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Quantitative study of knee joint surface configurations using a morpho-functional approach

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Abstract— **Several models exist in the literature to describe knee kinematics. In this paper we propose a morpho-functional approach based on the determination of a simulated kinematics of flexion/extension from a unique CT scan acquisition. We will compare this kinematics to the real one obtained from experiments on one cadaver. In parallel, we have developed quantitative tools for the assessment of the motion. As the computation of these tools depends on the bone morphology, they can describe the state of the joint, which is not classical in the literature. Both tools follow the evolution of the distances between two bones during motion. They are called the Figure of Articular Coherence and the Index of Articular Coherence. In order to verify the relevance of these tools, we have tested them to compare different surgeries of Anterior Cruciate Ligament (ACL) reconstruction.**

I. INTRODUCTION

The knee joint plays a major role in human gait as it allows the mobility and stability of the femur with respect to the tibia. An accurate description of knee joint motion is essential for specific diagnosis of articular pathologies or the design of biomechanical models for medical purposes. The kinematics of flexion/extension of the knee is classically modeled by a rotation around a static mean flexion/extension axis. However, the trend of current biomechanical studies is to improve this modeling by introducing morphological knowledge.

In this paper, we propose to highlight the morpho-functional relationship of this joint. Section II.A. proposes a method that allows extraction of flexion/extension kinematics of the knee from the 3D morphology of bones obtained by segmentation of a single CT-scan acquisition. This method is based on the determination of a mobile axis accounting for the description of the rolling/sliding motion of the femur relative to the tibia. We will compare this simulated kinematics to flexion/extension kinematics obtained by direct measurements on a cadaver. This quantitative comparison will be made with the help of figures and index of joint coherence. The Figures and Index rely on the evoluting distances between articular surfaces during the motion as explained in section II.B. As our method considers that ligaments play an implicit role in maintaining bone structures in smooth contact, it is of interest to study the impact of ligaments on knee kinematics [1]. We will focus on Anterior Cruciate Ligament (ACL) which is important for knee kinematics. Therefore we will evaluate, in section III, the impact of the ACL resection and different surgeries of ACL reconstructions, on the knee flexion/extension motion by means of the proposed tools in section II.B.1.

II. ESTIMATION OF A HEALTHY KINEMATIC AND COMPARISON WITH A REAL ONE

A. *Morpho-functional modelisation of knee flexion*

Regarding knee kinematics, several theories exist in the medical literature. The first one hypothesized that the tibia rotates about a fixed transepicondylar axis during knee flexion and extension. For some authors, this axis is easily identified by palpation and approximates the optimal flexion axis [2], [3]. However a static axis is inconsistent with the observation of rollback of the femur relative to the tibial plateau [4], [5] implying that the axis should theoretically move posteriorly during the flexion. Hence we need rather to consider that the flexion axis is a mobile one. Its calculation relies on measurement of bone kinematics. This can be done either by using cortical pins (which is accurate but very invasive) [6] or by using skin markers [7]. In the latter approach, relative movement between bone and skin induces measurement errors [8] that largely affect the definition of finite helical axis. Those artifacts can be reduced by integrating ligament constraints [9]. However, personalised ligament insertion is not easy to define, unless multiple imagery techniques are available.

In this paper, we propose an alternative method for extracting knee flexion/extension kinematics from bone morphology using a single 3D morphological acquisition. The working hypothesis is to assume that the centers of curvature of each condyle are connected to describe the successive axis of rotation. Previous works [10] have shown that contact points follow a curve of contact which stays in a medio-lateral plane. The study of this curve gives the position of the centers of curvature, or evolute, which correspond to the positions of the instantaneous helical axis (IHA). In order to locate the centers of curvature, each condyle is approached by an ellipsoïd, but as the curvature of a condyle does not vary significantly in the different mediolateral planes we adopt the approach utilized by anatomists [11]. This approach consists in calculating the successive centers of the ellipse in a sagittal slice of each condyle as an approximation of the entire condyle. The fitting of an ellipsoid model [12] is only used here in order

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to extract the major axis and hence determine the orientation of the sagittal slice of interest.

The first step consists in defining the sagittal section of each condyle. Once we have the main orientation of a condyle and the fitted plane on the tibial plateau, we define the sagittal section as the plane that includes the major axis and that is perpendicular to the tibial plateau. Then, an ellipse is fitted on the portion of the posterior condyle that is involved in the motion of flexion/extension of the knee and the evolute is computed for this portion in the Frenet frame. Finally, we obtain the mobile axis of rotation by a matching between the centers of curvature of each condyle, based on the position of the contact point between the sagittal section and the tibial plateau.

A method of computation of mobile axis is thereafter synthesized.

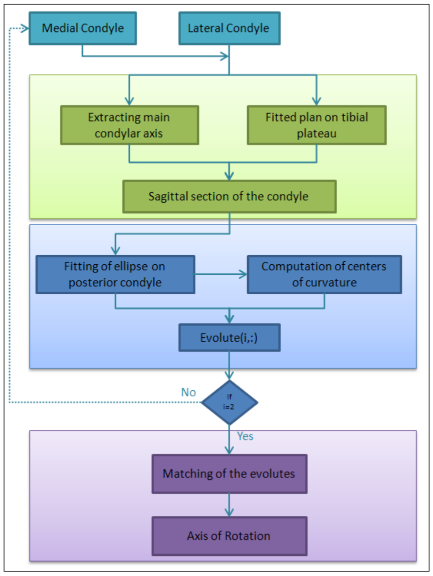

Figure 1. Flowchart of the method of determination of mobile axis for the knee flexion

This method is then compare to the method of transepicondylar axis (static axis) and to kinematics recorded on a cadaver knee. In order to compare the fixed and mobile axes methods, we developed the tools described in the next section.

B. Comparison of the different kinematic

1) Figures and index of articular coherence

The flexion/extension kinematics will be compared thanks to an index of articular coherence based on Schwartz [13]. This index measures the instantaneous joint surface configurations, more specifically the position between two articular surfaces facing each other. In order to measure the instantaneous state of the joint, the index has to refer to a position known to be physiological. This initial position of the bones, named reference, directly results from the segmentation of 3D anatomical acquisition. As Schwartz took into account the mean distance between the two surfaces, we consider all distances and follow the temporal evolution of the cumulative distribution function (CDF) of these distances. For two facing surfaces, we compute the distance between vertices of one surface (femur) and the facets of the other (tibia). The chosen facet is the one which normal is collinear to the normal at the studied vertex. Once we have all the distances between the two articular surfaces, we compute the associated CDF. We process this way for each successive iterations of the motion. All the CDFs curves form the Figure of Articular Coherence (FoAC) (Figure 2 and 3). This FoAC graph provides qualitative information relative to the motion such as potential collisions or dislocations.

In order to complete this qualitative information of the joint comportment, the Q-Q plots are thereafter used to have a quantitative criterion for consolidating the observations of the FoAC. These diagrams allow the evaluation of the distributions around the first bisector which correspond to the distribution of reference. If the distributions are close to the initial position or reference, data will be projected around the first bisector of the Q-Q plot (Figure 5). Conversely, if the distributions are not close to each other, data will move away from the reference (Figure 4). Finally, we use the Hausdorff Distance to validate the observations and obtain a quantitative criterion named Indice of Articular Coherence (IoAC). The distribution function is likened to a trajectory for computing the similarity between the reference and the temporal distribution.

$$IoAC = \max\left\{\sup_{x\in X}\inf_{y\in Y} d(x,y)\,,\sup_{y\in Y}\inf_{x\in X} d(x,y)\right\}$$

Where X is the distribution of distances of the reference and Y the temporal distributions during the motion.

2) Comparison between mobile and static axis

These tools have been utilized on CT scans of five subjects taken from a database without any articular pathologies. CT scans were semi-automatically segmented, according to clinician advice and using the Amira software (Amira 5.1, Visage Imaging, Inc.) in order to obtain 3D reconstruction of bony structures. The five acquisitions were done on the lower limb in extension. For each acquisition, we compute two simulated kinematics of flexion of 100° around first the static axis and second the mobile axis as explain in section II A. The results of the 4th subject are presented below.

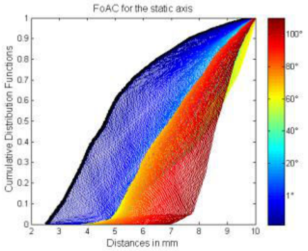

Figure 2. FoAC for static axis : evolution of the distributions during a motion of flexion for the subject 4. Reference is represented by the black curve. The colorbar represents the successive iterations of the flexion in

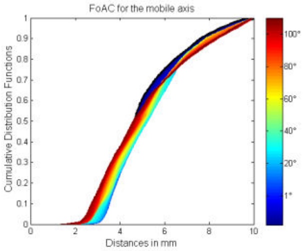

Figure 3. FoAC for mobile axis : evolution of the distributions during a motion of flexion for the subject 4. Reference is represented by the black curve. The colorbar represents the successive iterations of the flexion in

degrees.

degrees.

For the static axis (Fig. 2), cumulative distribution functions are shifted in the direction of increasing distances until about 60 degrees of flexion. This large FoAC would mean a dislocation between the two articular surfaces. The surfaces then approach the reference in black before finally moving away again. For the mobile axis (Fig. 3), cumulative distribution functions are close to the reference during the whole motion. This thin FoAC characterizes a good articular coherence. These results can also be visualized through the Q-Q plot diagrams as suggested below (Figure 4 and 5).

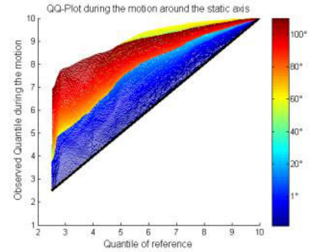

Figure 4. evolution of the QQ-plot diagram during the knee flexion for the static axis for the subject 4. Reference is represented by the black curve. The colorbar represents the successive iterations of the flexion in degrees

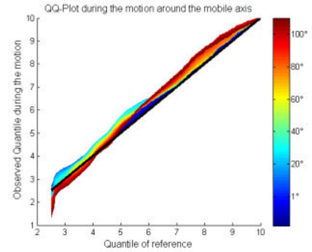

Figure 5. evolution of the QQ-plot diagram during the knee flexion for the mobile axis for the subject 4. Reference is represented by the black curve. The colorbar represents the successive iterations of the flexion in degrees.

As expected, the results are in agreement with those of the FoAC. Functions are closer to the reference (first bisector) for the mobile axis than for the static axis and we observe the same back and forth phenomenon around the reference. These graphics are a good qualitative instrument for the interpretation of articular coherence. Indeed, they bring an improvement to the index developed by Schwartz since collisions and dislocations between two facing bones can now be identified. Nevertheless, in order to complete the interpretation of the FoACs in a quantitative way, we use the IoAC such as presented in Figures 6 and 7. These figures represent the evolution of the IoAC for the two computed kinematics (static and mobile axis) for the five subjects.

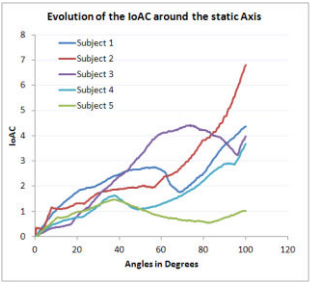

Figure 6. Evolution of the IoAC during the flexion around the static axis for the five subjects.

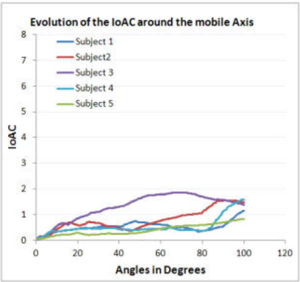

Figure 7. Evolution of the IoAC during the flexion around the mobile axis for the five subjects.

These curves highlight that the motion of flexion is better modeled by a rotation around the mobile axis for the five subjects. Indeed, the IoAC's curves evolve between 0 and 2 during the whole motion, which means a good similarity between the temporal distributions and the reference. As for the result for the static axis, IoAC increases for the five subjects. The observations of the FoAC for the first subject also appear in Figure 6. As the cumulative distribution functions move either away or towards the reference, the IoAC increase and decrease from 0 to 60°. Although the results for the 5th subject are quite good for the static axis, performances are even better for the same subject with the mobile axis.

3) *Comparison to a real kinematics*

The aim of this section is to compare our method of computing fixed and mobile axis to that of kinematics recorded on a cadaver knee. The measured kinematics comes from an experimental set-up constructed by Hagemeister et al. They recorded the motion of extension/flexion cadaver knees. The experimental protocol is entirely described in [1]. Briefly, the kinematics of flexion/extension was obtained thanks to magnetic sensors (Fastrack, Polhemus, Vermont, USA) attached on the bones. The motion of extension/flexion of the knee has been performed via the tension on the quadriceps tendon. First, computation of intact knee kinematics is performed. The results are presented below for one knee.

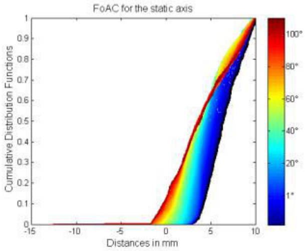

Figure 8. FoAC for static axis : evolution of the distributions during a motion of **flexion** for the knee cadaver. Reference is represented in black. The colorbar represents the successive iterations of the movement in degree.

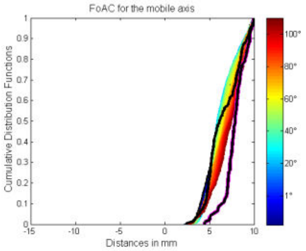

Figure 9. FoAC for mobile axis : evolution of the distributions during a motion of **flexion** for the knee cadaver. Extreme distribution function of intact kinematics are represented in black. The colorbar represents the successive iterations of the movement in degree.

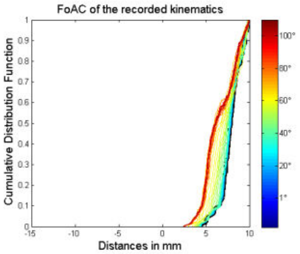

Figure 10. FoAC of the intact knee: evolution of the distributions during a motion of **extension** for the intact knee cadaver. Reference is represented in black. The colorbar represents the successive iterations of the movement in degree.

While figure 8 shows the collision between the articular surfaces, figure 9 shows that computed kinematics with mobile axis remains in the same range of distances as recorded kinematics. The black curves of the figure 9 correspond to the distribution function of the beginning and the end of the recorded motion. Although our method does not take into account the ligaments, it appears, thanks to the figures 9 and 10, that bone morphology plays an important role in guiding bone structures during motion.

In order to further validate the relevance of these tools, and especially that of IoAC, we tested them on experimental data. We used them to compare different surgeries of ACL reconstruction.

III. APPLICATION TO THE COMPARISON OF ACL RECONSTRUCTIONS IN KNEE SURGERY

In Hagemeister's work, different ACL reconstructions, performed on cadaver knees cadaver from men aged from 64 to 88, have been compared. We used our tools (FoAC and IoAC) and compared our results for one cadaver knee.

A flexion/extension movement was tested in different situations: intact knee, after ACL resection, after bone-patellar-bone double tunnel reconstruction, after synthetic double tunnel reconstruction and after ‘over-the-top’ reconstructions on the same knee [14], [1]. All resulting kinematics are compared with FoAC and IoAC. For the flexion motion of the intact knee, the functions are well correlated to the reference (Figure 10). We consider the results obtained for the intact knee as the reference kinematics. Consequently, after ACL resection, FoAC (Figure 11) indicates that the functions go in the direction of decreasing distances more rapidly, which means that both articular surfaces are close to collision when they are in full extension.

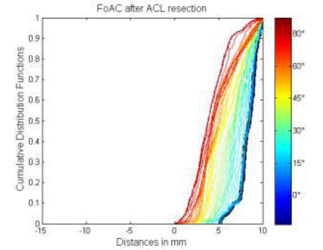

Figure 11. FoAC of the knee after ACL resection: evolution of the distributions during a motion of **extension**. The colorbar represents the successive iterations of the movement in degree.

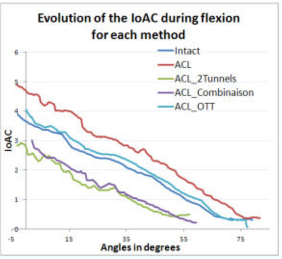

Figure 12. Evolution of the IoAC during the flexion for each method of surgery.

Figure 12 presents the evolution of the mean IoAC for the five situations. Mean IoAC was computed as a mean of ten flexion/extension cycles. It can be seen that the highest index is obtained for the resected ACL (ACL, red curve). The OTT method produces results that are comparable to those for the intact knee. Both 2 tunnels reconstructions gave index values that are lower than those obtained with the intact knee. In the work of Hagemeister, this phenomenon is explained by an over-constraint on the knee movement, the knee appears to be more stable but it might rigidify the joint as well.

IV. CONCLUSION AND PERSPECTIVE

Through the use of the FoAC and IoAC, we reached the same conclusions as Hagemeister et al. [1] with new information concerning possible dislocations or collisions. Our tools describe the instantaneous state of the joint and are able to compare kinematics corresponding to different ACL reconstructions. Besides they provide qualitative and quantitative information on the articular state without 3D visualization to understand what happened during the motion. In order to ensure the quality of FoAC and IoAC, we are testing these tools on the 6 other subjects and comparing the results to the study conducted by Hagemeister et al. [1]. To improve the quality of the IoAC, it is also possible to take into account the geometrical differences between the cumulative distribution functions and use other similarity indicators [15]. In addition, and in order to consolidate the mobile axis method and determine the position of the IHA, experiments on cadavers are in progress. As expected, initial results confirm that morphology plays an important role in guiding bony structures in order to maintain contact in healthy knees. However, it would be interesting to know the light that our tools could shed on pathological data. As we have preliminary results about the impact of ACL resection, a better understanding of this part and how it impacts the position of IHA should improve our model.

V. AKNOWLEDGMENT

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