drivers of motorbikes. The ultimate goal during the surgical treatment of such cases is the precise restoration of the joint’s mobility. Several clinical studies in total shoulder arthroplasty have clearly demonstrated that the restoration of the original anatomy is of critical importance for the long-term results [1]. Due to the high individual variability and the lateral asymmetry of the shoulder joint [2], only the proper reassembly of the bone fragments provides sufficient information about the original anatomical relationships of a fractured humerus. Nevertheless, surgeons orient themselves today mostly on average male and female morphologies when planning and performing interventions. This often leads to suboptimal results, causing serious biomechanical consequences such as eccentric loading, impingements, poor soft tissue balancing, and ultimately loosening [1]. Therefore, the target of our work was to develop an interactive surgical planning system, which supports the reproduction of the anatomical relationships in
the joint as closely as possible. Our system allows segmentation of the individual bony fragments in the CT scan of the patient, their reconstruction in 3D, and surgical planning via virtual assembly in an immersive visuo-haptic environment.

2 Related Work

The spatial reconstruction of the cortical bone from its fragments can be considered as a 3-dimensional puzzle problem, aiming at the full assembly of a hollow object. Quite some attention has been paid to the computer-assisted performance of this task during the past few years, mostly driven by archaeological needs [3–5]. The goal of these efforts is the reconstruction of pottery vessels from a collection of shards in an automatic fashion. These algorithms often rely on matching 3-dimensional break-curves subject to additional assumptions such as rotational symmetry. Similar techniques have also been tested in the context of fracture fragment repositioning in orthopedics [6, 7]. Unfortunately, these methods are currently only capable to assemble two or sometimes three fragments and cannot adequately deal with missing or faulty data, as they rely on clearly defined, characteristic break-lines: limitations which are prohibitive in the context of dealing with complex shoulder fractures.

Alternatively, reassembly tasks have also been addressed by enhanced interactive systems. A multi-modal human-computer interface for assembly in industrial computer aided design has been presented in [8]. They demonstrated the importance of using feedback simultaneously for different human sensory channels. Similar results were also indicated in [9], where the benefits of force feedback for virtual reality training of construction of a LEGO™ biplane model was examined.

Finally, a hybrid approach has been proposed in [10]. Real-world replicas of the involved components are created with stereolithography and then manually assembled by a surgeon. Unfortunately, the applied technology for the physical replication of the fragments is quite complicated and very expensive, wherefore this method was not further considered.

3 Interactive Segmentation System

The identification of the fragments in the underlying CT images of the patient requires an efficient segmentation procedure which can be applied under the strong constraints of the daily clinical routine. Due to noise in the images, neither automatic threshold-based identification of bones based on Hounsfield units nor watershed-based algorithms (e.g. [11]) provided satisfactory results. Using statistical shape models for the segmentation [12] is not feasible either in the considered case of complex, dislocated humerus fractures. Therefore, a semi-automatic approach has been taken, which relies on minimal user control. The cropped volume of the CT images of a patient’s shoulder are used as input data.

The first step of the segmentation system is the extraction of the cortical layer of proximal humerus joint fragments. The process is relying on the sheetness
measure as given in [13], which is an extension of earlier work in [14]. The method
starts with an eigenvalue analysis of the Hessian matrix. This matrix encodes
second-order local variations of the CT data. With the eigenvalues $0 \leq |\lambda_1| \leq |\lambda_2| \leq |\lambda_3|$ of the locally computed Hessian matrix, three ratios are determined:

$$R_{sheet} = \frac{|\lambda_2|}{|\lambda_3|}, \quad R_{blob} = \frac{2|\lambda_3| - |\lambda_2| - |\lambda_1|}{|\lambda_3|}, \quad R_{noise} = \sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2} \quad (1)$$

The first two ratios are labeled as undefined in case of $\lambda_3 = 0$. As discussed
in [15], sheet-like structures are characterized by $\lambda_1 \approx \lambda_2 \approx 0, |\lambda_3| \gg 0$. Using
the above ratios, the sheetness measure $M$ is then given by

$$M = \left[ \exp\left(\frac{-R_{sheet}^2}{2\alpha^2}\right) \right] \left[ 1 - \exp\left(\frac{-R_{blob}^2}{2\beta^2}\right) \right] \left[ 1 - \exp\left(\frac{-R_{noise}^2}{2c^2}\right) \right] \quad (2)$$

Where $\alpha, \beta, c$ are weighting factors for the separate ratios. For our tested
datasets, optimal results were achieved with $\alpha = \beta = 0.5, \quad c = 7.5 \cdot 10^{-3}$. In contrast to [13], we only evaluate $M$ on a single user-defined scale $\sigma$, which corresponds to the assumed average thickness of the cortical bone in the humerus’
head. Moreover, it should be mentioned, that the eigenvalues are invariant to the contrast of the CT data, thus not requiring any scaling operations. On a
cropped dataset of $256 \times 256 \times 221$ voxels, the runtime of the algorithm is about
160 seconds. The result of the sheetness measure on a slice of an example dataset
is depicted in Figure 1.

As a next step, semi-automatic region growing is carried out on the obtained
3D sheetness data. Seed points for the region growing algorithm are set inter-
actively by the user. Voxels with a sheetness measure larger than a predefined
threshold (in our case 0.18), are labeled as belonging to a cortical bone fragment.
This operation is repeated until all fragments have been labeled in the dataset.
The individual pieces resulting from this process are displayed in the original
CT data with different colors in order to determine if all fragments have been extracted. It should be noted that due to the considerable size of the datasets ($10^6 - 10^7$ voxels) the region growing is carried out following a wave propagation strategy, which reduces memory consumption and increases computation speed, thus rendering interactive processing viable.

After the labeling process, triangular surfaces of the cortical fragments are extracted. The reason for this step is twofold. Firstly, real-time dynamic visualization of the fragments is required in the subsequent interactive manipulation phases. One option for this would be volume rendering, however, even GPU-accelerated 3D texture based approaches can only provide sufficient framerates for datasets considerably smaller than $256^3$ voxels. Therefore, we maintain interactivity by rendering the fragments as polygonal surfaces. Secondly, the necessary topological modifications as well as dynamic simulations are also simplified by using a surface representation. The triangle surfaces are extracted from the volume data using the modified marching cubes algorithm described in [16]. In contrast to the original technique this method results on average in 2-4 times less triangles as well as equally smaller computation time. The average number of surface elements resulting from this process is $5 \cdot 10^5$ requiring a computation time of about 10 seconds.

The final preprocessing step is the manual separation of erroneously connected fragments. This can be caused by noisy data as well as the surface extraction step. Experiments with our test datasets have shown that mainly the former case is prevalent, especially due to cancellous bone. These artificial connections between the pieces of the humerus head have to be removed by the user. To this end, a cut line can be interactively drawn onto the surface of the bone fragments. This can be carried out using a 3D as well as a 2D mouse. With the latter, the 2D screen coordinates are orthographically projected onto the surface to determine the mouse position in the 3D scene. Based on this line a set of sep-

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Separation of bone fragments by deletion of artificial connection.}
\end{figure}
ration voxels is defined. These voxels are determined by a parallelepiped-shaped volume that is given by the cutting line. The latter is first grown parallel to the screen by a factor \( k \) to form the base of the parallelepiped. This base is then extruded along the viewing vector by a factor of \( 2k \) and in the opposite direction by a factor of \( k \). Currently, \( k \) is set to the length of 10 pixels. After marking these voxels, a region growing operation is repeated for the involved pieces, in order to determine, if an unwanted connection still exists. Figure 2 illustrates an example of this process with a cutting line drawn on the bone surface via a 2D mouse.

The described separation process is carried out in a stepwise fashion in order to disconnect all fragments. Individual bone pieces can be hidden during this process to allow focusing on the remaining parts. A sequence of this procedure is displayed in Figure 3. Due to the manual input the processing time is about 5 minutes. The described segmentation and extraction step has been successfully applied to four CT datasets of complex fractures. The obtained surface representations of the bone fragments will be used as input for the subsequent surgical planning procedure.

4 Surgical Planning System

After obtaining the individual bone fragments, the next step focuses on the reassembly of the fractured joint. In order to facilitate this process, we have developed a visuo-haptic virtual environment, in which the individual pieces can be interactively repositioned. Immersive stereo rendering as well as force-feedback from haptic devices assist a user in this task. In this regard, it should be noted that the main goal of our system is not to simulate every detail of physical reality, but to build an intuitive environment for the virtual reassembly process.

A key component in this respect is the collision detection and response. Due to the size of the triangle meshes of about \( 5 \cdot 10^5 \) polygons, most currently available rigid body collision detection engines are not appropriate for satisfying the necessary update rates for haptic rendering (about \( 1kHz \)). Therefore, we have developed a specialized vector field approach for handling collisions of complex, non-convex, rigid objects as well as for haptic rendering [17]. A GPU-based technique is applied to precompute 3D Voronoi cell information for runtime collision queries. For the interaction with the bone fragments, initially a bimanual haptic interface has been used, which provides force feedback to thumb and index finger of one hand. This setup should allow a surgeon to pick up a bone piece and reposition it, while the remaining ones are fixed in the environment. While our method provides satisfactory results for general object geometries, it still suffers from a typical drawback of vector field approaches – pop-through effects for very thin structures due to time discretization. Therefore, we moved to a different interaction metaphor, where a bone piece is selected by a user and then rigidly attached to the tip of a single haptic device stylus.
Moreover, for the immersive visualization of the bone fragments, stereo rendering using Crystal Eyes shutter glasses has also been incorporated into the setup. In addition, depth perception is also enhanced by including motion parallax. By adding head tracking to the setup via a hybrid tracking system by InterSense, the scene view can be updated according to head movements, thus providing a depth from motion effect. A further extension of the immersive environment is the integration of visuo-haptic collocation via a mirror-setup. This allows to collocate visual and haptic feedback thus facilitating hand-eye coordination. Figure 4 shows bone fragments in their initial position and after the virtual assembly. After finishing this task, information about the complete process can be stored for later consultation including bone trajectories and multiple views of the fragments.

The described system is running under Linux in C++ on standard PC hardware. The assembly process has been tested with three different commercial haptic devices. All of them provided comparable results [18]. Since the main goal of our work is routine clinical operation we are currently focusing on the
evaluation of the system’s influence on surgical decision making. Initial tests with four clinical cases have been successful. Depending on the complexity of the fracture the virtual reassembly can be carried out in about 20 minutes. First qualitative clinical feedback has been very positive, especially stressing the value of the intuitive interface.

5 Conclusion and Future Work

In this paper we have presented an enhanced environment for surgical planning for complex proximal humerus fractures. Two components facilitating fragment segmentation and bone reassembly were outlined. This includes an intuitive interface for preprocessing volumetric CT data as well as a visuo-haptic, physically-based virtual environment for simulated interactive reassembly. The planning system has been successfully tested in a pilot study on four clinical cases. Initial feedback from our clinical partners hints at the enhanced support through the system for fragment extraction, navigation, and reconstruction of the original bone anatomy. Future work will focus on improving the haptic feedback, enabling a user to grasp bone pieces between thumb and index finger without experiencing any rendering artifacts. In addition, the clinical usefulness will be examined in additional evaluation studies.

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