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Analytical study on the kinematic and dynamic behaviours of tibiofemoral joint

H.Q. Guo, Z.K. Ling, E. Lumsdaine
Department of Mechanical Engineering and Engineering Mechanics, Michigan Technological University, Houghton, MI 49931, USA

Abstract

The focus of this study is to simulate the kinematic and dynamic behaviors of a two dimensional tibiofemoral joint with a quasi-static and a dynamic model. Parameters of interest include the joint surface contact point, ligament forces, and slide/roll ratio between the femur and tibia. Model results are compared to experimental cadaver studies available in literature. Furthermore, the effect of femur surface geometry on the above mentioned characteristics is also determined. The pattern of ligament forces from the analytical study matches well qualitatively with the experimental study. Change of femur surface geometry has little effect on the pattern of slide/roll ratio.

1 Introduction

Knee is the largest and most complicated joint in a human body. Statistics show that over two million cases of knee injury occur in the United Sates each year. A well-defined analytical knee model can provide the prevention procedures to avoid these injuries. Furthermore, a well developed analytical model can also be used to determine the effects of system variables on the performance of the knee joint efficiently, and to guide experimental and clinical investigations.

Analytical knee joint models have generally adapted a four bar linkage methodology by grounding either the tibia or femur, Bradley, et al. [1]. The two cruciates are assumed rigid links, with neutral ligament fibers staying a constant length with flexion-extension. Other studies have adapted a quasi-static approach. They include Crowninshield et al. [2], Wismans et al. [3], Blankevoort et al. [4] and others. Quasi-static models resolve the short coming of the four bar linkage model by allowing the cruciate ligaments to change their length. Yet, they still can not take into account the role of inertia on the behaviors of a knee. Development of a dynamic model has been presented by follows: Moeinzadeh, et al. [5], Wongchaisuwat et al. [6], and Abdel-Rahman and Hefzy [7]. It is found that there is not any study which provides a quantitative analysis of instant centers and slide/roll ratio. Yet, instant centers and slide/roll ratio can be used effectively to distinguish a normal knee from an abnormal one. Furthermore, the effect of inertia on the kinematic and dynamic behaviors of a knee is also of an interest.

2 Analytical Model

Because the fibula does not contact at the articulating surface of the tibiofemoral joint, its effects are ignored. Both the femur and tibia sagittal plane contours are acquired using radiographs of a female cadaver. The radiographs are digitized with a meter stick to provide a magnification factor. It is found that using a fourth order polynomial or a circular arc to describe the entire femur surface, is not sufficient. So,the profile of the femur is described with two segments. The anterior part is a 4th order polynomial, and the posterior part is modeled with a circular arc. A second order tibia polynomial is also generated.

2.1 Model Establishment

Figure 1 illustrates the knee model set-up. Four major ligaments are represented: the medial collateral (MCL), lateral collateral (LCL), anterior cruciate (ACL), which is represented by the anterior and posterior bundles, and posterior cruciate (PCL), which is also represented by the anterior and posterior bundles. Their 2-dimensional insertion and origin points are transformed from 3-dimensional data provided in a previous publication (Crowninshield, et al., [2]).

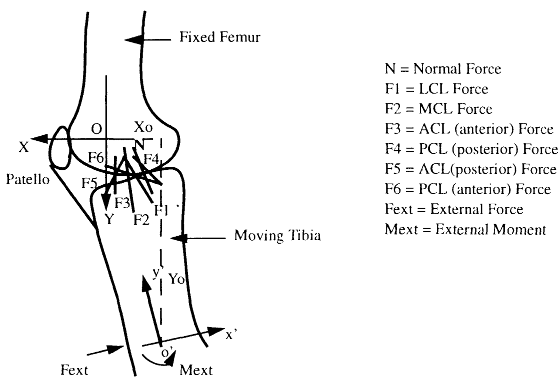

Figure 1. 2-D Knee Model in the Sagittal Plane

Two constraint equations exist for both models. First, the tibia surface must always stay in contact with the femur surface at one point, as shown:

$$\begin{bmatrix} femxc \\ femyc \end{bmatrix} - \begin{bmatrix} x_0 \\ y_0 \end{bmatrix} - \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} tibxc \\ tibyc \end{bmatrix} = 0 \tag{1}$$

The second constraint requires colinearity of the unit normals at the respective contact points on both the femur and tibia. This can be represented by the zero cross product of the two normals as shown below:

$$\sin\alpha \left[1 + \left(\frac{df_1}{dx} \right)_{x = fc} \cdot \left(\frac{df_2}{dx'} \right)_{x' = tc} \right] - \cos\alpha \left[\left(\frac{df_1}{dx} \right)_{x = fc} - \left(\frac{df_2}{dx'} \right)_{x' = tc} \right] = 0 \tag{2}$$

In this study, the ligament is modeled as nonlinear spring. The magnitude of ligament force is shown as:

$$fmag_j = \begin{matrix} k_j (lnow_j - lstart_j)^2 if (lnow_j \geq lstart_j) \\ 0 if (lnow_j \leq lstart_j) \end{matrix} \tag{3}$$

The ligament stiffnesses, k_j, are taken from the literature (Kennedy, et. al., [8]). $lstart_j$, the taut length of the ligament j, is calculated by multiplying the initial length at full knee extension of the ligament j by its strain ratio [2]. This is shown in following;

$$lstart_j = linitial_j \times \varepsilon_j \tag{4}$$

Besides ligament forces, a force at the contact point exists. Because the synovial fluid present in the knee capsular provides negligible resistance, a zero coefficient of friction is assumed, resulting in only a normal force component. To set the knee in motion, a force is applied in the dynamic model along the x-axis at the tibia mass center, combined with an external moment.

In this study, the tibia mass was estimated at 3.45 kg, the mass for a 50 percentile male. The mass moment of inertia is set to be 392.8 kg cm^2. The tibia is governed by the following three equations of motion.

$$mass \left(\frac{d^2 x}{dt^2} \right) = (F_{ext})_x + \lambda (norm) (\hat{n}_1)_x + \sum_{j=1}^{6} fmag_{jx} \tag{5}$$

$$mass \left(\frac{d^2 y}{dt^2} \right) = (F_{ext})_y + W + \lambda (norm) (\hat{n}_1)_y + \sum_{j=1}^{6} fmag_{jy} \tag{6}$$

$$I_z \left(\frac{d^2 \alpha}{dt^2} \right) = (M_{ext}) + \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} tibxc \\ tibyc \end{bmatrix} \times \lambda (norm) \hat{n}_1 +$$

$$\sum_{j=1}^{6} \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} (x_j')_t \\ (y_j')_t \end{bmatrix} \times [fmag_{jx}\hat{i} + fmag_{jy}\hat{j}] \tag{7}$$

2.2 Numerical Procedures

For the quasi-static model, the Newton-Raphson's method is used to solve for the six nonlinear equations, i.e., equations 5 to 7 with zero acceleration, and equations 1 and 2. For the dynamic model, there are nine equations. Since the nine equations are mix of nonlinear and differential equations, this study uses both the Implict Euler and Newton-Raphsons simultaneously.

The aforementioned two numerical schemes are implemented into the MAPLE [9] package in their symbolic forms, and simulated numerically for the quasi-static and dynamic models.

2.3 Instant Centers and Slide/Roll Ratio

The instant center is determined by constructing two velocity lines at the contact point and the mass center on the moving tibia. The intersection point of the two perpendicular lines is the instant center location.

To calculate the slide/roll ratio, the arc lengths traveled on the surfaces of the tibia and femur are found using numerical integration. The slide/roll ratio is defined as the difference between the larger distance (D) and the smaller distance (d) travelled on the femur and tibia, over the smaller of the two arc lengths traveled (d) as follows:

$$\frac{slide}{roll} = \frac{(D-d)}{d} \tag{8}$$

Pure rolling of the tibia on the femur surface occurs when the distance traveled on the tibia surface equals the distance traveled on the femur surface (D = d), associated with a ratio of zero. Pure sliding of the tibia on the femur occurs when its contact point stays stationary (d=0), while the contact point on the femur travels a distance, associated with an infinity ratio.

3 Results and Discussion

The aforementioned quasi-static and dynamic models are used to simulate knee motion in this study. A constant impulse force with the magnitude of 20 N is applied along the x axis of the tibia with the duration of .1 second for the dynamic model. Furthermore, surface geometry of the femur is varied. The curvature on the femur is reduced twice. The original and the two new profiles are classified as profile 1, 2, and 3. The following kinematic and dynamic characteristics for three profile are observed.

3.1 Contact location between the femur and tibia

In Fig 2, it can be observed that X component of contact point on the femur remains the same for both the quasi-static and the dynamic models and it travels posteriorly with flexion. This is in agreement with the results reported by Moeinzadeh et al. [5], and Abdel-Rahman and Hefzy [7]. Furthermore, as the curvature of the femur surface profile becomes smaller, contact points shift towards the anterior direction. It is also shown that the transition from the first to the second profile of the femur is not perfectly smooth. This is due to the fact that the slope at the connection point of the two profiles is not completely continuous. Rest of the results are also affected by this phenomenon.

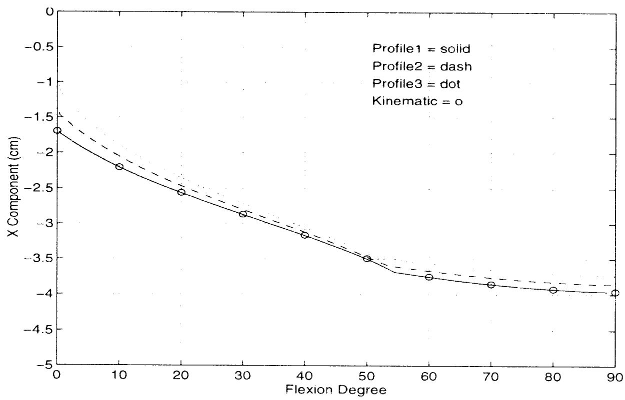

Figure 2. Femur contact point

3.2 Ligament Forces

Ligament forces in both LCL and MCL exhibit maximum magnitudes at the full extension position, which is shown in Figs. 3 and 4. As flexion starts, the ligament forces start to decrease and are faded to zero before the full flexion of 90 degrees is reached. It is found that there is no difference in ligament forces of MCL and LCL by using either the quasi-static or the dynamic model. Furthermore, the ligament forces decrease as the curvatures of the femur surface decrease.

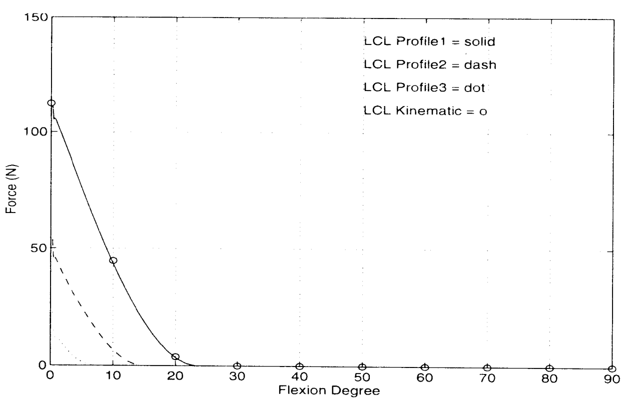

Figure 3. Ligament Force in LCL

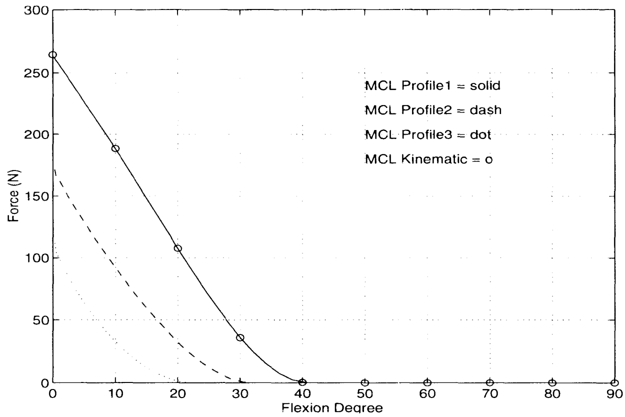

Figure 4. Ligament forces in MCL

While the ligament force of the anterior PCL increases and then decreases with respect to the flexion angle, force in the posterior PCL decreases very rapidly. This is also shown in Fig. 5. It is found that forces in both fibers of the PCL using the dynamic model is larger than those using the quasi-static model. Furthermore, as the curvatures of the femur decrease, the ligament forces in both fibers of the PCL decrease.

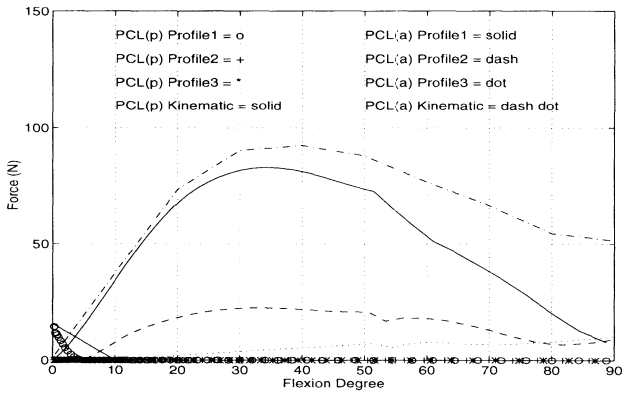

Figure 5. Ligament forces in PCL

While the ligament force of the posterior ACL increases and then decreases with respect to the flexion angle, force in the anterior ACL decreases. This is exactly reversed in comparison to the PCL. It is found that the ligament forces of both fibers of ACL is smaller for the quasi-static model than the dynamic model, which is shown in Fig. 6. Furthermore, as the curvatures of the femur decrease, the ligament forces in both fibers of the ACL decrease.

For the ligament, results from this study qualitatively agree with those found in the experimental studies by France et al. [10].

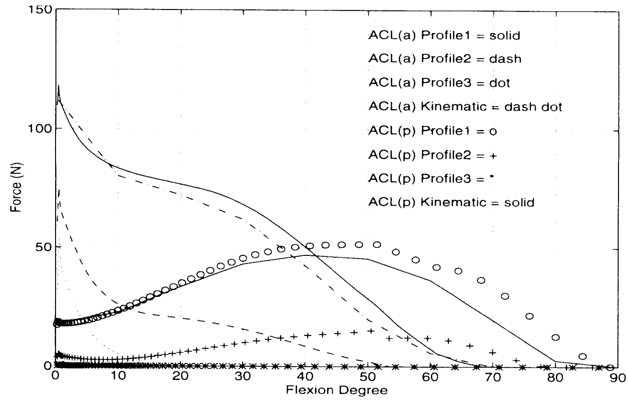

Figure 6. Ligament forces in ACL

3.3 Slide/Roll Ratio and Instant Centers

The slide/roll ratio for the quasi-static, and dynamic models with different surface geometries are illustrated in Fig. 7. From the results, it can be concluded that rolling is dominant at the beginning of flexion, and sliding becomes the dominant factor as the flexion increases. This matched with the conclusion in the literature, such as Steinderler [12]. There is very little difference between slide/roll ratio of the quasi-static and dynamic models. Furthermore, it is also shown that the slide/roll ratio decreases as the curvature of the femur decreases.

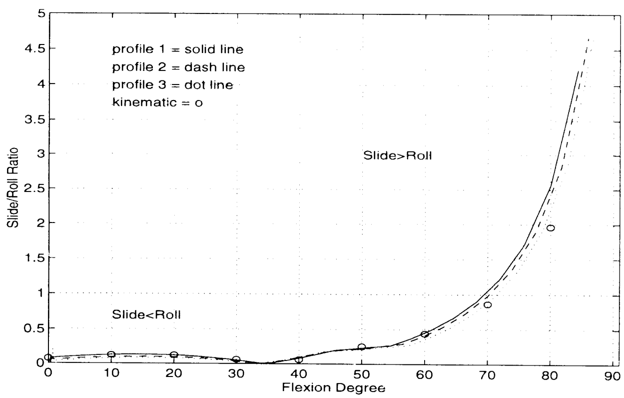

Figure 7. Slide / Roll Ratio

The instantaneous centers obtained from the quasi-static model follow a circular path, beginning at around 20 degrees of flexion anteriorly on the proximal femoral condyle, and ending at 90 degrees posteriorly closer to the joint surface also on the proximal femoral condyle. This is similar to the experimental results by Soudan et al. [11].

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For the dynamic runs, the instantaneous centers shifted to the tibial side, followed a path, beginning anteriorly, and ending posteriorly closer to the joint surface for the flexion using the first profile of the femur. However, the instant centers with the second profile of the femur start on the tibia side, move into the femur side, and end up going back to the tibia side.

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