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Automatic acquisition of femoral bony landmarks

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Abstract

Navigated orthopaedic surgery relies on bony landmarks and the accuracy of their acquisition can impact the surgery outcomes. We propose an automatic workflow to determine 11 femoral bony landmarks on virtual 3D meshes.
The studied landmarks were first determined on the mean shape of a statistical shape model of the femur. Then the statistical shape model was fitted to the virtual 3D meshes, and the landmarks of the mean shape were projected onto the fitted mesh. The proposed method was validated by comparing the computed landmarks to ground truth landmarks acquired manually on 41 knees. We also investigated the impact of the landmarks' accuracy on the variability of axes and resection planes derived from the considered landmarks. The 11 femoral bony landmarks were automatically determined in less than 2 minutes with an accuracy of 2.81 ± 1.86mm. Such error impacted the accuracy of the derived axes and planes with less than 0.5° angular deviation.
Three landmarks had poorer accuracy and precision attesting how ambiguous their definition is and the difficulty to identify them. The proposed method allows the fast acquisition of femoral bony landmarks, with similar accuracy to manual approaches.

1 Introduction

Total knee arthroplasty (TKA) is the most common joint replacement performed worldwide and its incidence is expected to still increase for the next decades. Navigation systems have been shown to improve the surgery accuracy, mainly regarding the bone cuts. For instance, the precision of the currently available robotic solution is close to 0.5mm and 0.5° [1]. Most navigation solutions are based on the intraoperative acquisition of landmarks usually performed by surgeons. However, those landmarks can suffer from high variability in their acquisition [2]. It is also becoming clear that patient-specific joint replacement is the key solution to improve TKA outcomes [3]. In this sens, identifying a large number of landmarks can help establishing a personalised and accurate pre-operative planning. Nevertheless, it remains time-consuming. Therefore we developed an automatic approach to automatically identify femoral bony landmarks in a robust and straightforward manner. The aim of this study is to validate the proposed method.

2 Methods

A statistical shape model (SSM) of the femur was built from 90 segmented CT scans, following an unbiased protocol already described in [4]. Such SSM represents the mean shape of the meshes used to built it, and can be deformed so as to fit any new shape. When identifying landmarks on the SSM mean shape, any SSM deformation will shift those landmarks along with the mean shape. Once the SSM fitted to a target mesh, the target landmarks are identified by projecting the fitted shape landmarks onto the target [5].

Thus, we identified 11 landmarks on the femur SSM mean shape (see Figure 1) useful in total knee arthroplasty to determine the orientation of resection planes and femur axes. Then, we fitted the SSM to new femur meshes and transferred automatically the 11 landmarks on them. For the landmarks defined as the most distal and anterior, a local search was conducted around the fitted SSM landmarks to improve their positioning. Based on those 11 landmarks, 3 axes (mechanical axis, primary axis, antero-posterior axis) and 3 planes (anterior, posterior and distal resection planes) were computed.

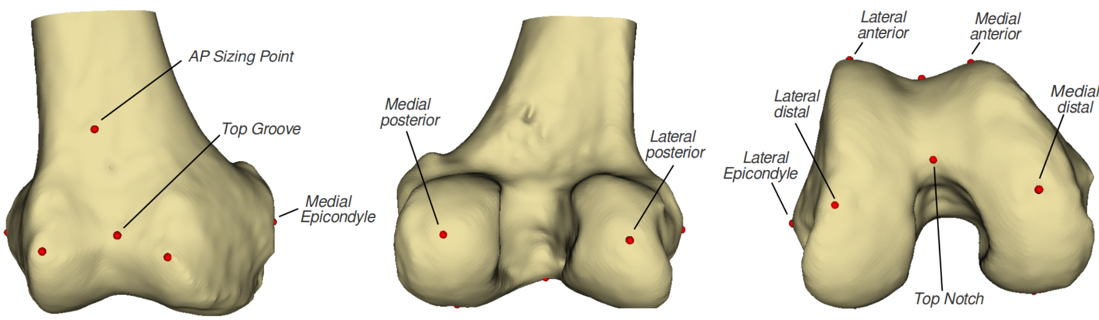

Figure 1: The 11 femoral bony landmarks acquired.

To validate the proposed approach, the landmarks of 41 unseen femurs were identified automatically and compared to their ground truth acquired manually. To determine the landmarks ground truth, two surgeons picked manually the 11 landmarks on the 41 femurs through 3 different modalities: CT scans, 3D meshes and 3D printed models issued from the segmentation of the CT scans. The intra-observer precision of the manual picking regarding the modality used, has been already analysed in a previous publication [6]. It was found that the existing variability on the acquired landmarks did not impact the axis and planes derived from them, and that no modality was more reliable than another. A similar study was conducted on the inter-observer precision. We found that the inter-observer variability was equivalent or higher than the intra-observer variability, whatever the modality used for picking. As no modality nor observer was found more reliable than the other, the ground truth for each landmark was defined as the barycenter of the manual pickings performed by both observers on the 3 modalities.

The accuracy of the planes and axes derived from the automatically identified landmarks was evaluated by computing their angular deviation wrt the planes and axes derived from the ground truth landmarks.

3 Results

The 11 femoral bony landmarks were automatically determined in less than 2 minutes with a mean accuracy of 2.81 ± 1.86mm. The computation error for each femoral bony landmarks is

Landmark	Mean ± SD	[Min - Max]	Landmark	Mean ± SD	[Min - Max]
Lateral anterior	2.65 ± 2.11	$[0.48 - 11.76]$	Medial anterior	2.12 ± 1.51	$[0.36 - 6.23]$
Lateral distal	5.47 ± 2.71	$[2.10 - 14.93]$	Medial distal	3.15 ± 1.93	$[0.93 - 9.80]$
Lateral epicondyle	2.03 ± 1.10	$[0.30 - 4.75]$	Medial epicondyle	2.66 ± 1.42	$[0.65 - 6.74]$
Lateral posterior	2.43 ± 1.44	$[0.29 - 6.07]$	Medial posterior	1.84 ± 0.73	$[0.26 - 3.68]$
Top groove	2.04 ± 1.05	$[0.39 - 4.56]$	Top notch	3.64 ± 1.32	$[1.27 - 6.37]$
AP sizing point	2.84 ± 1.30	$[0.65 - 6.94]$			

Table 1: Accuracy of the automated acquisition for the 11 femoral bony landmarks.

detailed in Table 1. Most landmarks are identified with a mean error below 3mm, except the lateral distal point, the top notch point and the medial distal point.

As in a previous intra-observer precision study [6], the impact of the landmark's variation on the derived axes and resection planes were marginal, with angular variations below 0.5°.

4 Discussion

We proposed an automatic method based on statistical shape modelling, to infer the position of 11 femoral bony landmarks on a femur 3D mesh. Our approach is fast and reaches a mean accuracy of the landmarking below $3mm$. The automatically detected landmarks allow an accurate computation of axes and resection planes derived from them.

The obtained accuracy meets navigation requirements (considering the median manual marking error can go up to $5mm$), and is in line with other automatic methods proposed in the literature [7, 8, 9]. The highest errors were obtained for the lateral distal point, which is used only to determine the distal resection plane. As the lateral distal point lays within a flat area parallel to the distal resection plane, a lower accuracy in this point detection does not impact the plane orientation. A similar phenomenon occurs with the medial distal point. Those two landmarks were found to be the hardest to identify on the 41 femurs by both operators.

We observed poorer inter and/or intra observer precision for the AP sizing point, the lateral distal point, the medial distal point and the top notch point, which attests to the ambiguity in these landmark definitions and occasional disagreements between both observers. Such variability impacts the estimation of the ground truth and therefore the accuracy of the automatically identified landmarks.

As it exists a variability on the manual acquisition (intra and inter observer), we considered the barycenter of those manual acquisitions as the best estimation of the ground truth [7]. Consequently, we observed for one operator that the landmarks acquired at the end of the experiment were closer to the barycenters than the landmarks acquired at the beginning. This demonstrates a learning curve in identifying the landmarks and the convergence of the pickings toward a consensus, namely the barycenter or ground truth.

This study has however some limitations, the main one being that the femurs used for landmarking had no high level pathologies, while strong deformations of the bone could influence the accuracy of both manual and automatic measurements.

5 Conclusion

The proposed method for automatic acquisition of femoral bony landmarks is much faster than manual acquisitions and provides similar accuracy. It can therefore be used with a navigation system to help improve surgical accuracy and personalise total knee arthroplasty.

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