Towards Robust Measurement of Pelvic Parameters from AP Radiographs using Articulated 3D Models

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Purpose

Patient-specific parameters such as the orientation of the acetabulum or pelvic tilt are useful for custom planning for total hip arthroplasty (THA) and for evaluating the outcome of surgical interventions. The gold standard in obtaining pelvic parameters is from three-dimensional (3D) computed tomography (CT) imaging. However, this adds time and cost, exposes the patient to a substantial radiation dose, and does not allow for imaging under load (e.g. while the patient is standing). If pelvic parameters could be reliably derived from the standard anteroposterior (AP) radiograph, preoperative planning would be more widespread, and research analyses could be applied to retrospective data, after a postoperative issue is discovered.

The goal of this work is to enable robust measurement of two surgical parameters of interest: the tilt of the anterior pelvic plane (APP) and the orientation of the natural acetabulum. Recently, methods have been proposed to reconstruct the patient-specific 3D pelvic surface and orientation as well as component orientation from standard 2D postoperative X-ray images [1], however the orientation of the natural acetabulum is not recovered. We present a computer-aided reconstruction method to determine the APP and natural acetabular orientation from a single, preoperative X-ray. It can easily be extended to obtain other important preoperative and postoperative parameters solely based on a single AP radiograph.

Methods

The APP and acetabular orientation are derived in a two-stage process. First, the patient-specific anatomical shape and pose are approximated by fitting a deformable 3D model to the reference AP radiograph. In a second step, the landmarks are extracted from the reconstructed model and are then used to compute the pelvic parameters of interest.
Our reconstruction method utilizes novel articulated statistical shape and intensity models (ASSIMs) that express the variance in anatomical shape and bone density of the pelvis/proximal femur between individual patients and model the articulation of the hip joints. ASSIMs extend the shape and intensity model described previously [2] by a constrained rotation of the proximal femur along three axes. The center of rotation corresponds to the center of a sphere that is fit to the acetabulum, and is embedded in the statistical analysis of the model [3].

The reconstruction is performed by means of an iterative process, in which the ASSIM is fit to an X-ray image until the model’s 2D projection onto the X-ray plane matches the anatomy depicted in the 2D reference [2]. In each iteration, the ASSIM is deformed, transformed and articulated. Virtual 2D X-ray images are generated from the deformed ASSIM instances, utilizing the bone density information that is contained in the statistical model. A normalized gradient field similarity measure [4] is then applied to quantify the similarity between the virtual X-ray and the reference image. Once a suitable match is established, the process returns a tetrahedral grid which represents the pelvic and proximal femoral 3D shapes as depicted in the 2D reference.

The APP is defined on the reconstructed model using a total of four landmarks - at the anterior superior iliac spines and pubic tubercles (see Figure 1). It is used as a reference plane to compute inclination and version parameters of the acetabulum from another set of anatomical landmarks located around the acetabular rim. All landmarks are extracted automatically from the reconstructed grid, utilizing the correspondence between individual vertices of the model’s statistical mean shape and the reconstructed instance. In principle, other parameters of interest such as the femoral neck offset can be derived in a similar fashion by adding respective landmarks to the statistical analysis of the model.

We performed a preliminary evaluation on 11 preoperative AP X-rays and matching CT datasets, for the pelvis and femur of 11 different patients. The patient-specific 3D anatomies were first reconstructed from the 2D images and the APP tilting angle and inclination/version parameters obtained afterwards using the proposed method. These parameters were then compared to gold-standard values assessed independently from the individual patient’s CT data. In order to derive a ground truth for the APP in the standing position, the CTs were registered rigidly to the X-ray images using a mutual-information based similarity measure.

**Results**

Average acetabular orientation errors, in absolute values, between the 3D-reconstructed values and the CT gold standard for the right/left hips were 3.3°/3.3° in inclination and 2.7°/4.1° in version. The tilting angle was derived with an average error of 3.2°. Maximum errors were 10.3°/7.2° in inclination, 7.2°/8.6° in version and 7.3° in tilting angle of the APP.
Conclusion

We developed a novel, computer-aided reconstruction approach that considers statistical information about both the 3D bone density distribution and the articulation between the pelvis and proximal femur to extract pelvic parameters from 2D radiographs.

In most cases, the method produced acetabular inclination/version results close to the CT gold standard (e.g. with an error margin of 4°). For the outlier with an error above 10° in inclination, a non-rigid 3D-3D registration of the ASSIM to the respective CT dataset revealed that the current statistical model can not accurately represent the patient-specific acetabular region. We believe this is due to the small number of training sets (48) used for the statistical analysis. The overall accuracy might be enhanced further by expanding the training base of the ASSIM.

The tilting angle of the APP is reproduced with an error below 3°, except for three cases with an error of 5-7°. All outliers have in common that the respective AP radiographs do not show the iliac crest and the upper anterior superior iliac spline (see Figure 1). While the ASSIM is capable of extrapolating the missing regions, the lack of information in the reference X-ray image might induce errors during reconstruction and ground truth fit of the CT to the X-ray image. Our further goal is to identify features of outlier pelvises a priori so that the user can be notified when the X-ray or the patient-specific pelvic shape is not suitable for 2D/3D analysis, and incorrect results can be avoided.

We believe that the ASSIM-based method has great potential in deriving a variety of patient-specific surgical parameters of interest from a single X-ray image.

References

Figure 1: AP radiograph with reconstructed ilia, anterior pelvic plane and acetabular reference landmarks (red), and global acetabular orientation vector (blue).