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Original Article

3D Sequential Kinematics of the Femoro-Tibial Joint of Normal Knee from Multiple Bi-planar X-rays: Accuracy and Repeatability

K. Langlois [a,*], H. Pillet [a,*], F. Lavaste [a], G. Rochcongar [b], P. Rouch [a], P. Thoreux [a,c], W. Skalli [a]

[a] *Arts et Métiers ParisTech, LBM/Institut de Biomécanique Humaine Georges Charpak, 151 bd de l'Hôpital, 75013 Paris, France*
[b] *INSERM U1075 COMETE "Mobilité: Attention, Orientation & Chronobiologie", Département de Chirurgie Orthopédique et Traumatologique, Université de Caen Basse-Normandie, Centre Hospitalier Universitaire de Caen, France*
[c] *Service de Chirurgie Orthopédique Hôpital Avicenne, Université Paris XIII, 125 rue de Stalingrad, 93009 Bobigny, France*

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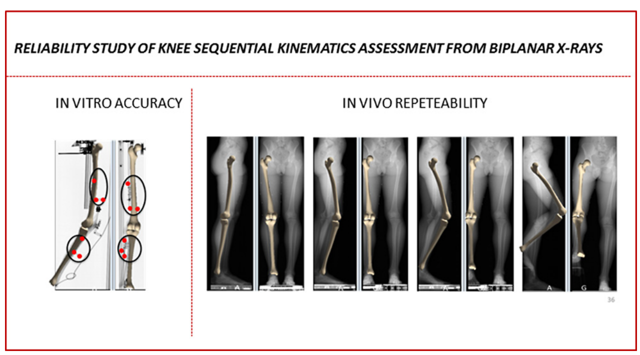
Highlights

- The EOS system allows the sequential kinematic analysis of the femoro-tibial joint.
- The reliability of the registration of 3D model on 2D views has been quantified.
- The accuracy of the registration is inferior to 1.6 mm and 0.4°.
- The repeatability of the registration is 0.3°, 2.1° and 1.6°, for the rotations.
- The repeatability of the registration is inferior to 1.8 mm for the translations.

Graphical abstract



Abstract

Background: Several methods can be used to assess joint kinematics going from optoelectronic motion analysis to biplanar fluoroscopy. The aim of the present work was to evaluate the reliability of the use of biplane radiography to quantify the sequential 3D kinematics of the femoro-tibial joint.
Methods: Bi-planar X-rays (EOS imaging) of 12 lower limbs (6 specimens in vitro and 6 subjects in vivo) were taken for various knee flexion angles. 3D personalized models of the femur and the tibia were registered on each pair of views. To quantify the bias, the kinematic parameters calculated from the registered models were compared to those obtained from the tripods embedded in the specimens. Intra and inter-operator repeatability of each parameter were assessed from the registrations made by 3 operators in vivo.
Results: In vitro, the bias of the tibia pose estimation obtained from the registration method was inferior to 1.6 mm and 0.4°. In vivo, the repeatability of the sequential kinematic parameters was inferior to 0.3°, 2.1° and 1.8°, for respectively flexion, varus-valgus and medial-lateral rotation and inferior to 1.8 mm for translations.

* Corresponding authors.
E-mail addresses: karine.langlois@ensam.eu (K. Langlois), helene.pillet@ensam.eu (H. Pillet).

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Conclusion: Compared to simple fluoroscopy, the accuracy of our method based on sequential images was of the same order of magnitude, with better results for the translation in the frontal plane. The low dose of radiation of the EOS system offers promising prospects for a clinical use of this method to assess the femoro-tibial sequential kinematics.

Keywords: Bi-planar radiography, low dose; Knee 3D sequential kinematics; Registration; Lower limb

1. Introduction

The assessment of 3D femoro-tibial joint kinematics is essential to understand the complex function of the knee and the mechanism of degeneration. Indeed, some studies have already shown that joint disorders such as osteoarthritis affect these kinematics [1,2]. However, in vivo extensive evaluations remain difficult due either to the radiant or invasive nature of direct bone localization techniques [3–8] or to inaccuracies associated to external measurement procedures like optical motion capture [9–11]. Thus, the registration on 2D fluoroscopic images of a 3D model obtained from CT-scan is so far considered as the gold standard for the capture of skeletal motion and the accuracy of the method has been evaluated through in vitro studies [4,12,13]. Considering that this technique exposes the subject to a high level of radiation, an alternative has been proposed taking advantage of magnetic resonance imaging (MRI) to visualize bones during sequential knee joint motion. To overcome the drawback of the lying position, some loading apparatus have been developed [14–16] and a protocol combining supine and upright MRI data [17] has recently been proposed. However, the technic suffers from several drawbacks: the acquisition time is long, the confine environment makes it difficult to reproduce realistic weight-bearing on the lower limbs, the restricted field of view limits the available information and the image processing remains time consuming [18].

Currently, 3D modeling from low dose bi-planar radiographs (BPR) is able to produce a 3D subject specific reconstruction of the lower limbs from calibrated images in weight-bearing condition [19,20]. The shape reconstruction algorithm relies on the identification of several morphological features on the radiographs and has been validated against CT-scan-based model for both shape and derived morphological parameters [19,21]. Several clinical applications have been investigated such as cerebral palsy [22], knee osteoarthritis [23] and hip osteoarthritis [24]. Nevertheless, these analyses were performed in a standing posture, e.g. with an extended knee, and did not provide any information about the joint kinematics.

In the same time, sequential analysis of the femoro-tibial joint motion was proposed using multiple stereoradiographic images of the considered joint in different knee flexion poses. This kind of analysis requires the registration of the 3D personalized model on each pair of images acquired by the BPR corresponding to one specific flexion pose of the joint. The registration can be made manually and femoro-tibial joint kinematics derived from this procedure were previously used as a reference to evaluate and compare several tracking methods with marker cluster [25] or to test an automatic process based on image processing [26]. Some authors also proposed a semi-automatic method based on image processing to perform this registration, which has been evaluated in two studies [27,28]. However, in these studies, the quantification of the accuracy of the method relied on the use of simulated radiographs of 3D models virtually positioned in different configurations. On the contrary, some authors assessed the accuracy of similar registration technique through in vitro study for the patellofemoral joint [29] and the scapulo-humeral joint [30]. It remains to be quantified in the context of the femoro-tibial joint motion. Therefore, there is a need to perform a complete validation study to assess the accuracy and the repeatability of the 3D femoro-tibial motion quantification from sequential bi-planar images of the joint. Indeed, the reliability of the sequential kinematic parameters directly depends on the reliability of the registration method. The hypothesis of the current study was that biplane radiography can be used to reliably assess femoro-tibial sequential kinematics in weight bearing conditions.

In this framework, the aim of the study was to estimate the uncertainties of the 3D sequential analysis of the kinematics of the femoro-tibial joint obtained from bi-planar radiographies by quantifying the registration reliability.

2. Methods

To quantify the reliability of the registration of 3D models on 2D views, two sets of data collected in vitro and in vivo were used. First, the accuracy of the registration was assessed using an in vitro data set to compare the registration to reference values derived from marker clusters screwed in the bones. Second, the intra and inter-observer repeatabilities of the registration method were quantified from an in vivo data set. Both accuracy and repeatability of sequential kinematic parameters of the femoro-tibial joint were calculated.

2.1. In vitro analysis

Six human cadaveric lower limb specimens were harvested after approval of the ethical committee of the laboratory of Anatomy of Caen University (Normandie, France).

Each specimen included the femur, the patella, the fibula, the tibia and the intact joint passive structures. The ages of donors were between 47 and 79 years old. Specimens were checked regarding trauma, surgery and evident deformity and were fresh frozen, then thawed at room temperature during a twenty-four hour period. Clusters made of three retro-reflective markers each were screwed in the femur, the tibia and the patella in order to get reference values for motion tracking. The specimens were