Estimation of knee ligaments loads using the modelling approach applied on in-vivo accurate kinematics and morphology of a young subject

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Abstract

The knee joint is a key structure of the human locomotor system. Any lesion or pathology compromising its mobility and stability alters its function. As direct measurements of the contribution of each anatomical structure to the joint function are not viable, modelling techniques must be applied. The present study is aimed at evaluating the importance of anatomical twist in the determination of mechanical stabilising action of the cruciate ligaments during the execution of a daily living activity. For this purpose accurate parameters from nuclear magnetic resonance and 3D-fluoroscopy of a single selected subject during chair rising-sitting motor task were used. The modelling of the twist of fibres was fundamental in the determination of the specific behaviour of the posterior cruciate ligament in particular.
Keywords: knee model, ligaments, mechanical simulation, 3D fluoroscopy, magnetic resonance.

1 Introduction

The knee plays a fundamental role in determining the human locomotor ability. Any alteration of its anatomical structures can compromise its function. The development of effective methods for surgical reconstruction and rehabilitation is of great clinical interest, regarding both joint replacement and surgical reconstruction of the main anatomical structures. This interest is demonstrated by the 259000 total knee replacements, 25000 ligaments reconstructions and 15000 other repairs of the knee performed in the USA in 1997 as reported by the American Association of Orthopaedic Surgeons (AAOS). For the development of these procedures, an accurate knowledge of the mobility and stability of the whole articular structure, as well as of its different anatomical sub-units, is necessary. The need for this deeper knowledge led to a bulk of in-vitro and in-vivo studies, which allowed one to clarify several aspects of the physiological behaviour of this complex joint. In-vitro testing allows to directly observe and measure different aspects of joint mechanics, but not in physiological conditions. During its normal function, the knee lets the shank move with respect to the thigh, maintaining the stability of the structure under articular load. These are the result of several contributions: the inter-segmental contact load, ligament tensioning, loads applied by the muscles, the inertia of body segments. All these contributions are strongly dependent on the analysed motor task, as well as on the physical characteristics of the subject. Thus, if we want to quantify the contribution of each anatomical structure in determining the physiological function of the knee, modelling is the only possible solution, as direct measurements cannot be performed without altering the mechanical structure of the joint.

The problem of knee modelling has been approached at different levels of complexity. Two-dimensional models were designed in order to investigate the role of the cruciate ligaments in simple conditions, such as isometric quadriceps contraction [1,2]. Three-dimensional models, including articular surfaces and ligaments, were also proposed. Even these more complex models were applied in conditions far away from those of the physiological knee [3-6]. The natural evolution of this approach is inserting the model into a context which allows to evaluate the boundary conditions of the knee-structure during the performance of a simple task of daily living [7]. Even if the model is designed properly for the application devised, its potentials can be nullified by the effect of errors within the definition of subject parameters and during the acquisition of experimental inputs. In previous modelling attempts, these errors were due to discrepancies in the source of parameters and inputs, which were often obtained from different and non-homogeneous subjects.

In order to avoid this possible source of error, six different cruciate ligament models were compared by these authors, using parameters from a single selected subject analysed as accurately as possible. Plane, rectangular and circular sections were considered, and the mechanical effect of the anatomical twisting of the ligament fibres was also investigated [8].

The strain range of the modelled fibres was not relevantly influenced by the model adopted, which resulted to influence the geometrical distribution of the strain over the fibres in the section of the ligament.

The more conventional bi-dimensional model [9] showed the largest differences from the two three-dimensional ones. No significant difference could be highlighted between the rectangular insertion and the circular insertion three-dimensional models.

The twist showed significant influence in the strain distribution for each model.

In conclusion, when only the magnitude of the fibres elongation is to be calculated the selected model does not considerably affect the results. Instead, the model should be accurately selected when the geometrical distribution of the strain over the section of the ligament is required, i.e. when the strain is used for the calculation of the load applied to the joint by the ligament [10]. In this case, a three-dimensional model is suggested, independently from the selected insertion shape, and the anatomical twist of the fibres has to be taken into account, as it strongly influences the strain distribution over the section.

The purpose of the present work was to develop a three-dimensional model of the knee cruciate ligaments, which could show the importance of the anatomical fibres twist in the determination of the mechanical stabilising action of the ligaments, during the execution of a daily living activity, in particular of chair-rising/sitting. For this purpose, the specific geometry of articular surfaces and ligaments insertions were reconstructed using the three-dimensional reconstruction of segmented bone and soft tissues, obtained from Nuclear Magnetic Resonance (NMR). The specific accurate kinematics was obtained from cine-fluoroscopic images of a chair rising-sitting motor task. The aim was to quantify the differences in terms of load and strain distribution between the twisted and untwisted configurations.

2 Material and methods

2.1 Overview

A subject-specific model of the right knee of a young male subject (height 168 cm, weight 62 kg, and age 30 years) was developed from a high resolution NMR data set. Three-dimensional outer surfaces of the biological structures of interest were generated.

The subject performed chair rising-sitting with the knee under analysis inside the fluoroscopic field of view. The accurate 3D pose of the bones was reconstructed by means of single-plane lateral 2D fluoroscopic projections and relevant models previously obtained.

Each cruciate ligament was modelled with 25 linear-elastic elements joining the insertion points mapped on the tibial and femoral insertion areas. Two different fibres connection models were analysed: twisted and untwisted.

2.2 The NMR data set

A data set of high resolution NMR images was collected with a 1.5T Gemsow scanner (GE Medical Systems, Milwaukee, Wisconsin). Details of the scanning parameters are shown in Table 1.

Table 1: The NMR scanning procedure parameters.

Scanning sequence	Spin Echo (T1 weighted)
Number of slices	54
Pixel spacing	0.037x0.037 (cm·cm)
Scanned region length (across the knee)	15.9 (cm)
Slice thickness	2.5 (mm)
Slice spacing	3 (mm)

2.3 The segmentation procedure

A 3D tiled surface geometrical representation was generated using the software Amira (Indeed - Visual Concepts GmbH, Berlin, Germany), for the distal femur, the proximal tibia, and the insertion areas of the anterior (ACL) and posterior (PCL) cruciate ligaments.

A segmentation of the NMR data set was performed with an entirely manual 2D segmentation technique. For each slice, the outer contour of the structures of interest was detected and outlined, as shown in Figure 1. The resulting stacks of contours were interpolated to generate polygonal surfaces which represent the outer boundary of the objects to be modelled. The model used for the kinematic analysis is shown in Figure 2.

Figure 1: Outlined contours of femur and ligaments in a slice of the NMR data set.

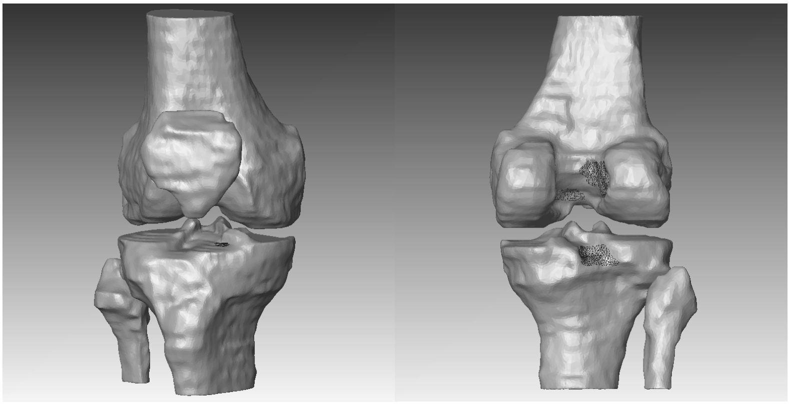

Figure 2: Anterior and posterior view of the complete knee model. The areas of insertion of ligaments are the dotted regions on the femur and the tibia.

2.4 Kinematics

Series of lateral images were acquired at the frequency of 6 samples per second with a standard fluoroscope (SBS 1600, Philips Medical System Nederland B.V.). Images of a 3D cage of Plexiglas with 18 tantalum balls in known positions and of a rectangular grid of tin-leaded alloy balls 5 mm apart were collected in order to calculate respectively the position of the camera focus and the parameters necessary for image distortion correction. This was obtained using a global spatial warping technique [11]. An established technique for 3D kinematics analysis of a known object from a single view was implemented [12] (Figure 3). Bone poses in space were obtained from each fluoroscopic image by an iterative procedure using a technique based on tangent condition between projection lines and model surface. Previous validation work on prosthesis components [12] showed that relative pose can be estimated with an accuracy better than 1.5 degrees and 1.5 mm.

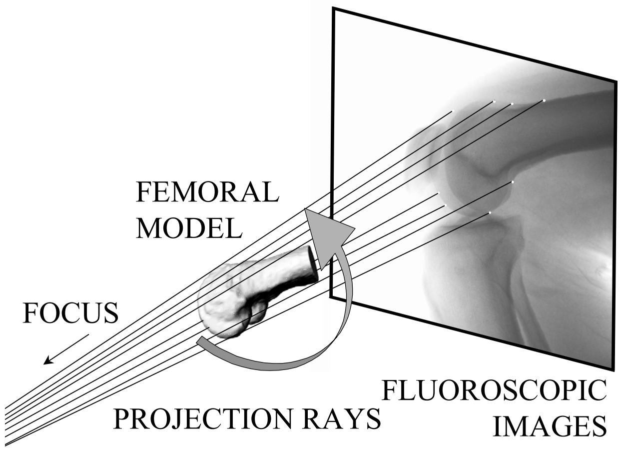

Figure 3: Sketch of the model for fluoroscopic image generation process.

2.5 Cruciate ligament geometrical models

The two geometrical models of the cruciate ligaments were both three-dimensional and exploited the same bone-fitting elliptical mapping, but one (Untwisted) did not take into account the anatomical twisting which can be observed in the geometrical distribution of ligament fibres, while the other (Twisted) did (Figure 4).

Both for the Untwisted and Twisted model the insertion points for the modelled fibres were defined through a bone-fitting three-dimensional elliptical mapping.

The contour of each insertion area was projected on the relevant bone embedded transverse plane. This contour was approximated in the least squares sense with an ellipse. The points on the insertion areas were selected uniformly mapping 25 points on the relevant elliptical area. Finally, these points were mapped on the relevant bony surface which were then fitted on the anatomical insertion area from NMR using thin-plate splines [13] (Figure 5).

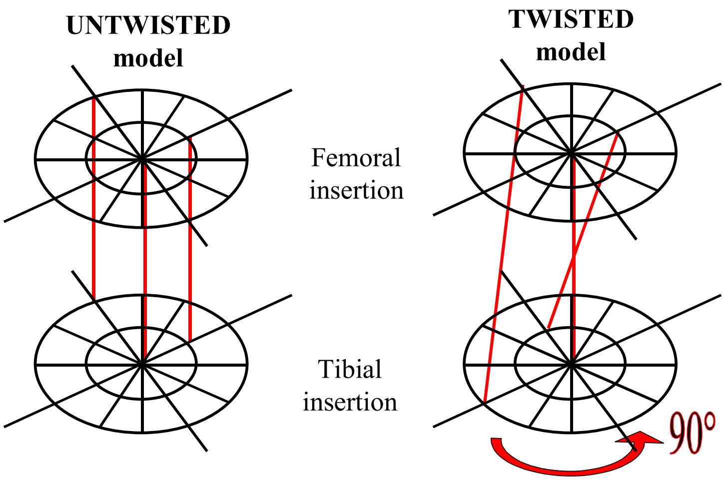

Figure 4: Sketch of how the anatomical torsion of the fibres is modelled.

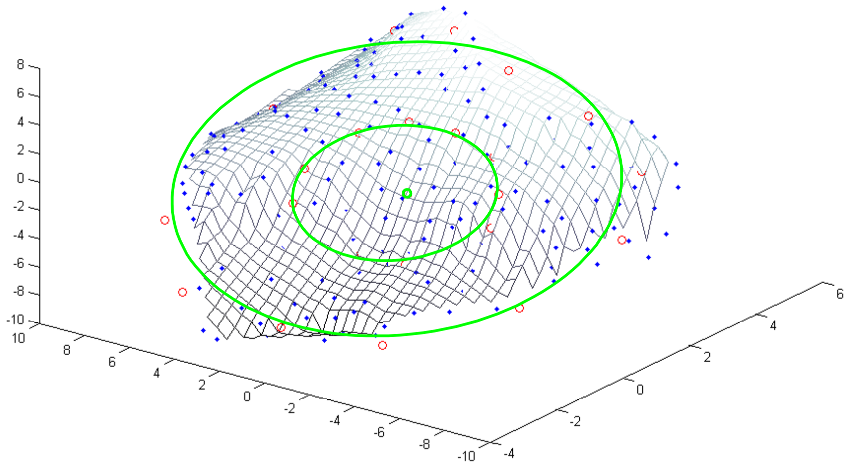

Figure 5: Sketch of the elliptically mapped points (continuous ellipse) fitted onto the bone articular surface by means of thin-plate splines (circles).

For each model, for each single fibre, the strain, ε, was calculated as follows:

$$\varepsilon(t) = \frac{L(t) - L_0}{L_0} \quad (1)$$

were L is the length of the fibre at time sample t, and L_0 is the reference length of the fibre. The elastic modulus and the reference length of each ligament was considered constant from literature [10].
The stiffness coefficient K_j was calculated for each linear element j with the equation (2):

$$K_j = \frac{E \cdot A_j}{L_0} \quad (2)$$

where E and L_0 are elastic modulus and reference length of the cruciate ligament, respectively, and A_j is the relative area of each fibre. The simulation of this mechanical system was performed with ADAMS/View (*MSC.Software Corporation 2 MacArthur Place Santa Ana,CA 92707 USA*).

3 Results

The global behaviour of the ACL was quite similar for the Twisted and Untwisted models (Figure 6). In the antero-posterior direction the ACL was always tight, developing tension, and exerted its maximum force around 40° of flexion, providing stability. In the tibial longitunal and medio-lateral directions the ACL was slack in extension and became tighter with flexion. Antero-medial fibres of the modelled ACL became tighter with flexion, while the latero-posterior ones with extension.

Forces in the PCL were very different in the Twisted and Untwisted conditions only along the antero-posterior direction. Actually, increasing flexion the Untwisted PCL model developed more stress along the antero-posterior direction, while the Twisted PCL was less effective during flexion. No relevant differences in the developed force could be observed in the medio-lateral and tibial longitudinal directions. Regarding the strain distribution on the cross-section area, the strain of the antero-medial and latero-posterior fibres in the Untwisted PCL model was very similar to that of the medio-posterior and antero-lateral ones in the Twisted PCL model, respectively.

4 Discussion

The proposed model was effective in evaluating strain and loads in the ACL and PCL. The results agreed with physiology, although the linearity of the mechanical parameters, during the execution of daily living activities.

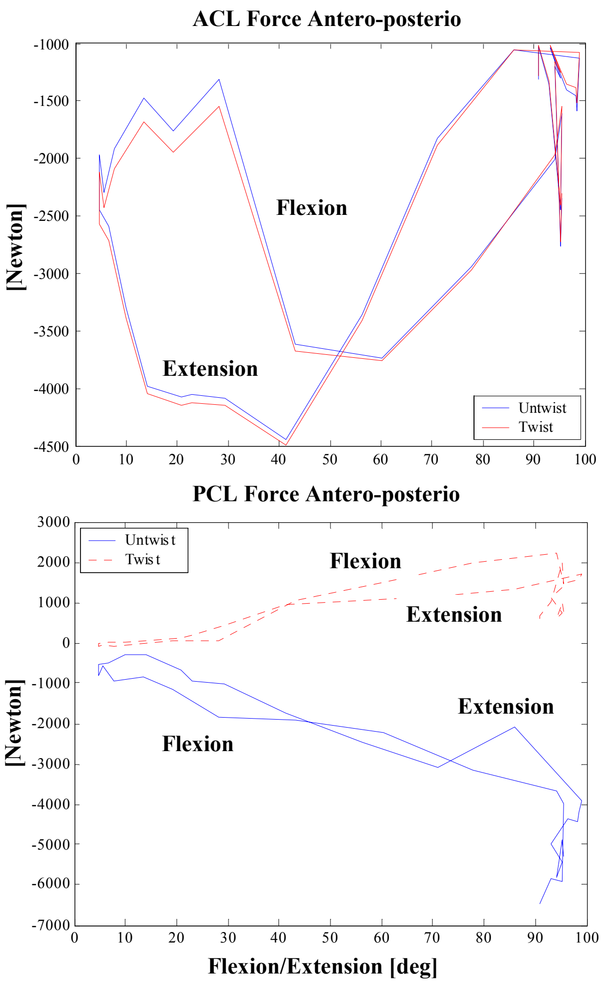

Figure 6: Antero-posterior force in the ACL and the PCL versus flexion-extension during chair rising-sitting in the Twisted (red-dotted) and Untwisted (blue-solid) models.

The modelling approach pointed out the importance of the geometrical configuration of the ligament fibres in term of twist. The anatomical twist must be modelled in order to replicate, in particular for the PCL, the specific mechanical action developed by the ligament for the stabilization of the knee joint during the execution of daily living activities.

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