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TECHNICAL NOTE

EXPERIMENTAL AND MATHEMATICAL METHODS FOR REPRESENTING RELATIVE SURFACE ELONGATION OF THE ACL

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Abstract—The common approach to assess the stabilizing role of the ACL in the knee has been to measure the elongation of a few marked fibers in the ligament. A comparison of the relative elongation (RE) of these marked fibers between different specimens and studies is delicate due to the difficulty of marking the same fibers. More consistent comparisons would be achieved if the RE of the whole ligament surface was presented.

Hence, we developed a mathematical method leading to a continuous description of the relative elongation of the ligament's surface based on experimental measurements of the RE of five fibers. The ligament fibers of two knee specimens were marked by radiopaque markers and a Roentgen Stereophotogrammetric Analysis system was used to reconstruct the three-dimensional positions of these artificial landmarks. The mathematical procedure used isoparametric cubic splines to interpolate the contours of the insertion sites.

The results showed that the general pattern of the RE for both specimens was similar, characterized by an undulation near full flexion. In fact, close to full flexion all the RE of the fibers increased. Such a representation describes the changes in the RE for a given fiber during knee flexion and at the same time characterizes the RE distribution at a given flexion angle.

Keywords: Ligament; ACL; Elongation; Strain.

INTRODUCTION

A common approach to understanding the role of ligaments in the stability of arthrodial joints consists of measuring the relative motion of their insertion sites during passive extension of the joint. This allows estimation of the different kinds of deformations in the ligament. The interpretation of these deformations is better achieved if ligament fibers are defined and their evolution described during the passive extension of the joint.

Previous experimental studies (Amis and Dawkins, 1991; Blankevoort et al., 1991; Hefzy and Grood, 1986) showed that the elongation of ligament fibers was not homogeneous but depended on their location in the insertion zones, therefore restricting the comparison between studies (Hefzy and Grood, 1986; Sidles et al., 1988). Hence, if the relative elongation of the whole ligament surface could be presented, using a unifying approach, results between specimens or studies could be more reliably compared. Moreover, representing the relative elongation over the ligament surface concisely characterizes the deformation of the ligament.

The objective of this study was thus to provide a continuous description of the relative elongation (RE) of the ligament's surface, based on an extrapolation of the measure made on particular fibers. More specifically we focused on a global representation of the surface relative length change in the ACL.

MATERIAL AND METHODS

The present study was performed in two steps. First, we obtained data by *in situ* experimentation, and secondly we processed the data with a mathematical procedure.

Two intact fresh frozen postmortem knees (female, ages: 63 and 76) were mounted in a device which allowed knee flexion angles and internal–external tibia axial rotational torques to be prescribed (Heegaard et al., 1994). Six radiopaque markers were inserted in both the femur and the tibia. A Roentgen Stereophotogrammetric Analysis system (Selvik, 1974) was used to reconstruct the three-dimensional positions of these artificial landmarks with an accuracy of 0.01 mm. The knees were flexed from full extension to 150° of knee flexion in 15° increments. The kinematics of the tibia were determined using constrained optimization (Veldpaus et al., 1988). The knees were then dissected in order to reach the insertion sites of the ACL. Five fibers were identified and then marked at their femoral and tibial insertions with additional radiopaque markers. An additional Roentgenogram allowed for completely determining the relative position of these new markers with respect to the previous markers in the femur and the tibia. It was estimated that the markers could be placed within 0.5 mm from the center of the identified insertion fibers. In the present study, the length of a fiber was defined as the length of the straight line joining its femoral and tibial insertions (Hefzy and Grood, 1986; Hollis and Woo, 1993; Sidles et al., 1988).

The five pellets of each insertion site were then used to interpolate the insertion contours using cubic splines. This ensures affine invariance of the interpolated contour (Farin, 1990). From this interpolation, we obtained the arc length on the femur s_F and the one on the tibia s_T. The arc length of the contour between the position of the first pellet on the tibia x_T^1 and the i th pellet x_T^i (respectively from x_F^1 to x_F^i for the femur)

was given by s_T^i for the tibia and s_F^i for the femur ($i = 1, 5$). A correspondence had to be established between tibial insertion points of any surface ligament fibers and its femoral counterpart. To this end, the arc length between two consecutive pellets on the tibia and their counterpart on the femur were isoparametrized by an identical value of a parameter α:

$$\frac{S_F - S_F^i}{S_F^{i+1} - S_F^i} = \frac{\alpha - \alpha^i}{\alpha^{i+1} - \alpha^i} = \frac{S_T - S_T^i}{S_T^{i+1} - S_T^i}, \tag{1}$$

where $i = 1, 5$ and $\alpha^1 = 0.0$, $\alpha^2 = 0.2$, $\alpha^3 = 0.4$, $\alpha^4 = 0.6$, $\alpha^5 = 0.8$ and $\alpha^6 = 1$. Therefore, each entire insertion contour (femur and tibia) was obtained when α covered the unit interval $[0,1]$.

Given a value for the arc length parameter α between 0 and 1, a fiber insertion was determined on the two contours. For the femur,

$$S_F = \left(\frac{\alpha - \alpha^i}{\alpha^{i+1} - \alpha^i}\right)\left(S_F^{i+1} - S_F^i\right) + S_F^i. \tag{2}$$

An analogous relation was obtained for s_T. These relations ensured that, for any given value of the parameter α, the corresponding points on the tibial and femoral ACL insertion contours defined a fiber. Hence any fiber of the surface ligament was characterized by a unique value of the parameter α leading to a continuous description of the ligament's surface.

The actual length of any fiber defined by α at the knee flexion ϕ was denoted by $L(\phi, \alpha)$. As there is no way of knowing the rest position of each fiber α, the reference length $L_0(\phi_0, \alpha)$ was defined at knee flexion angle ϕ_0, corresponding to full extension of the joint. The relative elongation of any fiber α at knee flexion ϕ could be now expressed by the formula

$$RE(\phi, \alpha) = \frac{L(\phi, \alpha)}{L_0(\phi_0, \alpha)}. \tag{3}$$

The positions of the insertion tibial pellets were identified by CT-scan measurements and used to establish an anatomical classification of the surface fibers which were grouped in four classes according to their position in the tibial insertion, namely anterolateral, anteromedial, posteromedial and posterolateral (Fig. 1). Arbitrarily we chose α^1 as the fiber located at the junction of the anterolateral and anteromedial quadrants.
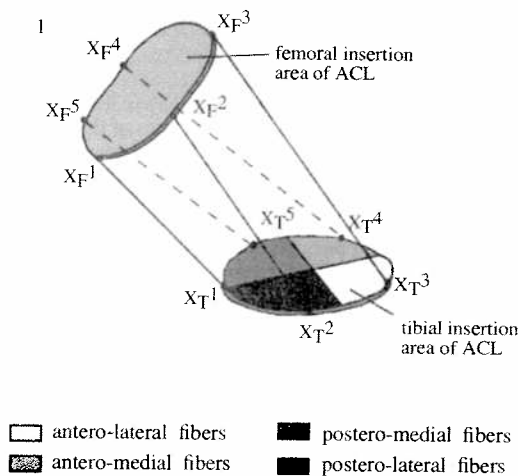

Fig. 1. Description of the isoparametrization. Five pellets were used to mark each insertion site contour (X_F^i: Femur; X_T^i: Tibia) and then interpolated by cubic splines. The arc lengths of these two interpolated contours were characterized with a unique parameter α. Surface fibers were grouped in four anatomical classes according to their position in the tibial insertion, namely anterolateral, anteromedial, posteromedial and posterolateral.

RESULTS

The general pattern of the RE for both specimens (Figs 2 and 3) was similar. The RE of all the surface fibers of specimen 1 was relatively constant during the first $10°$ of flexion (Fig. 2). From 10 to $120°$, the RE of lateral fibers decreased, while it remained constant up to $60°$ for the medial ones. At the end of the flexion, the posterior fibers shortened while the anterior ones were elongated. The anteromedial fibers were the most elongated. This is further shown by the undulating shape on the $RE(\phi, \alpha)$ surface (Fig. 2). Close to full flexion, all the RE of the fibers increased. A comparison between the three kinds of knee rotations (neutral, external and internal) showed that the ACL RE was greater for the knee in neutral position than under external rotation, but smaller than the RE under internal rotation.

DISCUSSION

In order to provide a comprehensive representation of the ACL elongation behavior, we proposed a method to describe the relative elongation of the ligament's surface. This method, based on the elongation measurements of five fibers of the ACL, used an isoparametrization of the tibial and femoral insertion sites.

Since the arc lengths on the femoral and tibial insertion were different, isoparametrization was equivalent to assuming that the fiber density per unit of arc length was the same on the femur and on the tibia. In other words, we assumed a one-to-one correspondence between fibers on the surface of the tibial insertion and on the femur insertion, meaning that the surface fibers did not penetrate inside the ligament or that there was no branching or coalescence of fibers. This fact was macroscopically observed in our dissections. However, it is important to note that these surface relative elongations provided only an interpolation of the real ligament elongation. Obviously, the greater the number fibers marked, the more representative the interpolation.

In this study we assumed that the length of a fiber was equal to the length of the straight line joining its femoral and tibial insertion sites, and that the RE of this fiber was defined by the ratio between its actual and reference (full extension of the knee joint) length. Two main assumptions were therefore made. First, the choice of each ACL fiber reference length was arbitrary because it was not possible to determine its rest position. However, the choice of the reference length enabled a qualitative comparison of the behavior of the fibers during elongation. If the rest length of each fiber could be determined, it would be possible to implement them in our procedure by adjusting the value of L_0 in equation (3). The second important assumption, which has been widely used in the literature (Hefzy and Grood, 1986; Hollis and Woo, 1993; Sidles et al., 1988), was to consider the length of the fibers as the straight lines joining the femoral and tibial insertion sites. This definition did not take into account the possible wrapping of the ACL around the PCL and the waviness of the fibers. It follows that the length of the actual and reference fibers could be both underestimated. However, given that the RE was defined as the ratio between these two lengths, the resulting error on the RE was less affected by this underestimation.

It appeared that the RE was constant for angles of flexion between 0 and $10°$ and that the RE of the posterior fibers decreased further during knee flexion. It could thus be inferred that during early flexion, only the posterior fibers were recruited. On the contrary, the RE of the anterior fibers increased at the end of knee flexion, suggesting that these fibers were recruited at larger angles of flexion. This was also observed in previous studies (Blankevoort et al., 1991; Van Dijk, 1983).

However, as has already been noted (Hefzy and Grood, 1986; Sidles et al., 1988), comparisons between studies are difficult because of different choices of marked fibers. In fact, even the

2(a)

☐ antero-lateral fibers   ■ postero-medial fibers
▨ antero-medial fibers   ■ postero-lateral fibers

2(b)

☐ antero-lateral fibers   ■ postero-medial fibers
▨ antero-medial fibers   ■ postero-lateral fibers

2(c)

☐ antero-lateral fibers   ■ postero-medial fibers
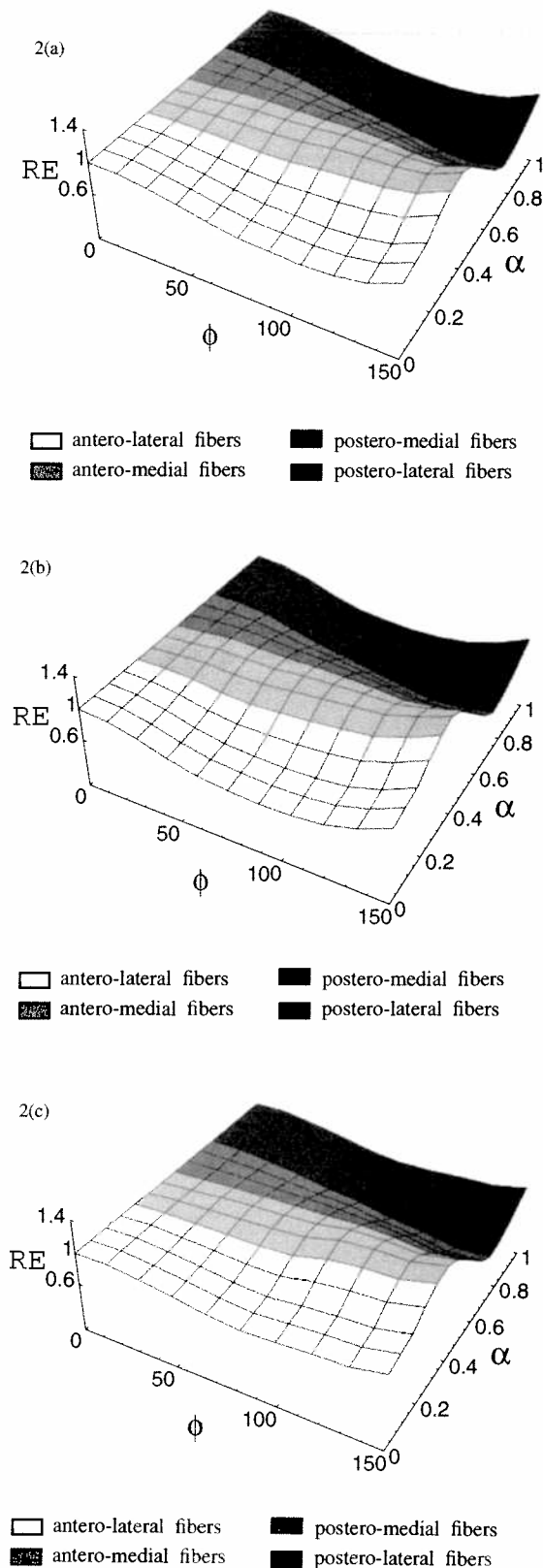▨ antero-medial fibers   ■ postero-lateral fibers

Fig. 2. Relative elongation of the ACL surface for the knee specimen 1: (a) neutral rotation; (b) external rotation; (c) internal rotation. RE is represented as a function of the flexion angle of the knee (ϕ) and of circumferential location in the ACL tibial insertion (α) .

3

☐ antero-lateral fibers   ■ postero-medial fibers
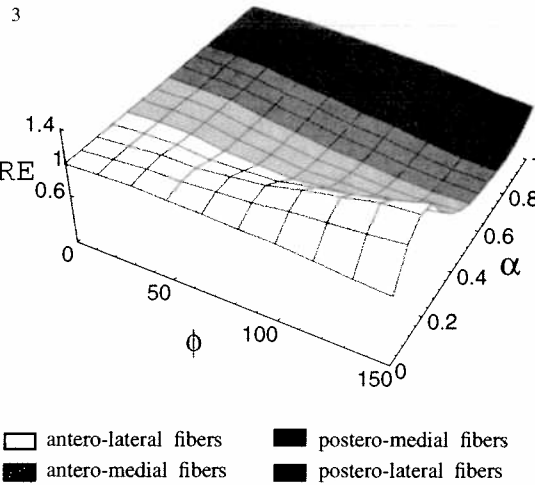▨ antero-medial fibers   ■ postero-lateral fibers

Fig. 3. Relative elongation of the ACL surface for the knee specimen 2 in neutral rotation. RE is represented as a function of the flexion angle of the knee (ϕ) and of circumferential location in the ACL tibial insertion (α) .

comparison between specimens is questionable due to the difficulty of marking the same fibers. In this study, this difficulty reduced to the determination of α^1 corresponding to the more recognizable fiber located at the junction of the anterolateral and anteromedial quadrants. Having interpolated the contour of the insertion sites and given the RE of the whole surface, we could compare globally the RE of the ligament's surface or we could study specific fibers on different specimens. This leads to a more convenient exploitation of the results.

The RE patterns of the two specimens were similar. Some differences existed between corresponding parts of the ligament surface, which could be attributed to interspecimen variations (Hefzy and Grood, 1986).

The surface ACL RE had a particular pattern marked by an undulation near full flexion. For the first knee this undulation was located in the medial fibers while for the second one it was located in the lateral fibers. This suggests that the distinction between fibers must simultaneously take into account the mediolateral and the anteroposterior orientation. In fact, the fibers' separation in four groups tended to be insufficient due to the fibers' behavior differences within each group.

This study gave a kinematic description of the ligament's surface elongation. A future extension will be the estimation of the rest length of fibers as in Blankevoort et al. (1991), in order to estimate the surface strain and the stress of the ligament. It would also be interesting to determine the internal RE of the ligament. This could be achieved by digitizing the insertion position of internal fibers with a method similar to that of Sidles et al. (1988). Finally the application of this method to a greater number of specimens could enable us to verify if certain invariants of the RE—such as the undulation at the end of the flexion—could be observed systematically.

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