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The Knee

A new method for the evaluation of the end-to-end distance of the knee ligaments and popliteal complex during passive knee flexion

G. Rochcongar [a,b,*], H. Pillet [b], E. Bergamini [c], S. Moreau [d], P. Thoreux [b,e], W. Skalli [b], P. Rouch [b]

[a] Département d'Orthopédie et Traumatologie, INSERM U1075 COMETE "Mobilité: Attention, Orientation & Chronobiologie", Université de Caen, France
[b] Arts et Metiers ParisTech, LBM|Institut de Biomécanique Humaine Georges Charpak, Paris, France
[c] Interuniversity Centre of Bioengineering of the Human Neuromusculoskeletal System, Department of Movement, Human and Health Sciences, University of Rome "Foro Italico", P.zza Lauro de Bosis 15, 00135 Rome, Italy
[d] Laboratoire d'Anatomie, Université de Caen, France
[e] Service de Chirurgie Orthopédique et Traumatologique, Hôpital Avicenne — Université Paris 13, Sorbonne Paris Cité, Bobigny, France

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ABSTRACT

Background: Accurate knowledge about the length variation of the knee ligaments (ACL, PCL, MCL and LCL) and the popliteal complex during knee flexion/extension is essential for modelling and clinical applications. The aim of the present study is to provide this information by using an original technique able to faithfully reproduce the continuous passive knee flexion–extension kinematics and to reliably identify each ligament/tendon attachment site.
Methods: Twelve lower limbs (femur, tibia, fibula, patella) were tested and set in motion (0–120°) using an *ad hoc* rig. Tibio-femoral kinematics was obtained using an optoelectronic system. A 3D digital model of each bone was obtained using low-dosage stereoradiography. Knee specimens were dissected and the insertion of each ligament and popliteal complex were marked with radio opaque paint. ACL, PCL and MCL were separated into two bundles. Bone epiphyses were CT-scanned to obtain a digital model of each ligament insertion. Bones and attachment site models were registered and the end-to-end distance variation of each ligament/tendon was computed over knee flexion.
Results: A tibial internal rotation of 18° ± 4° with respect to the femur was observed. The different bundles of the ACL, MCL and LCL shortened, whereas all bundles of the PCL lengthened. The popliteal complex was found to shorten until 30° of knee flexion and then to lengthen.
Conclusion: The end-to-end distance variation of the knee ligaments and popliteal complex can be estimated during knee flexion using a robust and reliable method based on marking the ligaments/tendon insertions with radiopaque paint.
Level of evidence: Level IV

1. Introduction

The knee is one of the most studied joints with more than 110,000 occurrences in Pubmed. It is also probably the most complex one, characterised by a compromise between great stability and mobility. This is allowed by the interaction of different passive structures: femur, tibia, patella, ligaments, and menisci. Among them, the four major knee ligaments (anterior and posterior cruciate ligaments, ACL and PCL, medial and lateral collateral ligaments, MCL and LCL, respectively), together with the popliteal complex (comprising the femoral insertion of the popliteus tendon and the fibular insertions of the popliteo-fibular ligament [22]), play a crucial role in guiding the knee passive kinematics and stabilising this joint [39,42]. The knowledge of the biomechanical behaviour of these elements is essential to understand the complex kinematics of the healthy joint, and is an important prerequisite to understand ligament injury mechanisms, predict the consequences of ligament disruption, and properly design surgical interventions.

The variation of the length (commonly defined as the geometric distance between the ligament origin and insertion and hereinafter referred to as "end-to-end distance") of the major knee ligaments has been widely dealt with in the literature. However, most studies considered each ligament individually, with particular attention to the ACL [1,16,44] or the PCL [8,17,19,31] or, to a lesser extent, to the MCL [33,41] or the LCL [33,40,41]. Few works studied the popliteal complex [40], although it has a critical role in the control of the rotation of the knee joint, especially limiting the external rotation of the tibia with respect to the femur [34]. Last but not least, methodological issues still exist related to the reliable identification of each ligament insertion [36] and, when *ex-vivo* studies are considered, to the reproduction of the knee passive

* Corresponding author at: Département d'Orthopédie et Traumatologie, CHU de Caen, avenue de la côté de Nacre, 14033 Caen Cedex, France. Tel.: +33 2 31 06 46 49.
E-mail address: rochcongar-g@chu-caen.fr (G. Rochcongar).

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kinematics, which are both crucial aspects when the accurate estimation of the ligament end-to-end distance is aimed.

To the authors' knowledge only two publications studied the end-to-end distance variation of all the four major ligaments simultaneously during passive knee flexion *ex-vivo*, including the individual identification of the ligament attachment site locations [4,5]. In the first study, Belvedere et al. [4] used an optoelectronic system to identify the ligament attachment sites after minimal cadaver dissections and the position of each ligament insertion was digitised and expressed with respect to tibia and femur anatomical systems of reference by means of cluster of markers attached on a pointer and on the bones. However, although optoelectronic systems are considered as the gold-standard for the estimation of the knee kinematics, this is not the case for what concerns the ligament insertion identification. The above-mentioned procedure, in fact, apart from being time consuming, is affected by uncertainties due to difficulties for the surgeon to accurately palpate the ligament attachment sites without performing a complete dissection, particularly those of the medial and lateral collateral ligaments and of the PCL on the tibia. In the second study [5], a virtual palpation procedure was carried out to identify the ligament insertions on generic digital bone models. Subject-specific insertion locations were then estimated by matching the generic models to low-dose stereoradiography images of knee specimens. However, the accuracy of the ligament insertion identification was not assessed and no bundle separation was performed for the ACL, PCL and MCL. Moreover, none of these studies provided information about the insertion locations of the popliteal complex as well as about its end-to-end distance variation during knee flexion.

In the light of the above-mentioned considerations, the aim of the present study is to propose an original and robust technique to identify the knee ligaments and popliteal complex attachment sites and to describe how the end-to-end distance of these structures vary over passive knee flexion–extension movement.

2. Methods

2.1. Specimens

Twelve fresh frozen lower limbs were used in this study, six left and six right knees harvested from subjects aged between 47 and 79 years. Each specimen included entire femur with femoral head, patella, fibula and tibia without the ankle. Absence of trauma was checked and integrity of cartilage, meniscus and ligaments was inspected at the end of the experimentation during specimen dissection. Limbs were thawed at room temperature for 24 h. Skin and muscles, except eight centimetres of quadriceps tendon and popliteus muscle, were removed before the study. Nine tantalum balls were placed into the metaphysis of each bone, three into the tibia, three into the femur and three into the patella.

2.2. Kinematic data acquisition

The specimens were set in motion using a device described and validated in previous literature [3] (Figure 1). The femur was rigidly fixed to a rig and the tibia was free to move (Figure 1). As no constraints have to be applied to coupled movements between the femur and the tibia, the device was slightly modified to allow free varus/valgus movements and a flexion–extension range of movement of 0°–120°. A motor was connected to the tibial pilon by a rope and was used to pull the rope thus allowing the flexion–extension movement. A 10 N force was applied to the quadriceps tendon *via* a pulley hung in order to guide the patella. The direction of this force was as parallel as possible to the tendon itself. Clusters made of three retro-reflective markers each were screwed in the femur, the tibia and the patella (Figure 1). As different alignments between the femur and tibia could affect both the knee axial rotation and varus–valgus kinematics, special attention was paid

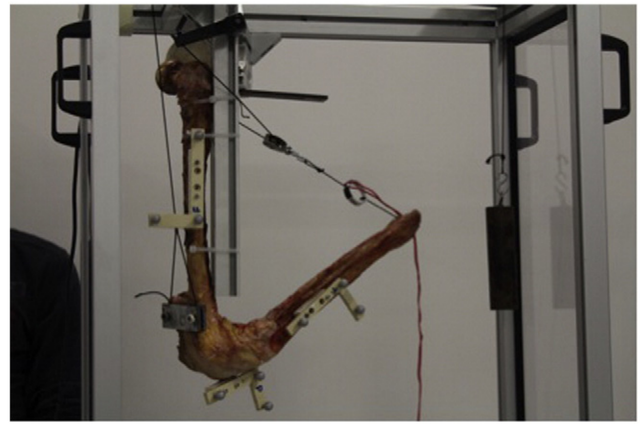

Figure 1. View of the device used to set in motion the knee specimens. The clusters of markers fixed to the femur, tibia and patella bones are also depicted.

to the correct alignment of the bones when mounting the specimens on the rig. The position and orientation of each cluster of markers were registered with an optoelectronic system previously used in motion analysis (Polaris, Northern Digital Inc., Canada, sampling frequency = 60 samples/s) [7].

To obtain the three-dimensional (3D) tibio-femoral and patello-femoral kinematics, anatomical frames associated with each bone were defined. To this aim, two orthogonal digital radiographs of each knee specimen were simultaneously acquired using a low dosage X-ray system (EOS, EOS-imaging, France) and 3D digital models of the femur and tibia, with fibula and patella, were obtained through a reconstruction algorithm described in a previous study [5]. Femoral, tibial and patellar anatomical frames were defined following the indications reported by Schlatterer et al. [37]. The tantalum balls pierced in each bone, as well as the markers of each cluster, were also identified and the 3D coordinates of the centroid of each ball and marker with respect to the EOS system of reference were obtained. Technical frames associated with the marker clusters were defined allowing acquisition of a mathematical relation between anatomical and technical frames expected to be invariant due to the rigid body assumption. The bone models and the relevant anatomical axes were then registered with respect to the movement data obtained in the optoelectronic system of reference. The 3D kinematics of the tibio-femoral joint was estimated from the instantaneous position of the clusters of markers and flexion/extension, adduction/abduction and internal/external rotation angles were obtained using the Cardan convention and the sequence “ZXY”. For each specimen and each angle, a similarity analysis was performed to investigate if significant differences existed in the kinematics obtained during the different cycles. To this aim, the Spearman correlation coefficient was calculated using IBM SPSS Statistics (IBM Corp., Armonk, NY, USA).

The kinematic variability during the six flexion–extension cycles was less than one degree and one millimetre with a high Spearman correlation ($r = 0.98$, $p < 0.001$ for each knee). Therefore, as no significant hysteresis was present among the cycles, the average curve was considered as representative of the individual kinematics of each specimen. This confirmed the good reliability of the tested rig, which was previously reported by Azmy et al. for the patello-femoral joint [3], as well as the proper alignment of the bony segment during the kinematic acquisitions.

2.3. Ligament attachment site identification and registration

After kinematic data acquisition, knee specimens were fully dissected, according to anatomical references previously published [12,13,22,38] in order to identify and mark ligaments/tendon origins and insertions using radio opaque paint composed of barium sulphate (Figure 2). The following structures were taken into account: ACL, PCL,