Patient-specific 3D Reconstruction of A Complete Lower Extremity from 2D X-rays: A Cadaveric Validation Study

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Introduction

Knee osteoarthritis (OA) is a degenerative disease of the knee joint, affecting 40% or more of the population over the age of 40, which results in a heavy socio-economic burden. Knee arthroplasty (KA) and lower extremity osteotomies (LEO) are two common surgical treatments for knee OA. Every year more than 1.2 million total knee arthroplasties (TKA) are performed worldwide.

In clinical routine surgeons depend largely on 2D x-ray radiographs and their experience to plan and evaluate surgical interventions at the knee. Numerous studies have shown that pure 2D x-ray radiography based measurements are not accurate due to the error in determining accurate radiography magnification and the projection characteristics of 2D radiographs. Using 2D x-ray radiographs to plan 3D knee joint surgery may lead to component misalignment in KA or to over- or under-correction of the mechanical axis of the lower extremity in LEO.

Recently we developed a personalized X-ray reconstruction-based planning and post-operative treatment evaluation system called iLeg for TKA or LEO. Based on a patented X-ray image calibration cage and a unique 2D-3D reconstruction technique, iLeg can generate accurate patient-specific 3D models of a complete lower extremity from two standing X-rays for true 3D planning and evaluation of surgical interventions at the knee joint. The goal of this study is to validate the accuracy of this newly developed system using digitally reconstructed radiographs (DRRs) generated from CT data of 12 cadavers (24 legs).

Materials and Methods

CT data of 12 cadavers (24 legs) were used in the validation study. For each leg, two DRRs, one from the antero-posterior (AP) direction and the other from the later-medial (LM) direction, were generated and used as the input to the iLeg software. In generating the DRRs, we set the distance from the focal point to film as 2000 mm and the pixel resolution in the range of 0.20 – 0.25 mm. The 2D-3D reconstruction was then done by non-rigidly matching statistical shape models (SSMs) of both femur and tibia to the DRRs [1]. See Fig. 1 for an example.

Fig. 1. Reconstruction of patient-specific 3D models of a complete lower extremity from 2D DRRs. Left two images: the DRRs used in the 2D-3D reconstruction; right two images: reconstructed surface models (grey) of the left leg superimposed on the DRRs

In order to evaluate the 2D-3D reconstruction accuracy, we conducted a semi-automatic segmentation of all CT data using the commercial software Amira (Amira 5.2, FEI Corporate, Oregon, USA). The reconstructed surface models of each leg were then compared with the surface models segmented from the associated CT data. Since the DRRs were generated from the associated CT data, the surface models were reconstructed in the local coordinate system of the CT data. Thus, we can directly compare the reconstructed surface models with the surface models segmented from the associated CT data, which we took as the ground truth. Again, we used the software Amira to compute distances from each vertex on the reconstructed surface models to the associated ground truth models.

Table 1. Full leg 2D-3D reconstruction accuracy (mm)

Subject	Femur		Tibia		Average
	Left	Right	Left	Right	
GL1302335	1.6	1.4	1.4	1.3	1.4
GL1402803	1.2	1.2	1.2	1.0	1.2
GL1402940	1.1	1.3	1.3	1.0	1.2
GL1402943	1.3	1.4	1.6	1.5	1.5
GL1402946	1.5	1.6	0.9	1.0	1.3
GL1402952	1.0	1.4	1.6	1.3	1.3
GL1402956	1.2	1.7	1.1	1.0	1.3
GL1402959	1.1	1.1	1.0	1.1	1.1
GL1402964	1.3	1.3	1.5	1.5	1.4
GL1402966	1.5	1.2	1.6	1.4	1.4
GL1403012	0.9	0.8	1.6	1.1	1.1
GL1403022	1.1	1.0	1.5	1.6	1.3
Overall	1.2±0.2	1.3±0.2	1.4±0.3	1.2±0.2	1.3±0.2

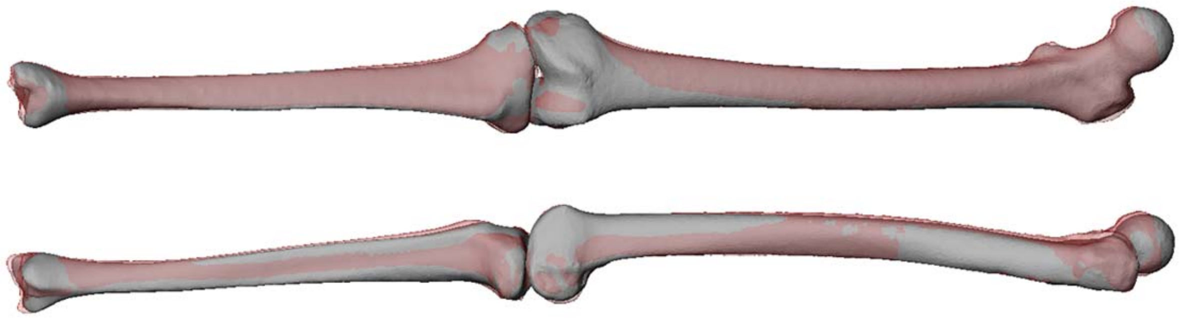

Fig. 2. Comparison of reconstructed surface models (grey solid) with the surface models segmented from the associated CT data (red transparent). Top: AP view; bottom: LM view

Results

The full leg 2D-3D reconstruction validation results are shown in Table 1. When the reconstructed models were compared with the surface models segmented from the associated CT data, a mean reconstruction accuracy of 1.2±0.2mm, 1.3±0.2mm, 1.4±0.3mm and 1.3±0.2mm was found for left femur, right femur, left tibia and right tibia, respectively. When looking into the reconstruction of each subject, we found an average reconstruction accuracy in the range of 1.1mm to 1.5mm. Overall, the reconstruction accuracy was found to be 1.3±0.2mm. Fig. 2 shows an example of comparison of reconstructed surface models (grey solid) with the surface models segmented from the associated CT data (red transparent).

Discussions and Conclusions

In this paper, we conducted a cadaveric study to investigate the accuracy of iLeg system. The advantage of using DRRs generated from CT data to validate the 2D-3D reconstruction accuracy lies in that the reconstructed surface models are in the local coordinate system of the CT data. Thus, we don't need to perform a rigid registration before we can compare the reconstructed surface models to the surface models segmented from the associated CT data. The errors that we reported in Table 1 thus contain errors from two different sources: pose reconstruction errors and shape reconstruction errors. In contrast, most of 2D-3D reconstruction validation studies in the literature [2, 3] only report the shape reconstruction errors. The pose reconstruction errors in these studies are eliminated due to the fact that usually a rigid registration between the reconstructed model and its associated ground truth model is conducted before these models can be compared with each other.

Besides evaluating the distances between the reconstructed surface models and the associated ground truth models, we also plan to compute differences of clinically meaning parameters, which will give more insights on the influence of reconstruction errors on the 2D-3D reconstruction-based planning of TKA or LEO.

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