KNEE JOINT LIGAMENT RECONSTRUCTION: ON PRETENSION AND COUPLING IN CRUCIATE LIGAMENTS

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Wide range of knee cruciate ligament reconstruction procedures with different materials, stiffness, pretensions, orientations, and insertion locations are currently used with the primary goal to restore the joint laxity. With the general lack of success in preservation of force in the reconstructed ligament, the concern, not yet addressed, arises as to the effect of reconstruction on the other intact cruciate ligament. Using a 3-D finite element model, we examined this hypothesis by varying the pretension in each ligament under flexion ±A-P loads and quantifying the extent of coupling between cruciate ligaments. A remarkable coupling was predicted. Moreover, changes in laxity and in ligament forces as ligament pretension was altered varied with flexion and loads. These findings have important consequences in proper management and rehabilitation of the joint ligament disorders.

KEY WORDS: knee joint, cruciate ligaments, finite element analysis, pretension, laxity.

INTRODUCTION: In various sport activities, such as skiing, the human knee joint is subjected to large static and impact loads and motions that place joint ligaments at a particularly high risk of injuries, either isolated or combined. The high incidence of acute rupture in the anterior cruciate ligament (ACL) has made its reconstruction attempts as one of the most widely studied procedures in sports medicine. Once ruptured, the knee joint cruciate ligaments are reconstructed with the rationale to return the joint to normal daily/recreational activities and to avoid joint instability, recurrent injury, damage to soft tissues, and osteoarthritis. An injury or alteration in a primary structure of the knee joint likely perturbs the entire joint kinematics and kinetics with the liklihood to generate or accelertae joint instability and degeneration. Patellar, quadriceps and hamstrings tendon grafts are frequently used in reconstruction of cruciate ligaments despite their much different, often stiffer, material properties. The laxity-matched pretensions have been more successful in restoration of joint kinematics than in preservation of force in the reconstructed ligament itself. The anterior (ACL) and posterior (PCL) cruciate ligament grafts with laxity matched pretensioning have been measured to experience forces much greater than those in the same, otherwise intact ligaments (Markolf et al., 1996 and 2003). It is recognized that larger pretension diminishes laxity and likely results in an over-constrained joint (i.e., over-correction).

Graft initial tension, orientation, insertions, and stiffness are important parameters that influence the long-term success in a ligament reconstruction. We hypothetize that such alterations in the mechanical role of a ligament following reconstruction would cause significant changes in the other intact cruciate ligament as well. No prior attempts appear to have been made to measure the force in the remaining structures such as the other intact cruciate ligament. Using a validated nonlinear 3-D finite element model of the human tibiofemoral joint, we set to examine and quantify the extent of this hypothesis on coupling between ACL and PCL ligaments in flexion with and without A-P forces up to 100 N. For this purpose, the prestrain (i.e., pretension) in ACL or PCL is individually varied and its effects on forces in both ligaments and on joint laxity are computed and compared with results in intact (reference) and ligament-deficient models.

METHODS: The model of the passive tibiofemoral joint consisted of tibia and femur simulated as rigid bodies (due to their much greater stiffness relative to joint soft tissues) and articular cartilage layers, menisci, as well as principal ligaments (collaterals and cruciates). Menisci were modeled as a nonhomogeneous composite of a bulk material reinforced by radial and circumferential collagen fibers. Nonlinear material properties were considered for menisci and ligaments. Ligaments were each modeled by a number of uniaxial elements with different prestrains (or pretension) at different bundles. Material properties were taken from the data

available in the literature. The model predictions have been validated under different loads and flexion angles (e.g., Benjaballah et al., 1998; Moglo and Shirazi-Adl, 2003a and b).
For a stable and yet fully unconstrained response, the femoral coupled translations (in 3 directions) as well as tibial coupled rotations (i.e., varus-valgus and internal-external) were left free while the flexion rotation was incrementally prescribed on the femur. At the first step, the joint reference or resting configuration was established by considering only the prestrain in ligaments resulting in initial strains of ~ -4.2%, 2.3%, -16.9%, -6.8%, 2.6% and 1.8% respectively in ACL-am (anteromedial) bundle, ACL-pl (posterolateral) bundle, PCL-al (anterolateral) bundle, PCL-pm (posteromedial) bundle, LCL (lateral collateral ligament) and MCL (medial collateral ligament). Negative strain indicates slackness whereas positive strain simulates initial tautness. Subsequently, the femur, while constrained in flexion-extension, was subjected in some cases to an A-P horizontal force reaching 100N. Finally, incremental flexion from 0° to 90° was prescribed at the femur. To investigate the coupling between cruciate ligaments, additional analyses were performed with the initial strain (i.e., pretension) in the ACL or the PCL either increased from foregoing reference values simulating a tauter ligament or decreased simulating a slacker ligament. Cases with a cruciate ligament entirely removed were also considered for the sake of comparison.

RESULTS: The ACL and PCL forces remained relatively small in flexion alone. In presence of 100 N A-P preload, the joint flexion from 0° to 90° substantially diminished ACL force in presence of constant femoral posterior preload whereas PCL force significantly increased with flexion in presence of constant anterior preload. Throughout the flexion, a change in either ACL or PCL initial strain or transaction of one of them substantially changed the force in not only the affected ligament itself but also in the other intact cruciate ligament (e.g., Fig. 1). This was also found in presence of 100 N A-P preloads. Analysis of joint laxity due to 100 N A-P loads indicated that ACL injury was best detected at flexion angles >30° whereas PCL rupture was best detected at larger flexion angles >60° (e.g., Fig. 2). Changes in Laxity due to variations in ACL prestrain or pretension were greatest at larger flexion angles. In contrast, these variations were larger at smaller flexion angles when PCL initial strain was varied (Fig. 2).

DISCUSSION: This work was set to investigate interaction between forces in ACL-PCL cruciate ligaments and joint A-P laxity in flexion by altering ACL or PCL initial strains (pretensions) simulating conditions following joint ligament injuries and reconstruction. Comparison of predictions for the intact reference cases with available measurements on joint laxity and ligament forces demonstrated a satisfactory agreement. Predictions confirmed our hypothesis on a novel coupling between the ACL and the PCL in flexion; mechanical contributions of cruciate ligaments are strongly dependent. This interaction was clearly evident in all cases studied. Alterations in ligament material (stiffness) or pretension used during reconstruction surgery would, hence, influence the mechanical role of not only the treated ligament itself but the untreated intact one as well. Such consideration of cruciate ligaments coupled together rather than alone and in isolation has important consequences in the knee joint mechanics following total joint replacement or ligament injuries/reconstructions and, thus, in the proper management and rehabilitation of joint disorders towards a near-normal function of the entire joint. This is particularly important in view of the high incidence of ligament injuries specially among young and active patients requiring effective long-term reconstruction procedures in response to demanding mechanical environments expected in occupational and sportive activities.

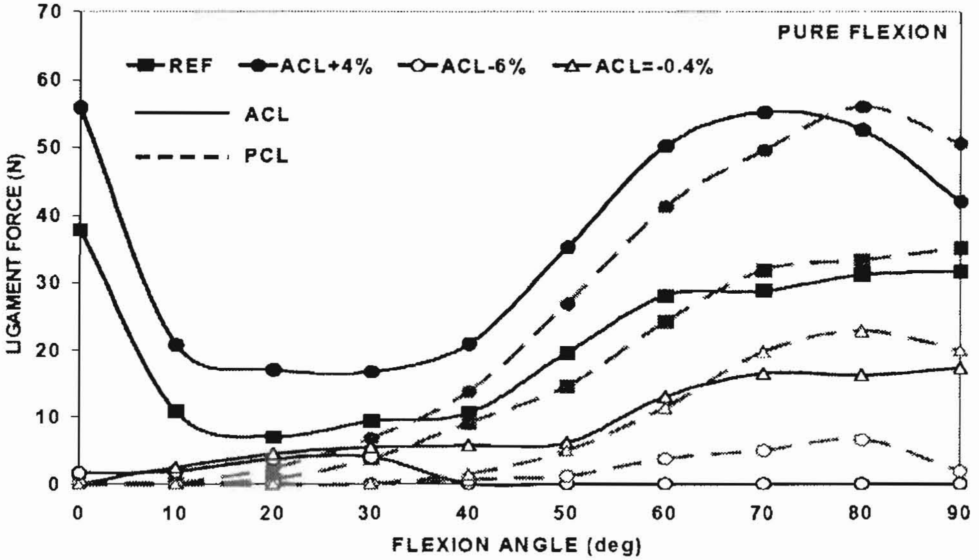

Figure 1: Changes in ACL and PCL forces in pure flexion due to variations in ACL prestrain by +4% or -6% strain from the reference case in both ACL bundles or for initial strain of -0.4% at both ACL bundles. Coupling between forces in cruciate ligaments is evident.

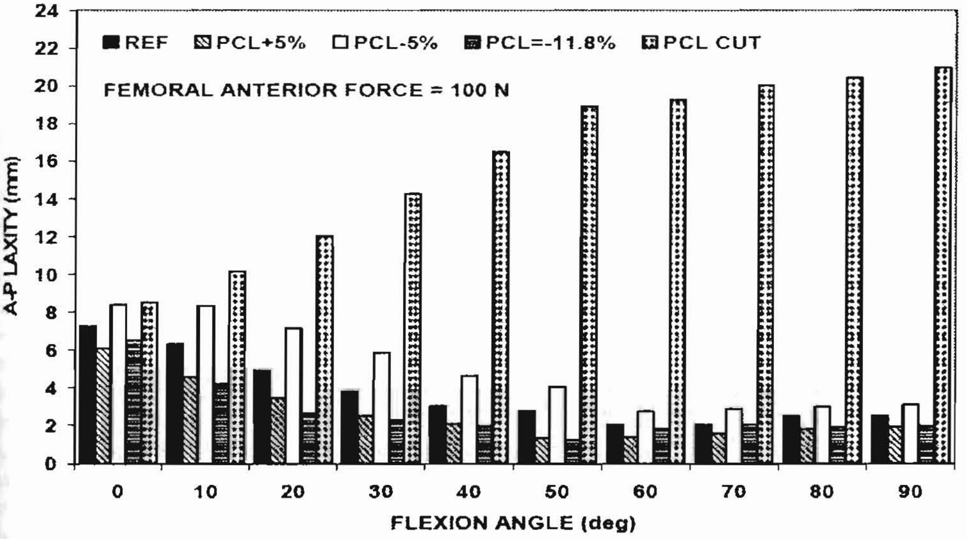

Figure 2: Changes in anterior femoral laxity at different flexion angles due to 100 N anterior force for different PCL prestrain values; reference intact case, ±5% strain from the reference case in both PCL bundles, initial strain of -11.8% at both PCL bundles, and PCL deficient case.

The current predictions also suggest that alterations or sensitivity in joint laxity and cruciate ligament forces due to changes in ligament prestrain (pretension) vary as a function of both flexion angle and applied load. For example, nearly the same forces were computed in ACL or PCL ligament irrespective of different initial strain conditions considered when the joint was flexed at 90° under 100 N A-P preload. In general, the effect of variations in initial strain on ligament forces was found to be more apparent and distinct under flexion without A-P forces or under A-P forces at small flexion angles. Similar to ligament forces, the effect of changes in initial strains (pretensions) on joint A-P laxity was neither constant depending on the flexion angle. The detection of a ligament rupture in drawer tests, by comparison of reference and ligament deficient laxities under 100 N force, is most evident at ~ 30° or larger for the ACL and at ~ 90° for the PCL. The foregoing predicted sensitivity in variations of ligament forces and joint A-P laxities due to changes in a cruciate ligament prestrain (or pretension) at different flexion angles and loads needs to be considered in order to improve laxity matched or ligament force matched pretensioning protocols.

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