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Original article

Study of the joint configuration of the knee using a morpho-functional analysis

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Abstract

Skin marker motion analyses are the most widespread techniques to study human movements. Nevertheless, trajectories obtained through such methods are biased because of soft tissue artifacts and lead, consequently, to false collisions and dislocations when bone motion is under investigation. It's an open challenge to enhance kinematics curves particularly for the knee joint involved in the mechanics of gait. The kinematics of flexion/extension of the knee is classically modeled by a rotation around a fixed axis. However, the trend of current biomechanical studies is to improve this modeling by introducing a morphological knowledge such as ligament constraints. In this paper, we propose to highlight the morpho-functionnal link on this joint thanks to two contributions. The first one consists in proposing a method capable of extracting a kinematics of flexion/extension of the knee from a unique CT scan. This method is based on the determination of a mobile axis capable of keeping the information of rolling/sliding. The second one consists in a qualitative and quantitative temporal analysis of the position of the bones during the movement. We compare the results of the two kinematics (static and mobile axis) using original figures of articular coherence and an associated index.

1. Introduction

The human musculoskeletal system is part of many studies, firstly, in order to increase fondamental medical knowledge, secondly to acquire functional and morphological parameters used in rehabilitation clinical routines or computer assisted surgery protocols [1].

Currently, acquisitions systems are either dedicated to kinematics studies (magnetic or optic systems) or used for 3D morphological studies (CT scan, MRI). No current sensor is enough optimized for both kinematics and movement segments anatomy with the exception of the use of extreme invasive methods (intracortical pins). Nevertheless, that is one of the most reliable methods used to estimate temporal positions of the bony structures [2,3]. External skin markers can also be used to estimate underlying bones movements. Unfortunately, the relation between markers positions and bones ones is not direct due to soft tissue artefacts [4]. Many corrective methods can be found in literature and are based on kinematics considerations [5,6], on geometrical considerations [7,8] and on multi 2D/3D recalibration process [9–12].

Our intention here is to develop a morpho-functional method to increase knee kinematics knowledge. This method consists of indentifying successive rotations axes involved (mobile axes) in the flexion/extension of the knee [13,14], from a unique 3D imaging system acquisition.

Then we compare the kinematics of mobile axes to the one more common of the transepicondylar axis (static axis). To compare these two methods, we submit an adaptation of the articular coherence index developed by Schwartz et al. [15] in order to obtain a qualitative and quantitative monitoring of the articular coherence of the knee.

2. Material

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

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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 3.1.

3. Methods

3.1. 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 [16,17]. However, a static axis is inconsistent with the observation of rollback of the femur relative to the tibial plateau [17,18] 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) [13] or by using skin markers [19]. In the latter approach, relative movement between bone and skin induces measurement errors [4] that largely affect the definition of finite helical axis. Those artifacts can be reduced by integrating ligament constraints [20]. 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 [22] 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 medio-lateral planes we adopt the approach utilized by anatomists [21]. 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 [23] is only used here in order 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.

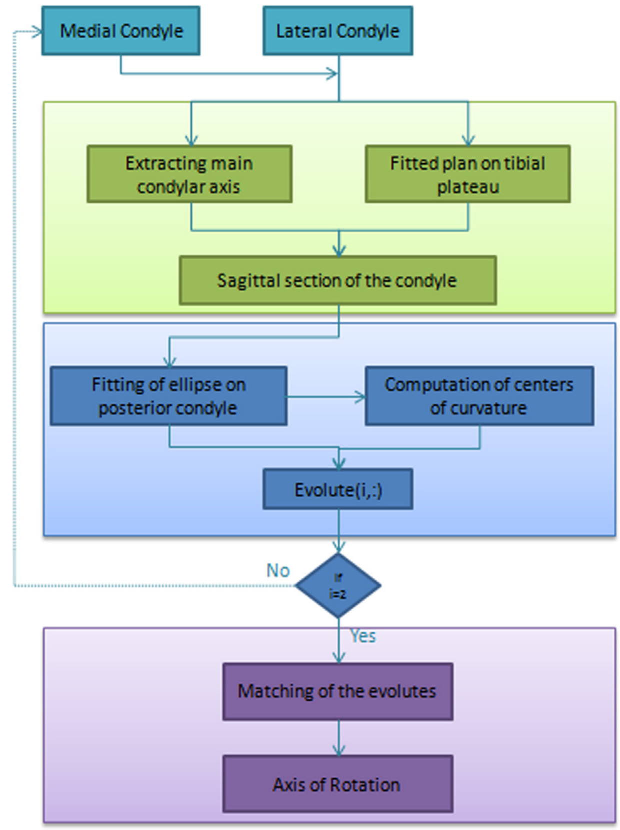

Fig. 1. Flowchart of the method of determination of mobile axis for the knee flexion.

A method of computation of mobile axis is synthesized in Fig. 1.

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.

3.2. Figures and index of articular coherence

3.2.1. Figure of Articular Coherence

The flexion/extension kinematics will be compared thanks to an index of articular coherence based on Schwartz [15]. 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 acquisitions. [24] shows that this previous index is well adapted for studying elbow flexion, but we have adapted it for the knee joint. As Schwartz takes into account the mean distance between the two surfaces, we consider all distances and follow the temporal evolution of the cumulative function 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. Consequently, the distribution of