Summary

In this thesis we investigate how medical visualisation provides insight into the articulation and range of motion (ROM) of joints, with the purpose of supporting surgical decision-making that addresses pathology at the articulating joint. To this aim, we study medical visualisation applications in image processing, diagnostic decision-making, pre-operative planning and evaluation of kinematics.

We present a technique for the segmentation of bony structures in computed tomography (CT) scans of rheumatoid shoulders (chapter 2). The segmentation process is complicated by holes (i.e. bone cysts), irregularities and a non-uniform density of the bone tissue, which are caused by the pathological state of the joint. For the specific case of the shoulder joint, existing segmentation techniques often fail and lead to poor results. Our approach enables users to quickly and accurately segment CT scans of gleno-humeral joints that have a varying bone density and a small joint space.

The technique consists of three steps and starts with a rough surface model of the bones. First, a loop that encircles the joint is extracted by calculating the minimum curvature of the surface model. Subsequently, the intersection points of this loop with the separate CT-slices are connected by means of a path search algorithm. Finally, errors in the segmentation are corrected by iteratively applying a Hough transform to the segmentation result.

The segmentation routine was developed to facilitate the extraction of surface models from CT scans for a pre-operative planning system. The limited time available in clinical practice introduces the requirement that the segmentation routine must lead to a sufficiently accurate segmentation result in under two minutes. This criterion was satisfied by our approach. We conclude that the combination of surface curvature, limited user interaction and iterative refinement via a Hough transform forms a satisfactory approach for the segmentation of severely damaged arthritic shoulder joints.

The segmented volumes can be converted to surface models of the shoulder bo-
Summary

The models play an important role in a system we developed for pre-operative planning of shoulder replacement surgery. The system includes a fast and efficient method for highly interactive visualisation of patient-specific bone-determined ROM for the gleno-humeral joint (chapter 3). The gleno-humeral ROM is visualised with motion envelopes that indicate the maximum ROM of the humerus in every direction. In our pre-operative planning system, the prosthesis alignment can be adjusted interactively, during which a novel comparative visualisation technique depicts the differences between the current and previous ROM. By using geometry clipping-based optimisation, as well as precalculation and interpolation techniques, it was possible to show in real-time the consequences of adjustments made to a planned shoulder prosthesis alignment.

Subsequently, the results of an evaluation experiment for the ROM simulator are presented (chapter 4). Both shoulders of a cadaver were replaced with a modular shoulder prosthesis. A data connection between the software environment and an existing intra-operative guidance system was created to track the relative positions of the bones. With the data connection, the position and alignment of patient-specific surface models within our visualisation software were matched with the position and alignment of the real bones. Using this set-up, all of the occurrences of impingement of a series of systematic movements were registered. These registrations were compared to the results of the ROM simulator. We conclude that the ROM simulator is sufficiently accurate to fulfil its role as a supportive instrument for orthopaedic surgeons during shoulder replacement surgery.

The use of the ROM simulator as a method to categorically analyse impingement and joint articulation of proximal humerus fractures (PHFs) is described in chapter 5. The morphology of the fractured shoulders varies greatly. Classification systems attempt to formalise these differences and relate them to clinical results. However, the repeatability of these classification systems has been shown to be poor, giving rise to the question whether a more objective measure entails improved predictability of outcome.

We demonstrate that it is possible to reproducibly evaluate the bone-determined ROM of a fractured shoulder joint and relate the results to morphological properties. It follows from this work that intra-articular fractures generally have a worse prognosis with regards to bone-determined ROM when compared to fractures with an intact articular surface. The bone-determined ROM of fractures with a displaced tuberculum major and minor is generally larger than that of intra-articular fractures, but often still limited in abduction by the coracoacromial arch. Finally, our results indicate that a low head inclination angle leads to a high probability of sub-acromial and gleno-humeral impingement.

We present a new analysis system that allows users to investigate multi-joint ki-
nematics (chapter 6). Kinematic analysis is the analysis of motions without regarding forces or inertial effects, with the purpose of understanding joint behaviour. Kinematic data of the upper extremity contains many interrelated degrees of freedom of several joints, complicating numerical analysis. The analysis process can be supported by visualisation techniques, thereby improving the effectiveness of kinematic experiments.

In our case, the kinematic data is acquired using motion registration systems. The data is used to evaluate clinical results. The challenge inherent in the data is that the upper extremity is comprised of five cooperating joints (excluding the hand) with a total of fifteen degrees of freedom. The ROM may be affected by subtle deficiencies of individual joints that are difficult to pinpoint. To highlight the subtle interplay between the joints our approach combines interactive filtering and multiple visualisation techniques.

Our system integrates simultaneous acquisition and visual analysis of kinematic data and forms an effective approach specifically tailored for the investigation and comparison of large collections of kinematic data. To facilitate complex queries, we have designed a visual query interface with visualisation and interaction elements that are based on the domain-specific anatomical representation of the data. An evaluation experiment is described where the technique was successfully used to view the kinematics of the left and right arm of a patient with a healed proximal humerus fracture, i.e. a healed shoulder fracture.

Finally, clinical case studies where the ROM simulation system was used to support treatment and diagnostic decision-making are presented in chapter 7:

1. The first case report concerns a patient with a PHF. Through analysis of the fracture by means of the ROM simulation system it was possible to calculate the correction required to prevent impingement.

2. The second case report concerns the evaluation of the risk of dislocation of a total hip prosthesis. Using the ROM simulation system it is possible to detect malalignment of prostheses and impingement, a possible cause for luxation.

3. The third case report concerns a patient who was diagnosed with femoroacetabular impingement. Primary arthroscopic treatment did not have satisfactory results. The ROM simulation system showed that there was still bony impingement that limited ROM. This was successfully removed in a second arthroscopic procedure, as was proved with a post-operative CT scan and ROM simulation.

The ROM simulator contributes in the decision-making process involved in patients with potential impingement.