biplanar frames). Further improvements in terms of accuracy and number of clinical applications may be reached for this technique by the employment of different commercial biplane fluoroscopic systems, with more suitable specifications for kinematics studies.

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Evaluation of automated segmentation of hip joint in revision arthroplasty

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Abstract We present a case of a 72-year-old female patient with a history of degenerative hip joint disease for whom a custom-made prosthesis—an acetabulum cage—was designed. With the growing number of total hip arthroplasty (THA) operations and the rapid development of technology, biology, and tissue bioengineering, there is a market to develop new artificial hip joints. The quality of the custom made prosthesis depends on the quality of segmentation to delineate accurately patient's anatomy. The error of segmentation may propagate to the overall error of the final prosthesis. We evaluate an in-house segmentation method, that was used in the design of the custom made prosthesis, and a commercial segmentation method, using qualitative and quantitative approaches.

Keywords Computer-aided surgical planning · Medical imaging · Segmentation · Evaluation of segmentation

1. Introduction

Custom-made prosthesis for hip joint revision is a novel approach that employs computer-aided and manufacturing technology in challenging surgical orthopaedic cases. Such prosthesis devices are designed and manufactured with high precision to match the anatomical characteristics of a patient. We present geometric revision reconstruction of the hip joint of a female patient. Because of extensive bone resorption and strong bone obstruction, a custom-made prosthesis, both for the pelvis and the femur, has been used. The design and manufacturing processes have been facilitated by computer-aided design (CAD) system and computer-aided manufacturing (CAM) system, respectively. The outcome of this engineering process was a successful, unique, total hip arthroplasty (THA) surgical operation.

The quality the custom-made prosthesis design hinges on the quality of the segmentation method that is used to delineate accurately patient's anatomy. The error of segmentation that is often ignored in the imaging, visualization and modeling pipeline, may propagate to the overall error of the final prosthesis, and may cause surgical failure of the implanted device. Commercial segmentation methods may not always serve well specific applications, and we employed our in-house segmentation method to delineate bone structures in the hip joint region. In the growing area of patient-specific applications, dedicated algorithms could designed to serve best specific applications; and a systematic approach to evaluation of image segmentation algorithms is needed. To evaluate segmentation algorithms, we use two approaches: (a) qualitative comparison of the outcome of two methods: a commercial and the in-house algorithms; (b) quantitative evaluation of segmentation, using approach described in [1, 2], that takes under consideration three factors: precision (reliability), accuracy (agreement with truth, validity), and efficiency (viability). In our evaluation study, we focus only on evaluation of accuracy for which we generate surrogate of ground truth, from repeated manual delineations of anatomical structures by multiple experts. We show our results in the context of revision reconstruction of the hip joint of a female patient. The surgical outcome, among other factors, depends on the quality of segmentation of the relevant bone structures in the hip joint region.

2. Methods

2.1. Clinical case description

According to data published (December 2000) by the American Academy of Orthopedic Surgery [3] there are approximately 310,000 prostheses implanted annually in United States alone, including 160,000 operations that are total hip arthroplasty (THA). With the increasing number of patients with implants, the problem of implant loosening has also been increasing as a result of mechanical wearing of contacting implant elements. Consequently the need for realloplasty arises. We present a case of a 72-year-old female patient with a history of degenerative hip joint disease, of idiopathic character. The patient was admitted into a hospital and radiography showed asymmetrical position-

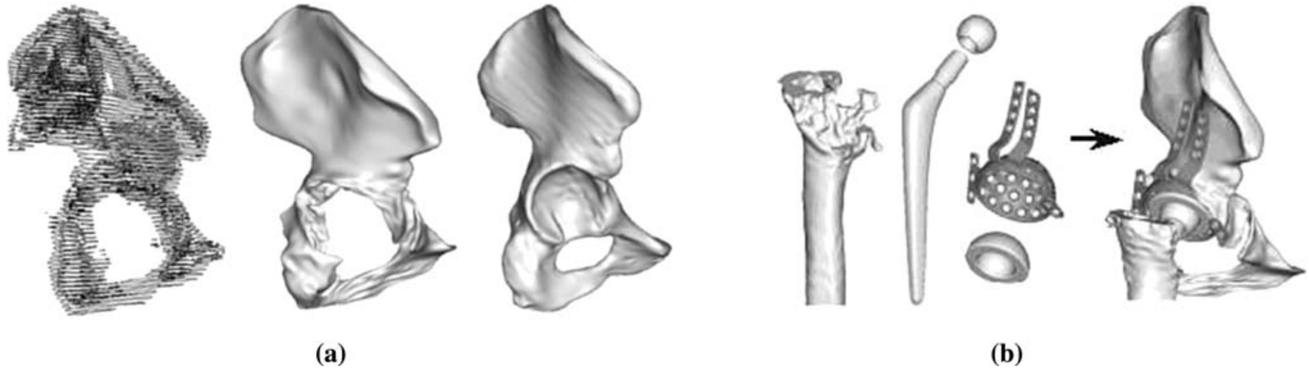

Fig. 1 Modelling and simulation. **a** Pelvic bone modelling from contours: comparing damaged pelvic bone to a normal one, **b** virtual simulation of reconstructed bone

ing of the prosthesis neck with respect to the centre of the acetabulum, displacement of the acetabulum prosthesis, and bone tissue resorption around the prostheses. During revision arthroplasty, a huge amount of degenerated bone tissue with polyethylene particles as well as vast bone resorption in the pelvis were observed. Reconstruction of the bone loss using the Slooff technique, which has been applied at the clinic, was not possible. Therefore, it was decided to leave the joint unarticulated. Due to the range and character of bone loss, it was decided to design and manufacture a custom-made prosthesis—an acetabulum cage.

2.2. Custom-made prosthesis design and manufacture

The process of designing and manufacturing the acetabulum and femur prostheses was undertaken utilizing computed tomography (CT), a system of tomographic image processing, computer-aided design and computer-aided manufacture (CAD/CAM) systems and a system of computer numerical control (CNC) machines [4]. The process comprises the following steps: (a) tomographical projection of the patient's hip joint; (b) conversion of the CT images; (c) modelling of the pelvis and femur; (d) virtual simulation of the reconstructed joint, (d) manufacture process design of prostheses on CNC machine

2.3. CT imaging, segmentation, bone modelling, and simulation

Our in-house, new segmentation algorithm of contour detection has been used [5], that generates accurately coordinates of the points defining the contours of bone tissue of the certain radiological density. The method provided us with correct delineation of anatomy of a patient. The algorithm, that can be generalized to 3D, in 2D, yields a closed marching curve that consists of line segments passing through the midpoints of the edges of the pixels. After completed segmentation, the curves defining the contours of the bones were used to generate surfaces of the structures; and to the design of hip joint custom-made prostheses in CAD systems. The process with the elements of the reconstructed joint with virtual simulations is shown in Fig. 1.

2.4. Evaluation of segmentation—generating surrogate of ground truth

We tested the in-house segmentation method for accuracy using delineation of bone structures in the hip joint region. Three experts performed the manual tracing of the bone structures, following a strict protocol, and repeating it three times. These nine delineations, represent intra- and inter-expert variability, and a surrogate of ground truth is derived as a fuzzy set, where each pixel (in a slice), or voxel (in a volume) has assigned value between 0 and 1 that corresponds to the relative number of experts that labeled it as "the target object". We call such a representation a fuzzy object.

2.5. Assessment of accuracy

To measure accuracy of a segmentation method against a "true" delineation, we compute three parameters: True positive volume fraction (TPVF), false positive volume fraction FPVF), and false negative volume fraction (FNVF) [1, 2]. Using notation from [1, 2], let $\mathscr{C}_{td}$ be the "true" delineation of a bone structure in the hip joint region. For any $\mathscr{C}_M$ representing a segmentation obtained by using a segmentation method M, the following measures are defined to characterize the accuracy of segmentation method M for delineation of stroke region.

$$\mathrm{FNVF}_M^d = \frac{\left|\mathscr{C}_{td} - \mathscr{C}_M\right|}{\mathscr{C}_{td}}, \quad \mathrm{FPVF}_M^d = \frac{\left|\mathscr{C}_M - \mathscr{C}_{td}\right|}{\left|\mathscr{C}_{td}\right|}, \quad \mathrm{TPVF}_M^d = \frac{\left|\mathscr{C}_M \cap \mathscr{C}_{td}\right|}{\left|\mathscr{C}_{td}\right|}. \tag{1}$$

3. Results

We performed qualitative comparison of two methods: our in-house algorithm and the commercial PCTOMO method [6]. In

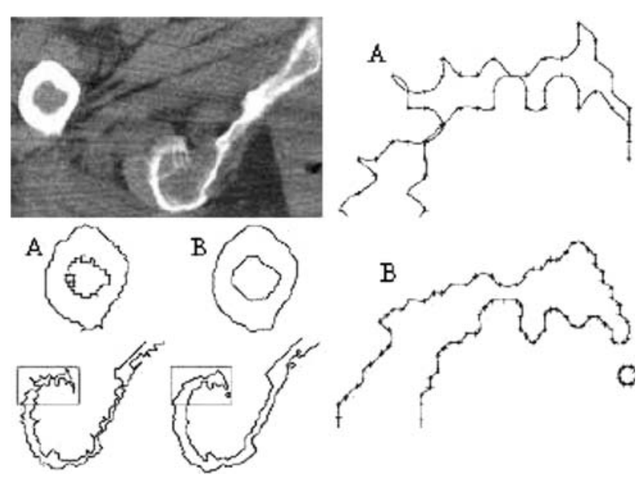

Fig. 2 Comparison of the contours determined by means of PCTOMO algorithm (**a**) and our in-house segmentation algorithm (**b**)

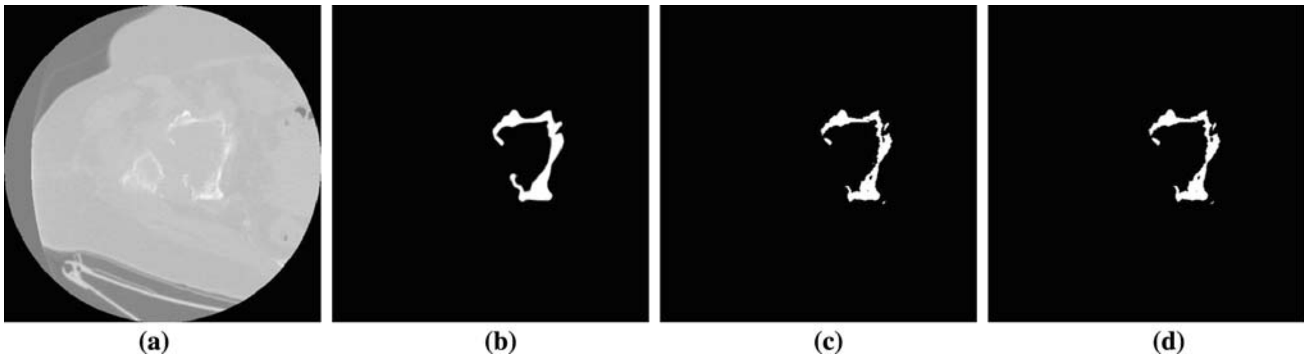

Fig. 3 Assessment of accuracy of segmentation of a structure in **a**; using surrogate ground truth, a fuzzy object in **b**, obtained from nine hand delineations; and segmentations obtained by the in-house method and PCTMO algorithm, in **c** and **d**, respectively

Table 1 Assessment of accuracy

Accuracy measurement	In-house segmentation method	PCTMO algorithm
Ground truth area	4,512.6	4,512.6
Segmentation area	3,702.0	3,734.0
Area difference	17.962%	17.253%
FNVF	0.192	0.198
TPVF	0.808	0.802
FPVF	0.019	0.01

Fig. 2., we show that the PCTOMO method (algorithm A) generates artifacts, in the form of self-intersecting contours, while the in-house algorithm is free of such artifacts. We compared the methods using quantitative evaluation of accuracy detection, as described in Eq. 1. We generated surrogate ground truth, using three expert delineating it three times, total of nine delineations; and compared the outcome of the two segmentation methods to the ground truth. We obtained close results, as illustrated on a representative slice in the volume, Fig. 3 and in Table 1. We anticipated this outcome, due to fact that both methods are based on region growing, and they missed similar sub-regions delineated in the ground truth: e.g. FNVF is of 0.192 and 0.198, respectively.

3.1. Evaluation of the reconstructed pelvis acetabulum

The initial results of the revision reconstruction of the hip joint of the female patient are very satisfactory because joint functioning had been restored and the patient's condition has been generally good. Also, during the procedure, the length of the lower limb was corrected. The patient's mobility and her gait parameters were investigated using a computer-aided VICON system and the results are good. Other assessments of the arthroplasty, such as implant durability, will be followed up on over time.

4. Conclusions

We presented evaluation of in-house segmentation method in the context of a successful revision reconstruction of the hip joint of the female patient. We demonstrated that dedicated segmentation algorithms are needed for specific, challenging applications, as this one, where imaging of degenerated bone structures were presented. Custom-made prosthesis for hip joint revision require such highly precise and accurate reconstruction of hip anatomy and commercial image processing methods are not always sufficiently sophisticated for that purpose.

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X-ray based system for measuring fracture gap movements in case of internal fixation

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Abstract In this article an X-ray-based measuring system is presented, which is able to measure relative motions in the fracture in vivo, supplied with internal fixation. Neither additional surgical procedures nor the development of new fixateur systems are needed. The system is based on a combination of high-resolution digital X-ray sensors, that are typically applied in dentistry and a standard C-arm X-ray source. The contribution describes the components of the system, an accuracy analysis and provides on outlook onto its clinical application.

Keywords Fixateur interne · X-ray · Fracture gap · Measurement

1. Introduction

In the orthopaedics therapeutic fractures are placed at the femur or the tibia in order to correct defective positions of the leg. For this purpose the bone is cut completely or partly, to do, for example, an axis conversion; similar as for the correction of osseous alignment of legs by a high tibia Osteotomy. After the fragments are successfully repositioned, the desired position is immobilized. This is carried out through external or internal fixateurs. Amongst others [1, 4, 10] showed, that for an optimal