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In Situ Characterization of the Mechanical Properties of Human Knee Ligaments

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ABSTRACT

Conventional total knee replacement (TKR) relies on balancing the surrounding ligaments. Incorrect ligament balancing during TKR can lead to persistent joint instability, which is a leading cause of revision surgery after the TKR. This highlights the rising need to better understanding of ligament biomechanics. Thus, the aim of this study is to characterize the mechanical properties of three major stabilizing structures in the knee, the posterior cruciate ligament and the entire medial and lateral ligamentous structure in situ after TKR.

In this study eight post-TKR human cadaveric knee specimens were mounted onto a AMTI VIVO joint motion simulator (AMTI, Watertown, MA). Each was subjected to loads that simulated passive flexion/extension, clinical laxity exams, and activities of daily living. During each motion, six degrees of freedom tibiofemoral kinematics of each specimen were recorded. To determine the ligament's in situ force, each ligament was resected separately and changes in the joint reaction forces/torques were measured while applying previously measured kinematics (principle of superposition). The mechanical properties of each ligament were characterized using an established non-linear ligament force-strain relationship. Seven main ligament groups were considered in this study including posterior cruciate ligament, lateral collateral ligament, anterolateral ligament, popliteofibular ligament, posterior oblique ligament and superficial and deep bundles of the medial collateral ligament. The attachment footprint of each ligament on a template knee model were determined using the attachment sites reported in the literature and were mapped to each subject-specific knee model using non-rigid iterative closest point method. In order to reduce the root mean square error between the experimental (in situ) and modelled ligament forces, a genetic multi-objective optimization algorithm was employed to calibrate ligament stiffness parameter, reference strain (strain at full extension), the number of bundles per ligament, and their attachment location. The stiffness characteristic of each ligament group was set so that all bundles within a ligament division have the same stiffness.

The ligament multiple-bundle models showed ranges of variations across each specimen as well as during varied movements. Ligament stiffness and reference strain were in good agreement with the literature. The predicted ligament forces in the anterior/posterior, medial/lateral and compression/distraction directions were well-correlated with the experimental results with a correlation of coefficient of above 90 percent. Results of this study showed that ligament bundle recruitment varied significantly across different motions, and therefore a more detailed bundle configuration is recommended for the purpose of studying the mechanical behavior of knee ligaments.