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3D Assessment of Osteosynthesis based on **2D** Radiographs

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Abstract:

We present a novel method to derive the surface distance of an osteosynthesis plate w.r.t. the patient-specific surface of the distal femur based on postoperative 2D radiographs. In a first step, the implant geometry is used as a calibration object to relate the implant and the individual X-ray images spatially in a virtual X-ray setup. Second, the patient-specific femoral shape and pose are reconstructed by fitting a deformable statistical shape and intensity model (SSIM) to the X-rays. The relative positioning between femur and implant is then assessed in terms of the displacement between the reconstructed 3D shape of the femur and the plate. We believe that the approach presented in this paper constitutes a meaningful tool to elucidate the effect of implant positioning on fracture healing and, ultimately, to derive load recommendations after surgery.

Key words: 3d-reconstruction from 2d X-rays, statistical shape and intensity models, osteosynthesis follow-up

1 Introduction

The goal of this study is to derive the distance between an osteosynthesis plate and the patient-specific surface of the distal femur based on 2D radiographs. The offset between plate and bone directly influences the stability and stiffness of the osteosynthesis construct [1, 2, 3]. Its stiffness alongside muscle and joint forces in turn determines the amount and type of relative movements of bone fragments, and interfragmentary movement is crucial for the process of fracture healing. We therefore aim at studying the relationship between plate-to-bone distance and bone healing retrospectively using clinical data. Recommendations for load bearing and physiotherapy may, for example, be adapted based on precise knowledge about the plate position (location and orientation, clearance and inclination). If the distance between plate and bone differs significantly from an ideal offset in a larger cohort, navigation should be introduced into trauma surgery [4, 5]. The relative positioning between implant and femur is, however, infrequently assessed, because it typically requires Computed Tomography (CT) scans to derive the patient-specific femoral shape. CTs impose a relatively high radiation dose on the patient, come at increased cost, and are difficult to process due to artifacts near metal components of the implant in the images. Instead, 2D-X-ray images in orthogonal planes are used in clinical routine to visually assess the alignment of bone fragments.

In recent years, computer-aided methods have been proposed to reconstruct the patient-specific 3D shape of an anatomy of interest from one or few 2D radiographs [6, 7, 8, 9]. At least two X-ray images from different angles (e.g. coronal and sagittal view) are required in order to derive the correct scale of the anatomy. In addition, the position of the individual X-ray sources and detector planes must be linked in a global coordinate system, assuming that the 3D position and pose of the anatomy of interest is not altered in between screenings. This can either be achieved by simultaneous screening in a bi-planar X-ray setup [7, 9] or by projecting a calibration phantom of known size together with the anatomy in consecutively generated X-rays [6]. The global X-ray setup is restored using point correspondences on the projected calibration object while keeping the relative positioning between phantom and anatomy fixed.

We present a method to reconstruct the 3D shape, scale and pose of the femur and the fracture implant position and orientation from 2D radiographs that are taken routinely for follow-up of osteosynthesis. Unlike previous reconstruction approaches, the method proposed in this work does not rely on simultaneous bi-planar imaging or custom designed calibration objects, but instead utilizes the known shape of the implant to derive the scale of the femur. A-priori statistical knowledge about the shape and bone-interior density distribution is applied to extrapolate the bone over fracture regions and in case the implant overlaps with the femur in the reference images. The relative positioning between bone and implant is assessed in terms of surface distance between the reconstructed femur and the reconstructed plate.

2 Materials and Methods

The method takes as an input a computer-aided design (CAD) model of the fracture implant, two X-ray images (e.g. in coronal and sagittal view), their corresponding pixel size and the distance between the X-ray source and scanner. CAD-models for the individual implant type can for example be created manually or segmented from CT-scans of the respective implant. The pixel size and the source-detector distance are typically standardized and recorded in the DICOM-header of digital scans. If not available, the source-detector distance can be tape-measured at the X-ray device for a given field-of-view.

The patient-specific shape and pose of the femur and the pose of the implant are estimated in three steps. First, the X-ray images are preprocessed in order to extract the outline of the implant/femur and to mask surrounding structures that are not reconstructed. In a second step, the known implant geometry is registered to each radiograph separately in 3D space. Based on the transformation of the implant in individual X-ray setups, a global setup is computed that relates the images spatially in a single coordinate system. The third step then consists of the computer-aided 3D-reconstruction of the patient-specific femoral shape in the global X-ray setup.

Preprocessing

In the preprocessing stage, one reconstruction mask and two segmentations are derived per X-ray image. The mask labels pixels that overlap with the implant, show the fracture gap, surrounding tissue or X-ray artifacts. The segmented X-ray images depict only those structures that are within the outline of the femur or implant (implant-only/femur-only). The rationale behind masking and segmenting the images is to enhance the robustness of the reconstruction. Information is removed that is not contained explicitly in the 3D models applied in later stages. Although we currently preprocess the radiographs semi-automatically, we believe that in future these steps can be performed fully automatically using available image-processing techniques.

X-ray setup and implant pose

Since the source-to-detector distance and the pixel sizes of the X-ray images are known, two virtual X-ray setups can be derived by placing the X-ray sources arbitrarily in 3D space and assigning a virtual detector plane at the respective distance. The goal is to relate the two individual setups in a global coordinate system, such that the implant position is fixed and the implant viewed from two virtual cameras at the correct angle. For this purpose, the CAD model of the implant is converted into a volumetric model by assigning a constant X-ray absorption property to all cells (e.g. to mimic the X-ray absorption of titanium). It is then registered rigidly to each segmented X-ray image (implant-only) using an intensity-based registration method [8]. The process returns a transformation matrix of the implant in the respective X-ray setup. The global X-ray setup and implant pose are then derived based on the relative transformation of the implant between the individual setups (Fig. 1).



Fig. 1: Two individual X-ray setups (left and center) are registered into a global setup (right) based on the transformation T_0 and T_1 of the implant (simplified by a bar). The camera translation and orientation in a setup is given by c, the dot illustrates the position of the virtual X-ray source (e.g. the camera origin)

3D-reconstruction of the femur

The reconstruction is performed by means of an iterative process, in which a deformable shape and intensity model is fit to a pair of X-ray images until the model's 2D projection onto the X-ray planes matches the anatomy depicted in the 2D references. We make use of statistical shape and intensity models (SSIMs) of the femur that were generated a-priori from clinical CT-datasets using the method described in [8]. In each iteration, the SSIM is transformed and deformed. In accordance with the global X-ray setup, virtual 2D X-ray images are generated from the deformed SSIM instances, utilizing the bone density information from the statistical model.

A normalized mutual information similarity measure is then applied to quantify the similarity between pairs of virtual X-ray images and the segmented reference image pair (femur-only). Pixels are excluded from the similarity evaluation if they are labeled by the mask defined in the preprocessing stage. The SSIM thus extrapolates over regions in the reference images that show the implant or the bone fracture. Once a suitable match is established, the process returns a tetrahedral grid which represents the femoral 3D shape as depicted in the 2D radiographs.

Experiments

We performed a preliminary cadaver study based on four pairs of distal femoral bones and two individual femora. The surrounding tissue was removed, then a standard locking plate (9-hole 4.5/5.0 LISS DF, Depuy Synthes, Zuchwil, Switzerland) applied distally using seven locking screws (all distal options). A 10mm fracture gap model of the distal femoral shaft was imposed and the plate was fixated using three screws proximally. Based on CT-scans of the fixated bone, Digitally Reconstructed Radiographs (DRRs) were generated in coronal and medio-lateral view in order to mimic clinical X-ray images taken at a source-detector distance of one meter. The global X-ray setup was then derived as proposed using a CAD model of the implant. Afterwards, the 3D shape of the femur was reconstructed in the global X-ray setup using an SSIM from 18 CT training sets. The cadaveric bones were not contained in the training base of the statistical model.

A surface model of the intact bone was registered to the CT data, which then acted as ground truth for evaluation. To assess the distance between implant and bone at consistent point locations, an ideal plate geometry was registered rigidly to each reconstructed plate as well as the plates depicted in the CTs. The surface distance between the reconstructed bone surface (from SSIM) and the reconstructed plate as well as surface distance between the intact bone and the ground-truth plate were then compared to each other. In addition, the surface error between intact femur and reconstructed femur was assessed after rigid registration of the reconstructed femoral shape to the ground-truth.

3 **Results**

Figure 2 exemplary shows the osteosynthesis from CT compared to the reconstructed femur and implant for case 1-L. The mean error in plate-to-bone surface distance over the whole plate is given for each case individually in Table 1. Root-mean-square-error (RMSE) remains ≤ 2.6 mm for all tested cases, with an absolute mean deviation of ≤ 1.5 mm. The span in deviation of individual nodes is highest for case 6-R, ranging from -5.4mm to +6.0mm. Unlike the ground-truth from CT, the 3D-reconstructions of cases 5-L and 6-R show the implant plate penetrating the reconstructed femoral surfaces, thus representing anatomically unrealistic osteosynthesis constructs. Excluding theses outliers yields an overall RMSE of ≤ 1.7 mm and a mean error of ≤ 1.1 mm, with a maximum error of ≤ 5.0 mm. Further restriction of nodes to the mid-section of the plate results in RMSE ≤ 1.4 mm, with the span ranging from -2.4mm to 2.9mm.

Compared to the intact bone surface, the femoral surface is reconstructed with a mean error of \leq 1.5mm and maximum error \leq 5.4mm, excluding cases 5-L and 6-R. The two outliers exhibit a mean error of 1.8mm and 2.0mm respectively.

Case	1-L/R	2-L/R	3-L/R	4-L	5-L/R	6-R
RMSE	1.5 / 1.2	1.3 / 1.5	1.7 / 1.2	1.36	1.9 / 1.7	2.6
[mm]						
Mean	0.1 / 0.8	0.3 / 0.8	0.6 / 0.2	0.2	1.5 / 1.1	1.5
[mm]						
Max	4.7 / 2.4	4.0 / 4.3	5.1 / 4.1	4.9	3.7 / 5.2	6.0
[mm]						

Table 1: Error in plate-to-bone distance in mm between reconstructed plate/femur and ground-truth per case. Listed are the root-mean-square-error (RMSE) and mean error over all plate nodes (proximal, distal and mid-section of the osteo-synthesis), as well as the maximum error. Cases 5-L and 6-R were treated as outliers, since the implant plate penetrates the femur (values highlighted in grey).



Fig. 2: Ground truth shape of the femur and implant from CT (left) of case 1-L and the 3D-reconstructed femoral shape and implant pose based on reference DRRs (right).

3 Discussion

A first evaluation based on DRRs shows that the surface offset between plate and femur is reconstructed with an RMSE of ≤ 1.7 mm and mean error of ≤ 1.1 mm. Previous work indicates a reduction in axial stiffness of the osteosynthesis construct by 24% when increasing the offset between plate and bone from 1mm to 3mm [3]. Further increasing the distance to 5mm significantly reduces the construct stability [1]. We therefore argue that a reconstruction accuracy of 1mm is sufficient to estimate the biomechanical behavior of the construct for practical use, such as deriving load recommendations after surgery.

For two outliers (5-L, 6-R), the implant penetrated the reconstructed femoral shape and the plate-to-bone RMSE as well as the femoral surface error are larger compared to non-intersecting cases. Overlaps between the implant plate and the femoral surface outside the fracture gap should be detected and avoided during reconstruction, since they can't occur in a realistic clinical setting. In future work, we will introduce additional priors that prevent plate-bone intersections and thus further constraint the reconstruction process to anatomically meaningful outcomes.

The RMSE reduces to 1.4mm in the midsection of the plate. This region is of particular interest for retrospective studies because the free plate working length (gap bridging plate length) in relation to the plate-to-bone distance in the midsection (close to the fracture) mainly determine the interfragmentary movement and therefore biomechanical behavior of the osteosynthesis [10, 11]. In the distal section of the implant, the mean and maximum error were slightly higher compared to the proximal or distal section. We partly attribute this to the relatively small (18 datasets) and homogeneous training base of the statistical model that only allows for a coarse approximation of the condyles.

The DRRs projected 3D-artifacts from CT due to the metal implant that are depicted as a "white mist" and "streaks". Although real X-ray images are also prone to metal artifacts, we believe that the DRRs induced an additional error when reconstructing the femoral shape, since artifact regions had to be masked that are normally preserved in clinical radiographs. This is especially true for the distal region of the femur, where the fixation screws cover larger regions of the bone in the images.

We consider the implant geometry to be an adequate calibration object, since the predefined X-ray source and detector positions to generate the DRRs and the reconstructed global X-ray setup only deviated slightly (e.g. within few millimeter in position and few degrees in orientation). It will be future work to assess, how deviations in the global setup influence the overall reconstruction result from clinical images.

5 Conclusion

We developed a reconstruction method to assess the 3D-positioning of fracture fixation implants w.r.t. the patientspecific femoral shape based on plain 2D radiographs. The method utilizes the known geometry of the implant as a calibration phantom and relates both images and the implant in a global X-ray setup. A-priori statistical knowledge about the 3D bone density is then used to derive the scale-correct femoral shape simultaneously from both reference images.

The reconstruction method reproduces the distance between osteosynthesis plate and patient-specific femoral shape with sub-millimeter mean accuracy for most of the tested cases. We therefore believe that the approach is feasible for studying the relationship between plate-to-bone distance and bone healing retrospectively based on post-operative 2D radiographs only. Unlike 3D Computed Tomography scans, 2D X-ray images are taken routinely for osteosynthesis follow-up. The proposed technique can thus be applied on clinically available data.

Our future goal is to further automate the preprocessing stage and provide means for a fully automated assessment of 3D implant positioning based on conventional 2D radiographs for retrospective studies and to predict the potential performance of the implant after surgery.

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