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Atlas-based automatic measurements of the morphology of the tibiofemoral joint

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Abstract

Purpose—Anatomical metrics of the tibiofemoral joint support assessment of joint stability and surgical planning. We propose an automated, atlas-based algorithm to streamline the measurements in 3D images of the joint and reduce user-dependence of the metrics arising from manual identification of the anatomical landmarks.

Methods—The method is initialized with coarse registrations of a set of atlas images to the fixed input image. The initial registrations are then refined separately for the tibia and femur and the best matching atlas is selected. Finally, the anatomical landmarks of the best matching atlas are transformed onto the input image by deforming a surface model of the atlas to fit the shape of the tibial plateau in the input image (a mesh-to-volume registration). We apply the method to weight-bearing volumetric images of the knee obtained from 23 subjects using an extremity cone-beam CT system. Results of the automated algorithm were compared to an expert radiologist for measurements of Static Alignment (SA), Medial Tibial Slope (MTS) and Lateral Tibial Slope (LTS).

Results—Intra-reader variability as high as ~10% for LTS and 7% for MTS (ratio of standard deviation to the mean in repeated measurements) was found for expert radiologist, illustrating the potential benefits of an automated approach in improving the precision of the metrics. The proposed method achieved excellent registration of the atlas mesh to the input volumes. The resulting automated measurements yielded high correlations with expert radiologist, as indicated by correlation coefficients of 0.72 for MTS, 0.8 for LTS, and 0.89 for SA.

Conclusions—The automated method for measurement of anatomical metrics of the tibiofemoral joint achieves high correlation with expert radiologist without the need for time consuming and error prone manual selection of landmarks.

Keywords

atlas registration; cone-beam CT; extremities imaging; tibiofemoral joint

1. INTRODUCTION

A variety of anatomical measurements and classification systems are used in orthopedic radiology.¹ Their applications range from risk assessment to diagnosis, to treatment planning. In the tibiofemoral joint, the metrics of Tibial Slope (TS) were found to be associated with risk of knee ligament injury.² Examples of surgical applications include arthroplasty and ligament repair.^{1,3,4,5} Traditionally, the anatomical measurements were performed in 2D radiographs. Growing proliferation of advanced volumetric imaging (multi-detector CT, cone-beam CT, MRI) in orthopedic applications necessitates translation of the 2D metrics to 3D imaging. The obvious challenge is the increased complexity of volumetric data. In this work, we present an approach to automate 3D variants of anatomical measurements, using metrics of the tibiofemoral joint and leg alignment as an example application.

Typical workflow for obtaining the morphological metrics involves manual selection of anatomical landmarks in the radiographs, CT or MR images. Both in planar and in 3D imaging, the anatomical metrics are prone to imprecision due to difficulty in identifying the landmarks and the variability in the orientation of the extremity with respect to the projection plane or the principal viewing planes. While volumetric imaging provides a more complete (and less dependent on patient positioning) depiction of joints than radiography, the added complexity of navigating through 3D space in search for the landmarks may hamper the speed and precision of the measurements, especially for less experienced readers¹.

To overcome these challenges, we propose an automated methodology for computation of the metrics in volumetric images of joints. The method utilizes a set of atlas images, which were annotated with the landmarks according to expert reader consensus. Registration of atlas images to the input image is performed to transform the location of the landmarks to the input volume. In comparison to conventional shape and appearance models, our approach does not involve a training stage and does not require a segmentation of the input volume. In the proposed method, only the atlas images need to be segmented. A mesh-to-volume registration method is developed to deform the atlas to the articular surfaces in the input volume. The registration approach is more computationally efficient than non-rigid registration of the volumes. The proposed algorithm is evaluated in measurement of three metrics of the tibiofemoral joint: Static Alignment (SA), Medial Tibial Slope (MTS) and Lateral Tibial Slope (LTS).

Validation is performed in clinical data obtained using a dedicated cone-beam CT (CBCT) system for extremities imaging (Fig. 1(a)). The scanner features patient dose of 10 mGy (lower than conventional CT), high spatial resolution of ~300 microns, field of view of 20 cm³, and soft-tissue contrast approaching that of conventional CT.⁶ Furthermore, the system is designed to enable weight-bearing volumetric imaging of the lower extremity (distal femur, knee, tibia, foot and ankle) in natural stance. This capability is a significant advance over the current clinical practice, where weight-bearing imaging is typically performed using radiography. Functional changes in joint anatomy due to weight-bearing are of diagnostic importance, e.g. in osteoarthritis. The proposed automated tools for anatomical

measurements support the development of extremities CBCT as a comprehensive platform for quantitative assessment of joint health.

2. METHODS

2.1 Data acquisition and metrics of tibiofemoral joint anatomy

Weight-bearing extremities CBCT scans of the tibiofemoral joint of 23 healthy volunteers were obtained under IRB approval. The subjects were imaged in natural standing stance (Fig. 1(a)) using the standard acquisition protocol (90 kVp, 72 mAs/scan 0.274 mm detector pixels, 384x384x576 voxels reconstruction volume with 0.56 mm voxels). Patient motion was minimized by immobilization using deformable cushions.

To validate the proposed method, the metrics of joint anatomy were first measured by an experienced radiologist using an in-house developed viewing and analysis package (JMAT). The software was developed using ITK and is DICOM-compatible. It provides a graphical user interface build around multi-planar rendering of the volume. To compute a metric, the user is guided through selection of the anatomical landmarks. The selection process is supported by descriptive text and screenshots. Landmarks that are utilized by multiple metrics are re-used between those metrics. The metrics are then automatically computed and added to a report that can be exported and re-loaded into the software if needed. Currently, 13 metrics of the tibiofemoral joint are implemented; ongoing work includes expansion to metrics of foot and ankle.

The following anatomical measurements were considered in this work: SA (Fig. 1(b)) involves evaluation of the angle between the anatomical axes of tibia and femur in coronal plane.¹ The user selects pairs of lateral and medial landmarks on the cortex, one pair on the superior aspect and one pair on the inferior aspect of each bone. The midpoints between each pair of the cortical points are computed and connected to form the anatomical axis of femur and tibia defining the SA angle. Normal ranges for SA are $186.85^{\circ} \pm 1.4^{\circ}$.¹

The MTS and LTS represent the angle between the sagittal tibial axis and a line connecting the anterior-most and the posterior-most points in the midsagittal cross-section of the medial (or lateral) tibial plateau (Fig. 1(c) and 1 (d)).⁷ The tibial axis is determined analogously to SA but using cortical points defined in the sagittal plane. Normal range for MTS and LTS are -3° – 10° and 0° – 14° .⁷

2.2 Automated atlas-based measurement of anatomical metrics

The proposed approach involves three steps: an initial registration of a set of atlas segmentations to the fixed input image, a refinement of the initial transformation performed separately on each bone (tibia and femur), and a mesh deformation of the tibial surface of the best fitting atlas to match the fine anatomical variations in the input image. The atlas database consists of some number (1–20) of volumetric images from the set of volunteer CBCT data. Semi-automatically obtained segmentations of those images are also included. To provide surface models of femur and tibia, vertices belonging to each bone are appropriately labeled in the segmentation. Each atlas image also includes ten anatomical

landmarks for the metrics of interest (four for SA and six for MTS and CTS) selected by an expert radiologist using the JMAT software as described in Sec. 2.1 and Fig. 1.

The algorithm is illustrated in Fig. 2. First, a registration based on a similarity transform (translation, rotation, and scaling) is performed to jointly align the atlas segmentations of the tibia and femur to automatically segmented input image obtained by thresholding using Otsu's method⁸. Dice similarity coefficient, measuring the overlap of segmented areas, is employed for registration. This provides a coarse initial transformation that is subsequently refined for each of the bones separately.

In the refinement step, grayscale models of each bone, obtained by cropping the atlas volumes with the segmented surfaces of the two bones, are registered to the input image using similarity transform and normalized cross-correlation as an overlap metric. By treating each bone individually, we preserve the directional relation between the tibia and femur in the input image (needed for SA) without the need for a computational intensive non-rigid transformation. After the refinement step, we select the atlas image that achieved the best normalized cross-correlation similarity measure (among all atlas volumes in the initial set) for the final stage of the algorithm, illustrated in Fig. 3. Compared to e.g. mean squared difference, cross-correlation is advantageous as a measure of overlap because it admits linear changes in the grayscale values in the compared images.

Because the typical variations in the shape of the tibial and femoral shafts are captured by the similarity transformation, the first two steps of the algorithm are sufficient to translate the landmarks defining the tibial and femoral axes from the atlas to the input image. However, the interpatient variations in the shape of the articular surfaces are not completely captured by the similarity transformation and thus an additional deformable registration step is needed for MTS and LTS. We propose to deform a mesh model of the segmented tibial surface of the atlas to match the grayscale input image (mesh-to-volume registration). The input image is smoothed and the gradient magnitude is calculated to highlight the cortex of the tibia. The surface mesh model of the registered atlas segmentation is deformed by selecting search lines perpendicular to the surface at each surface vertex of the tibial mesh. The search lines include all voxels traversed by the Bresenham line starting from inside the mesh and ending outside. The deformation at each surface vertex is defined as a vector from the vertex to a point on the search line corresponding to the cortex of the tibia.

The computation of the metrics involves transformation of landmarks defined in the atlas to the input image using the transformation obtained from the bone registration and mesh deformation. The landmarks are then projected onto a common sagittal (or coronal) plane and SA, MTS, and LTS are computed from the transformed points.

The proposed methods were implemented using C++ and the elastix toolkit⁹ for registration.

3. RESULTS AND BREAKTHROUGH WORK

We compare the automatically obtained measurements to an expert radiologist using JMAT for semi-automated analysis. The intra-reader variability of the radiologist is illustrated in Table 1, showing results of manual evaluation of four images with six iterations each.

Variability is typically below 10%, but for some metrics (e.g. LTS) is exceeds 10% of the mean value in some cases. This indicates the potential value of an automated approach in minimizing the imprecision of the metrics that arises from difficulty in maintaining consistent selection of the anatomical landmarks

The tests of the proposed algorithm involved an atlas database consisting of four randomly selected images. The correlation between the automatic measurements and the expert radiologist are shown in Fig. 4 for MTS, LTS, and SA (atlas images are excluded from comparison). Pearson correlation coefficient of 0.72 for MTS, 0.8 for LTS and 0.89 for SA suggests a strong agreement between the algorithm and the expert reader for all three metrics.

Fig. 5 compares the transformed anatomical landmarks of the atlas to the landmarks selected by the reader for two subjects representing the extreme values of MTS found in the dataset. The MTS for the image on the left was measured at 6.74° by the radiologist and 7.98° by the algorithm. The MTS for the image on the right was 13.58° according to the reader and 13.93° according to the algorithm. The difference between the algorithm and the radiologist remains within the internal variability of the reader shown in Table 1. Moreover, the slopes found by the algorithm correctly reflect the primary difference in the shape of the two tibial plateaus.

4. CONCLUSION

We have introduced a novel method for automatic computation of anatomical metrics in orthopedics. The algorithm requires no manual steps other than the initial segmentations of the atlas volumes and identification of the landmarks in the atlases. A deformable mesh-to-volume registration was developed to provide a reliable transformation of the anatomical landmarks from the atlas to the input image in the presence of the strong interpatient anatomical variations in the tibial plateau. The proposed approach is less computationally demanding than the non-rigid volume-to-volume registration. The algorithm is fully deterministic and no training stage is required. To the best of our knowledge, no previous work has demonstrated automated measurement of the morphological metrics in the tibiofemoral joint using 3D tomographic imaging.

Initial application to a set of 23 extremity CBCT images of the tibiofemoral joint showed that the proposed methodology achieves good correlation with an expert radiologist. Furthermore, by virtue of its automatic and deterministic nature, the proposed algorithm is likely to improve the precision of the measurements compared to a human observer. The method is general and can be extended to other joints and 3D imaging modalities.

Ongoing studies include extension to the patello-femoral joint and application to a study of diagnostic utility of the anatomical metrics in identifying subjects at risk of load-bearing injury. This study utilizes the weight-bearing imaging capability of the extremity CBCT system to compare the morphology of the tibiofemoral joint with and without additional load. The proposed automated algorithm supports development of new clinical applications for quantitative assessment of the joints by streamlining the evaluation of the anatomical

metrics and providing a unified measurement framework that mitigates errors due to variability in patient orientation and user expertise.

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Figure 1.

(a) Dedicated extremities CBCT system and a screenshot of the JMAT package for semi-automated measurement of anatomical metrics. The scanner provides a unique capability for weight-bearing and load-bearing (standing with additional load) imaging for knee, foot, and ankle. The automated method developed in this work was applied to imaging data from the CBCT system and validated against semi-automated measurements obtained using JMAT. (b) Coronal slice of a CBCT image with manually identified tibial and femoral axes (red) and the angle of static alignment (α). (c) and (d) illustrate the measurements of MTS and LTS, respectively, using sagittal CBCT slices. The tibial axis (red) is projected onto the slice used to select the landmarks in the tibial plateau. User-selected landmarks are indicated with yellow crosses.

Figure 2.
General workflow of the automated measurement of anatomical metrics.

Figure 3.

Illustration of the final stage of the registration and landmark transformation algorithm. (Left to right, top to bottom): The best fitting atlas segmentation, selected in earlier stages of the automated workflow, is marked with a pink line, overlaid on a volume for which the metrics are being automatically calculated. Gradient magnitude image of the volume is computed. For each point on the tibial surface of the atlas, a search along the line defined by the normal vectors of the surface is performed to find the cortex of the tibia in the gradient magnitude image of the input volume. This yields deformation vectors that transform the atlas surface (marked using a blue line) onto the tibial surface of the input image (mesh-to-volume transformation). The thus obtained transformation is applied to the anatomical landmarks from in the atlas (yellow circles).

Figure 4. Correlation between manual and automatic measurement of the anatomical metrics for 19 extremity CBCT images of the tibiofemoral joint.

Figure 5.

Comparison of manual (yellow) and automatic (blue) identification of the landmarks of MTS. The two cases represent extreme values of MTS found in the dataset (very flat tibial plateau on the left and a very steep plateau on the right). While there is some difference in the exact position of the landmarks compared to human reader (likely within the intra-reader variability of human observers shown in Table 1), the algorithm correctly captures the variations in the slope of the tibia.

Table 1

Intra-reader variability for MTS, LTS and SA. The analysis involved four images with six iterations each, presented in random blind order.

	Subject 1	Subject 2	Subject 3	Subject 4
MTS [°]	8.79±0.40	11.25±0.76	8.54±0.58	12.27±1.31
LTS [°]	12.43±0.35	11.59±2.12	9.83±0.96	11.04±1.16
SA [°]	184.86±0.63	183.70±1.68	184.29±1.08	182.51±0.79