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Identification of fracture zones and its application in automatic bone fracture reduction

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ABSTRACT

Background and objective: The preoperative planning of bone fractures using information from CT scans increases the probability of obtaining satisfactory results, since specialists are provided with additional information before surgery. The reduction of complex bone fractures requires solving a 3D puzzle in order to place each fragment into its correct position. Computer-assisted solutions may aid in this process by identifying the number of fragments and their location, by calculating the fracture zones or even by computing the correct position of each fragment. The main goal of this paper is the development of an automatic method to calculate contact zones between fragments and thus to ease the computation of bone fracture reduction.

Methods: In this paper, an automatic method to calculate the contact zone between two bone fragments is presented. In a previous step, bone fragments are segmented and labelled from CT images and a point cloud is generated for each bone fragment. The calculated contact zones enable the automatic reduction of complex fractures. To that end, an automatic method to match bone fragments in complex fractures is also presented.

Results: The proposed method has been successfully applied in the calculation of the contact zone of 4 different bones from the ankle area. The calculated fracture zones enabled the reduction of all the tested cases using the presented matching algorithm. The performed tests show that the reduction of these fractures using the proposed methods leaded to a small overlapping between fragments.

Conclusions: The presented method makes the application of puzzle-solving strategies easier, since it does not obtain the entire fracture zone but the contact area between each pair of fragments. Therefore, it is not necessary to find correspondences between fracture zones and fragments may be aligned two by two. The developed algorithms have been successfully applied in different fracture cases in the ankle area. The small overlapping error obtained in the performed tests demonstrates the absence of visual overlapping in the figures.

1. Introduction

The development of computer-assisted techniques increases the information available to specialists before surgery. This information allows reducing surgery time and potential misinterpretations, with the consequent benefits to treatment and recovery time [1]. The reduction of a bone fracture requires properly identifying all the bone fragments, placing them to their original position and stabilizing the fracture. Computer-assisted techniques facilitate the process by enabling interaction with virtual models of fragments, by assisting in the planning of the surgery, by detecting the lack of tissue or by analyzing different configuration of fixation devices. The computer-assisted preoperative planning of a fracture reduction may be divided into three steps: obtaining 3D models representing bone fragments, calculating the reduction of the fracture, and analyzing the obtained results [2].

The reduction of complex bone fractures requires solving a 3D puzzle in order to place each fragment into its proper position. In comminuted fractures, bone fragments usually have a many-to-many relationship, that is, a fragment may share its fracture zone with more than one fragment. For this reason, additional processing is necessary to determine which part of the fracture zone is shared with each fragment. Depending on the complexity of the

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fracture, the surgery could last several hours. The previous identification of the bone fragments, their matching, and their correct positioning could help specialists to plan the surgery and thus to reduce the intervention time [1].

The main contribution of this paper is an automatic algorithm to calculate the contact zone between two fragments. The contact zone may be defined as the area of the fracture zone that is shared between two fragments. Contrary to what happens with complete fracture zones, the calculated contact zones ease the use of puzzle-solving methods to compute the fracture reduction, because the correspondence between fracture zones is also implicitly calculated. The calculation of the contact zone between every pair of fragments is useful for the pre-operative planning of a bone fracture reduction. On the one hand, the fracture reduction may be computed by matching and registering contact zones. On the other hand, contact zones provide additional information to better understand the fracture. The process of calculating contact zones can be summarized as follows. Firstly, bone tissue is segmented from a CT stack and each bone fragment is identified. In order to segment and label bone fragments from CT images, the approach proposed in [3] is used. The results of the segmentation are processed to extract a point cloud for each fragment. Since the developed algorithm only requires the topological information of the contours, it is not necessary to generate 3D meshes representing bone fragments. Then the contact zone between fragments is calculated using the method presented in this paper. The calculated contact zones can be matched and registered in order to reduce the fracture. For that purpose, a method to calculate the reduction of complex bone fractures using the obtained contact zones is also presented. The proposed procedure obtains good results in the case of moderate fracture displacement. If the fragments are too displaced from their original position, a previous coarse alignment of the fragments may be required. With that goal, the contralateral bone can be used as described in the literature [4,5]. Otherwise, interactive methods can be utilized especially when the contralateral bone is not available [6,7]. The proposed method has been successfully applied in the reduction of different bone fractures.

This paper is structured as follows. Section 2 reviews the currently proposed approaches to calculate the fracture zone and to reduce bone fractures. Section 3 describes the proposed methods for identifying contact zones and matching and aligning multiple bone fragments. After that, Section 4 tests the suitability of the proposed algorithms in the reduction of different bone fractures. The obtained results are discussed in Section 5, extracting the main strengths and weaknesses of our approach. Finally, the paper is concluded in Section 6.

2. Background

In the literature, different approaches have been proposed to compute the reduction of bone fractures. Some works propose to reduce the fracture by calculating, matching and registering the fracture zones. Alternatively, other authors propose interactive tools, or intend to reduce the fracture by registering the bone fragments to a healthy template. In this section, the most relevant works are analyzed and classified. This classification helps to extract the main drawbacks of currently proposed methods.

2.1. Fracture zone calculation methods applied to virtual fracture reduction

Puzzle-solving methods require the calculation of the fracture zone of all the fragments involved in the fracture. Some different methods have been proposed to calculate the fracture zone after the segmentation of bone fragments. Then the fracture can be virtually reduced by matching and aligning the calculated fracture zones. Winkelbach et al. [8] take advantage of the specific shape of cylindrical bones. In order to identify vertices of the fractured area, they check the normal orientation of each vertex and compare it with the bone axis. This method does not work when fracture lines are almost parallel to the bone axis. Bone fragments are matched and registered by applying a modified Iterative Closest Point (ICP) algorithm to the fracture areas.

Statistical-based approaches have been proposed to identify fractured zones. Willis et al. [9] use a mixture model consisting of two Gaussian probability distributions to perform a binary classification that allows separating intact and fractured zones of each bone fragment. After classifying all points, the fractured surface is the largest continuous region of fractured surface points. Then the user has to interactively select fracture surface patches in pairs that coarsely correspond. Finally, bone fragments are automatically aligned using a modified ICP algorithm. Zhou et al. [10] present an extension of the previous method that improves fragment alignment in highly fragmented bone fractures. In order to separate fractured and intact surfaces, they use a two-class Bayesian classifier based on the intensity values previously mapped on the surface vertices. They upgrade the interactive method introduced in [9] by providing a user-directed search in order to match the fragments. To perform the final alignment of the fracture surfaces, authors also describe a new algorithm to improve the registration proposed by Willis et al. [9].

Other authors have proposed interactive methods to identify fracture surfaces in craniofacial fractures [11,12]. In these works, fracture contours are extracted interactively from segmented bone fragments. With that aim, specialists have to select points belonging to the fractured area and then a contour tracing algorithm generates the rest of the points. Once the fracture contours are calculated, the 3D surface is generated by collating the contours extracted from each slice. Chowdhury et al. [11] propose to match fracture surfaces using a Maximum Weight Graph Matching (MWGM) algorithm. To align the fracture surfaces, authors propose a modification of the ICP algorithm. A variation of this approach is presented in [12]. In order to match the fractured areas, they formulate a matrix score based on the appearance of mandibular fragments in the CT image sequence. Then they propose the Maximum Cardinality Minimum Weight (MCMW) algorithm for establishing the correspondence between each pair of fracture surfaces while registering them using the ICP algorithm.

Curvature analysis has also been used to identify fractured surfaces. Okada et al. [4] present a curvature-based procedure to obtain fracture lines in each slice. For that purpose, they generate a 3D curvature image from the CT stack. Then interactive line-tracking software allows extracting the fracture lines from the generated 3D curvature image. In order to reduce proximal femur fractures, authors propose to approximate bone fragments to their correct position using the contralateral bone as template and then fine-tune the result by registering the calculated fracture lines. That registration is performed using the ICP algorithm. Fürnstahl et al. [5] use a normal-based filter to identify points candidate to belong to the fracture surface. Then connected component analysis is applied in order to remove outliers. User interaction may be required to remove incorrect parts not belonging to the fracture surface. Then authors use the contralateral bone to perform a coarse initial alignment of the bone fragments. Finally, fracture lines are registered using both a pairwise registration and a multi-piece alignment. Kronman and Joskowicz [13] identify fracture surfaces using intensity and curvature filters. Then outliers are removed from the estimated contact surface with a connectivity test. The calculated fracture surfaces enable the reduction of simple fractures by applying ICP registration to the fracture surfaces. Buschbaum et al. [14] identify fracture lines using surface curvatures. Then the target position is calculated by matching fracture