

A Framework for Patient Specific Inverse Kinematic Analysis of the Anterior/Posterior Cruciate Ligaments

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INTRODUCTION

By in large, total knee arthroplasty (TKA) is universally considered to be a highly successful and cost effective medical procedure for alleviating pain and restoring physical function to individuals suffering from severe knee joint deterioration. This success is supported by the ubiquity of TKA's among the aging population. The American Academy of Orthopaedic Surgeons estimates that around 600,000 TKA procedures are performed annually in the United States [1]. Though TKAs experience relatively successful clinical outcomes, limitations are indeed prevalent. In a National Institutes of Health (NIH) consensus and state-of-science statement it was concluded that revision surgery is required in approximately 10% of TKA recipients at 10 years post-surgery and approximately 20% at 20 years [1]. Therefore, a considerable financial effort, on the order of billions of dollars annually [1], is currently being invested by implant companies, the orthopaedic community, and the federal government into research for improving TKA design and reducing implant failure.

Numerous investigations have been conducted to determine the sources of failure and survivorship of knee implants [2-5]. However, it is perhaps not so surprising that numerous contradictory philosophies have emerged as a result. One notable source of contention is whether the posterior cruciate ligament (PCL) should be left intact post-operatively or if it should be replaced by mechanical means [5]. Thus, the two most common types of the TKA's, the posterior cruciate retaining (PCR) and the posterior stabilizing (PS), illustrate these marked differences in the design philosophies. While both types resect the anterior cruciate ligament (ACL), the PCR design retains the PCL so that it can maintain its normal anatomical function; while the PS is designed

so that the PCL is resected and a cam-and-post system is instead employed to mechanically guide the motion of the knee, with the intention of simulating the PCLs function – that is, posterior femoral translation and roll-back.

In order to improve the design of total knee implants, and perhaps settle the debate between which design philosophy is in fact better, it is imperative to develop a thorough understanding of the *in vivo* forces that act on the cruciate ligaments throughout range of motion. What is more, before ligament function in a prosthetic can be fully realized, the ligament function in a healthy knee must first be analyzed. Therefore, the primary objective of this study was to investigate how patient specific cruciate ligaments interact during a deep-knee bend.

METHODS

Four major systems were employed to determine the ligament lengths (and subsequent first iteration of ligament forces): 3-D to 2-D fluoroscopic based kinematics, computer tomography (CT) extracted bone models, mixed mode CT/magnetic resonance image (MRI) to capture bone-to-ligament attachment sites, and the OpenSim software package to perform and monitor the kinematics (Fig. 1).

The bone models are generated by manually segmenting axial CT slices and appending the slices, applying a smoothing algorithm, and finally generating a 3-D surface model. The bone models generated at the Center for Musculoskeletal Research (CMR) are rendered in unit of millimeters, therefore, for implementation in OpenSim, the models had to be scaled by one thousand to conform to OpenSim's unit system (meters).

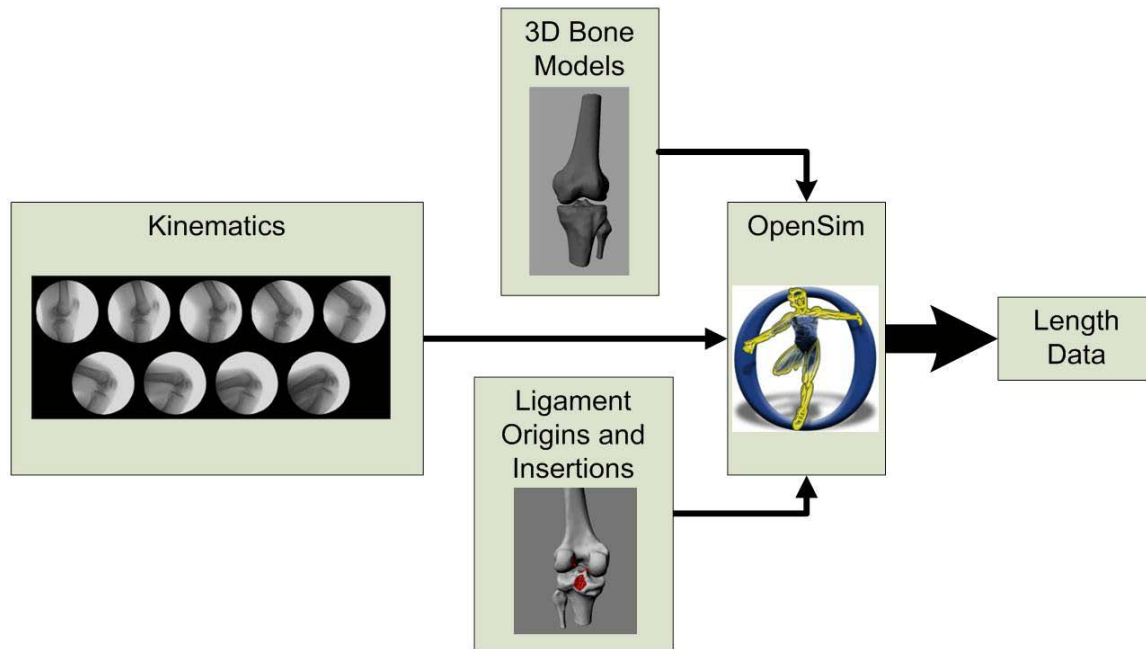


Figure 1. Schematic showing the work flow for the three patient specific input data and OpenSim processing which generates the ligament length data.

The ligament contact points were identified by overlaying the 3-D surface models into the MRI space of the same subject and selecting the soft tissue attaches to the bone. This process is performed using in-house (CMR) software that allows the user to “paint” soft tissue node location in a 3-D space. Again, adjustments were made for XYZ unit conformity.

The patient specific kinematic information was extracted from uniplanar fluoroscopy using 3D-to-2D registration algorithm that fits the surface bone models onto the 2D plane of a set of fluoroscopy images. This again is an in-house CMR software program titled Simulated Algorithmic Anatomical Modeling (SAAM). A final fit is established by affinely adjusting the position and orientation of the bone model until a global objective function has been minimized [5]. With the bone models in their final position, the 6 degree-of-freedom relative motion has been validated to an approximate RMS of 1.5° of rotation and 0.65 mm translation [5].

This Implementation of the patient specific data was facilitated through the use of the OpenSim software package. As stated earlier, introducing the bone models and ligament origins and insertions is simply a matter of maintaining consistent units. The coordinate systems were consistent, with the y-axis vertical (inferior-to-superior), the z-axis lateral and to the subject’s right, and the x-axis forward (posterior-to-anterior). The kinematics, however,

proved to be a bit more problematic. SAAM utilizes a left-handed coordinate system and outputs the rotation matrix in terms of a sequential ZYX-rotation. OpenSim, on the other hand, uses a right-handed coordinate system and a XYZ-rotation sequence. In addition, SAAM outputs the rotation matrices relative to the global origin. Therefore, in order to implement the SAAM kinematics within the OpenSim environment, several changes must occur: (1) SAAM outputs the rotations and translations from 0° flexion to maximum flexion with, in the present case, 20° increments; (2) output rotations and coordinates are converted to a right-handed coordinate system; (3) the motions are converted from global rotations/translation to those relative of the femur to the tibia (fixing the tibia) using a ZYX Euler angle rotation matrix; (4) units are converted for conformity (millimeters and radians); (5) the OpenSim cubic spline function is used to interpolate the motion from maximum extension to maximum flexion.

The ligaments were modeled using the Schuttle1993 muscle model packaged with OpenSim. Since the present manuscript was only concerned with the distance between the origins and insertions, the fiber length was set to zero and the tendon slack length was initially set to be the minimum 3D distance between the connections sites through flexion.

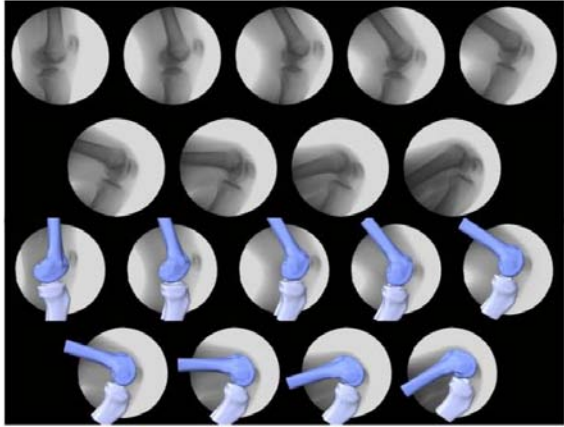


Figure 2. Overlay of the surface models on top of the fluoroscopy images during a deep knee bend.

RESULTS

The results from this experiment indicate that at full extension the ACL is already loaded with some tension, while the PCL is its minimum length through full flexion (Fig. 3). At approximately 25° flexion both ligaments are approximately the same length and continue in the opposite direction (Fig. 3). The PCL stretches to approximately 51 mm, while the ACL heads towards about 25 mm before sharply rising to 35 mm at full flexion (Fig 3). The forces were not calculated as anticipated due to issues concerning the slack length of the ligament.

DISCUSSION

The results of this study were consistent with other findings that suggest that ACL and PCL display a crossing pattern as they stretch during deep flexion.

Using the lengths determined from this study the forces could be determined by modeling the ligaments with a spring model. Often, this is accomplished by introducing a piecewise function with non-linear characteristics during low tension and linear properties during high tension. The one potentially detrimental shortcoming of this technique is that the slack of the ligaments are unknown. Common practices for calculate the slack lengths are to take the length at full extension, then by using reference strain the minimum ligament length is calculated. This approach is certainly suspect, and relies on non-patient specific information.

In order to calculate accurate slack lengths, more sophisticated measurements must be used than the methods mentioned earlier. Imaging techniques such as a MRI, or possibly functional-MRI, may lend to some usefulness towards solving this dilemma as the ligament might be captured it is relaxed (unstretched) state. Ultra Sound could also serve the same function to provide *in vivo* sight.

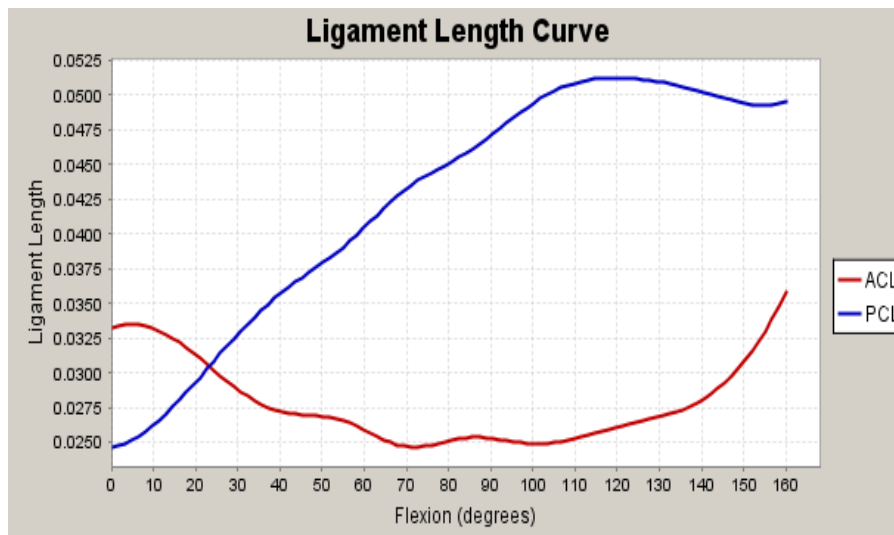


Figure 3. Ligament lengths from full flexion to full extension

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