Construction of statistical shape models of the knee and their application in reconstruction of patient-specific 3D models from a single X-ray: a case study

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Introduction: Models of the three-dimensional (3D) shape of the knee joint and knowledge of the statistical shape variability are of great interest in many orthopaedical and clinical applications. The common approach to derive 3D models is by direct segmentation of CT or MRI datasets. However, these have the disadvantage that they are expensive, time-consuming and/or induce high-radiation doses to the patient. In this paper, our goal was first to construct statistical shape models (SSM) of the knee joint, considering shape information from both distal femur and proximal tibia, and thereby to determine the principal modes of shape variation. Based on the constructed SSM, we then present a technique to reconstruct patient-specific 3D models of the knee joint from a single roughly calibrated two-dimensional (2D) X-ray radiograph.

Materials & Methods: The SSM of the distal femur was constructed from a training database consisting of 45 CT-segmentation based binary volumes of complete femur. A binary volume of a complete femur was randomly chosen as the reference. A non-rigid registration algorithm was used to estimate the deformation fields between the reference binary volume and the other 44 volumes. Each estimated deformation field was then used to displace the positions of the vertices on the reference surface model to the associated target volume. We thus obtained 45 surface models of the complete femur with established correspondences. The mean surface model of the complete femur was obtained by computing the average position of each vertex on these aligned model data. This mean surface model of the complete femur was then used to derive the SSM of the distal femur as follows. First, we manually remove the proximal part of the mean complete femur, leading to a surface model of the distal femur (Note: the exact amount of the proximal part to be removed is application dependent). For each vertex on this cropped surface model, we can find its correspondence in other complete femur models and thus we can obtain 45 distal femur surface models with correspondence. The mean shape and the principal eigen-modes of the SSM of the distal femur were then obtained by applying principal component analysis on these aligned model data. The exact same procedure was also used to construct a SSM of the proximal tibia from 17 CT-segmentation based binary volumes of complete tibia.

Based on the constructed SSMs, we developed a technique to reconstruct patient-specific 3D models from a single 2D roughly calibrated X-ray radiograph. Here the rough calibration means that an object with known geometrical shape and size was placed beside the knee joint (See. Fig. 1). With a roughly calibrated X-ray radiograph of the knee joint, we developed a hybrid 2D/3D deformable registration strategy combing a landmark-to-ray registration with a SSM-based 2D/3D reconstruction scheme [1] to derive patient-specific models of the knee joint. In this paper, we present a case study to validate this newly developed technique. To evaluate the reconstruction accuracy, the surface models reconstructed from the roughly calibrated X-ray radiograph of a cadaver knee joint (note: this cadaver is not part of our SSMs of the knee) were compared to the associated ground truth data derived from a 3D MRI-scan reconstruction technique. For each case, a surface-based matching was first used to recover the rigid transformation between the reconstructed surface models and the associated ground truth models before the distances between them were computed.

Results: Based on the SSMs, our technique could successfully reconstruct 3D surface models of the knee joint. Figure 1(c) shows the errors of reconstructing surface models of both femur and tibia. After recovering the rigid transformation between the reconstructed surface models and the associated ground truth models that were directly segmented from MRI datasets, it was found that the mean error for the distal femur was 1.0 ± 0.8 mm and the mean error for the proximal tibia was 1.7 ± 0.8 mm. Figure 1(d) shows the color-coded reconstructing error distributions.

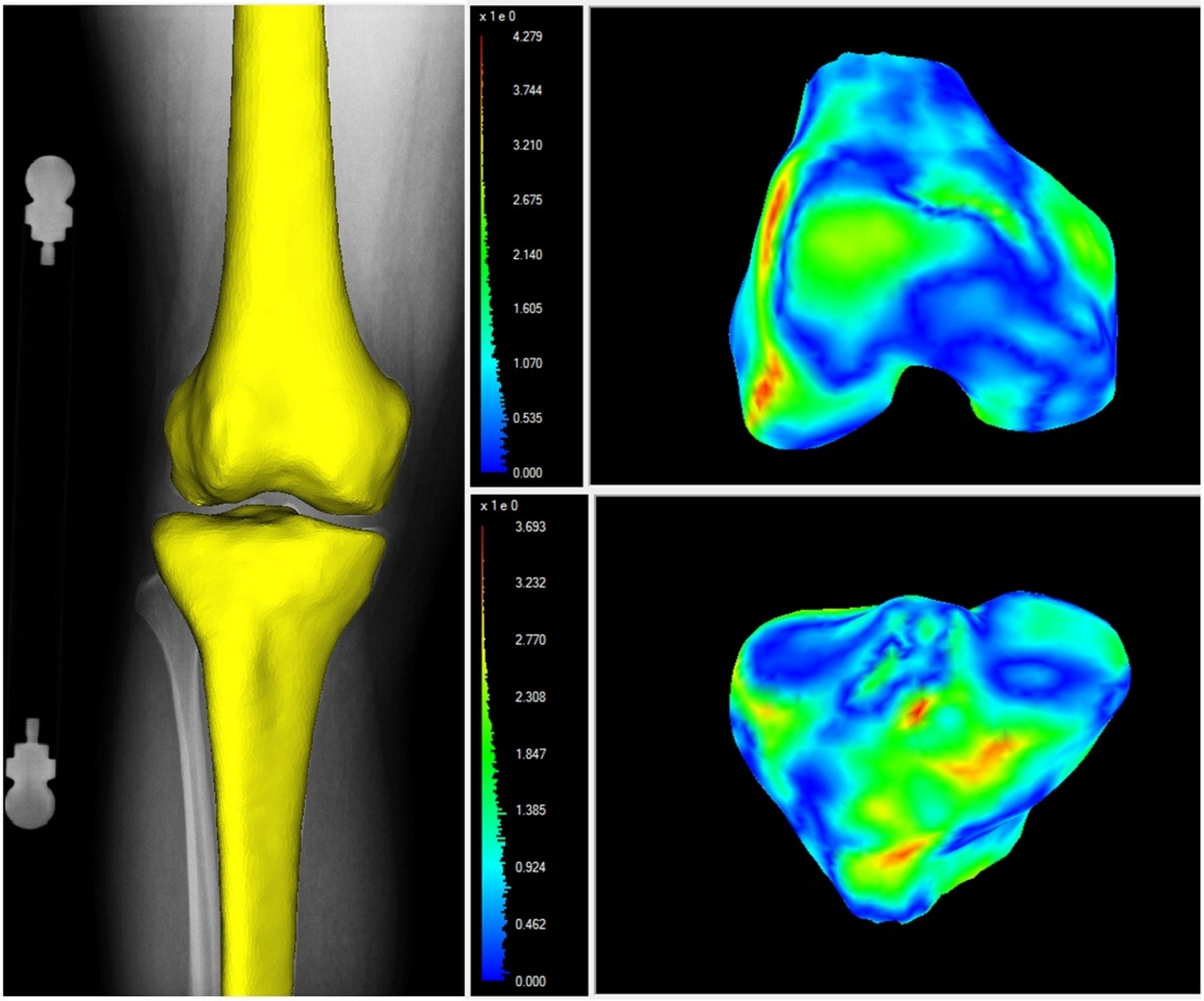

Fig-1. Reconstruction of patient-specific models of a knee joint from a roughly calibrated X-ray radiograph. Left: the reconstructed models (both distal femur and proximal tibia) superimposed on the X-ray image with calibration object; Top-right: the color-coded reconstructing error distribution for the distal femur; bottom-right: the color-coded reconstructing error distribution for the proximal tabia.

Discussions & Conclusions: In this paper we present a technique to construct statistical shape models of the knee joint. With the statistical shape models of the knee joint, a hybrid 2D/3D deformable registration technique was developed to reconstruct patient-specific models of the knee joint from a roughly calibrated X-ray radiograph. Our preliminary validation study conducted on one cadaver demonstrated efficacy of the technique. Currently, we are collecting more clinical data to conduct a comprehensive validation.

References

[1] Zheng G., et al. "A 2D/3D correspondence building method for reconstruction of a patient-specific 3D bone surface model using point distribution models and calibrated X-ray images", Medical Image Analysis, 13:883 – 899, 2009.