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A scale-space curvature matching algorithm for the reconstruction of complex proximal humeral fractures

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ABSTRACT

The optimal surgical treatment of complex fractures of the proximal humerus is controversial. It is proven that best results are obtained if an anatomical reduction of the fragments is achieved and, therefore, computer-assisted methods have been proposed for the reconstruction of the fractures. However, complex fractures of the proximal humerus are commonly accompanied with a relevant displacement of the fragments and, therefore, algorithms relying on the initial position of the fragments might fail. The state-of-the-art algorithm for complex fractures of the proximal humerus requires the acquisition of a CT scan of the (healthy) contralateral anatomy as a reconstruction template to address the displacement of the fragments. Pose-invariant fracture line based reconstruction algorithms have been applied successful for reassembling broken vessels in archaeology. Nevertheless, the extraction of the fracture lines and the necessary computation of their curvature are susceptible to noise and make the application of previous approaches difficult or even impossible for bone fractures close to the joints, where the cortical layer is thin. We present a novel scale-space representation of the curvature, permitting to calculate the correct alignment between bone fragments solely based on corresponding regions of the fracture lines. The fractures of the proximal humerus are automatically reconstructed based on iterative pairwise reduction of the fragments. The validation of the presented method was performed on twelve clinical cases, surgically treated after complex proximal humeral fracture, and by cadaver experiments. The accuracy of our approach was compared to the state-of-the-art algorithm for complex fractures of the proximal humerus. All reconstructions of the clinical cases resulted in an accurate approximation of the pre-traumatic anatomy. The accuracy of the reconstructed cadaver cases outperformed the current state-of-the-art algorithm.

1. Introduction

The treatment of comminuted fractures of the proximal humerus is challenging and the optimal procedure remains controversial (Cvetanovich et al., 2016; Gerber et al., 2004). Open reduction and internal fixation using conventional or locking plates is the mainstay of therapy for the young and active patient (Gerber et al., 2004; Grubhofer et al., 2016), while best results are obtained if anatomical or near anatomical reduction can be achieved (Gerber et al., 2004). Anatomical reduction is a pre-requisite for a joint-preserving surgical treatment of a fractured proximal humerus. If anatomical reduction cannot be obtained, joint replacement has to be considered (Gerber et al., 1998). The options for replacement surgery of the shoulder joint include hemiarthroplasty, anatomic total shoulder arthroplasty and reverse total shoulder arthroplasty (RTSA) (Cuff and Pupello, 2013; Cvetanovich et al., 2016; Fucentese et al., 2014; Grubhofer et al., 2016) with a current trend from hemiarthroplasty towards RTSA for complex humeral fractures in the elderly (Cvetanovich et al., 2016; Grubhofer et al., 2016). The main reason of this current trend is that, despite promising initial reports of the hemiarthroplasty (Neer, 1970), less satisfactory or even disappointing results have been reported (Shukla et al., 2016). Current literature suggests that RTSA might result in better clinical outcomes than hemiarthroplasty, due to the decreased reliance on tuberosity healing of the RTSA (Shukla et al., 2016). Nevertheless, the most important consensus across all surgical treatment options is, that the functional outcome is better with anatomical fixation of the tuberosities (Anakwenze et al., 2014; Boileau et al., 2002; Fucentese et al., 2014; Gallinet et al., 2009; Gerber et al., 2004; Grubhofer et al., 2016; Huffman et al., 2008). Therefore, it seems clearly justified

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that major effort should be made to achieve an anatomical reduction of the tuberosities.

The benefits of computer-assisted preoperative simulation and intraoperative navigation is well accepted in joint replacement surgery (Iannotti et al., 2014; Levy et al., 2014; Nguyen et al., 2009) and for corrective osteotomies after malunited fractures of the humerus (Murase et al., 2008; Vlachopoulos et al., 2016b). Computer-assisted approaches are promising, especially, since it is difficult or even impossible to preoperatively plan the orthopaedic procedure using only radiographs or computed tomography (CT) analysis (Vlachopoulos et al., 2016a). In presence of a complex fracture of the proximal humerus, the ultimate goal of these approaches should be the restoration of the normal humeral anatomy. However, the fundamental pre-requisite to apply computer-assisted navigation in the surgery to fractures of the proximal humerus is the preoperative reconstruction of the fractures (Cui et al., 2007; Fürnstahl et al., 2012; McBride and Kimia, 2003; Papaioannou and Theoharis, 2003; Üçoluk and Toroslu, 1999). Hitherto, one method (Fürnstahl et al., 2012) has been published and validated for the computer-assisted reconstruction of complex proximal humerus fractures (Jimenez-Delgado et al., 2016). Fürnstahl et al. (2012) demonstrated that their algorithm allows accurate reconstruction of the pre-traumatic anatomy. However, the main drawback of the method of Fürnstahl et al. (2012) is the dependency on the healthy contralateral bone model as a reconstruction template. A further computer-assisted method for the treatment of complex proximal humeral fractures via hemiarthroplasty was developed and validated by cadaver experiments (Bicknell et al., 2007). The alignment of the shoulder protheses and the tuberosity fragment was assessed by manual measurements of characteristic landmarks. Here, also the contralateral anatomy was proposed as a reconstruction template for the use in a clinical setting. However, existing bilateral differences in the humeral anatomy (DeLude et al., 2007; Vlachopoulos et al., 2016a) or the presence of a pathological altered contralateral anatomy (e.g., after a proximal humeral fracture or a joint replacement surgery) might limit the clinical application of both methods.

The task to be performed is similar to the assembly of a jigsaw puzzle as illustrated in Fig. 1, also introducing the terminology used throughout this paper. Pose-invariant reconstruction algorithms have been successfully developed in archaeology for the reassembling task of broken vessels and relicts (McBride and Kimia, 2003; Papaioannou and Theoharis, 2003; Üçoluk and Toroslu, 1999). The geometric reconstruction was performed by matching individual fracture surfaces using 3D curvature matching methods. The presented method builds on this idea from the approaches in archaeology. However, as the data acquisition scans in clinical practice is based on CT, the noise is greater that in archaeology, where laser scanning is used. Clinical data are characterized by a limited resolution (in-plane and axial resolution of 0.4 mm or worse) (Lecouvet et al., 2008), resulting in partial volume effects and diffuse fracture lines, in contrast to laser-scanned data with an isotropic resolution of 0.05 mm or less. Furthermore, bone fracture surfaces tend to be highly irregular (Thomas et al., 2011). Therefore, the adoption of the archaeological approaches (McBride and Kimia, 2003; Papaioannou and Theoharis, 2003; Üçoluk and Toroslu, 1999) for clinical application, i.e., bone fracture reconstruction, is not straightforward (Thomas et al., 2011).

In this paper, we present a novel method for the fully automated reconstruction of proximal humeral fractures, requiring only the information of the fracture surfaces. The idea is to use a scale-space representation of the curvature of the corresponding fracture lines, which permits determining the correct alignment between fragments. The key novelties about the proposed method are:

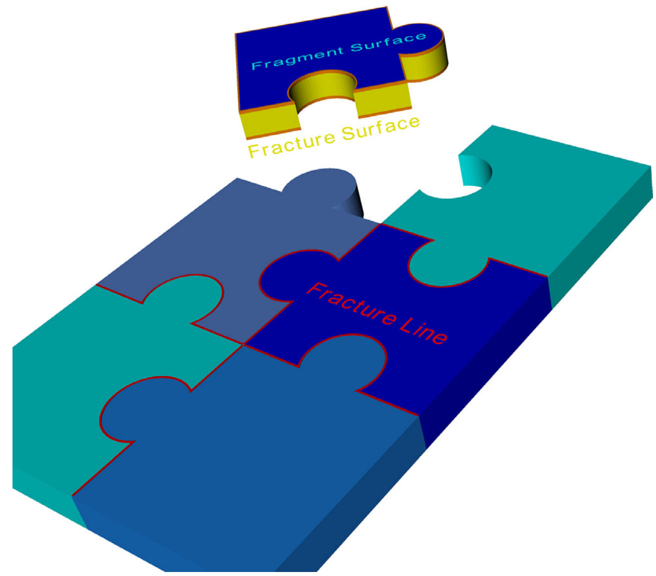

Fig. 1. Terminology for the present paper illustrated on a jigsaw puzzle. The fracture surfaces (yellow surface) represent the break through the cortex of the proximal humeral fragments and are simplified by fracture lines (red lines). The fragment surface (blue surface) corresponds to the unfractured outer cortical layer of the fragment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- B-spline based fracture line representation with a tailored weighting schema for proximal humerus fractures. In contrast to previous work that investigated the reassembling of two-dimensional planar fragments (McBride and Kimia, 2003) or curvature matching for binary two-dimensional images (Cui et al., 2007) our method was investigated on 3D fracture line representation of bone fractures.
- Curvature Scale-Space: Our scale-space representation incorporates the local shape of a curvature (i.e., concave or convex), in contrast to previous work (Cui et al., 2007; McBride and Kimia, 2003; Papaioannou and Theoharis, 2003; Üçoluk and Toroslu, 1999), permitting to reduce the number of incorrect matches in scale-space and to increase the robustness of the algorithm.
- Curvature Matching Algorithm: The developed similarity criteria detect correspondences based on the shape of curvature in scale space and the introduced normalized measure of reduction replaces the calculation of the torsion as a signature of a curvature – as proposed by Papaioannou and Theoharis (2003) and Üçoluk and Toroslu (1999), being robust against difference in magnitude (diffuse fracture lines, noise).
- A graph-based algorithm for robust merging of reduced bone fragments allowing automatic iterative fracture reconstruction.
- A reduction algorithm that determines the best solution based on all performed reconstructions and a warning mechanism, i.e., if only a partial fracture reconstruction is performed.

The proposed method was evaluated clinically on a consecutive series of patients treated with proximal humerus fractures and on four artificially created fractures on cadaveric humeri. Best to our knowledge, it is the largest published set of computer-reconstructed fractures of the proximal humerus. In addition, we compared our reconstruction results with the current state-of-the-art algorithm (Fürnstahl et al., 2012; Jimenez-Delgado et al., 2016).

In the following, we will give a brief overview of computer-assisted techniques for the simulation of fracture reduction. In Section 2 an overview is presented and the details of our approach are described. The clinical evaluation and the results of cadaver experiments are presented in Section 3. We discuss the method in