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The influence of deceleration forces on ACL strain during single-leg landing: A simulation study

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Abstract

Anterior cruciate ligament (ACL) injury commonly occurs during single limb landing or stopping from a run, yet the conditions that influence ACL strain are not well understood. The purpose of this study was to develop, test and apply a 3D specimen-specific dynamic simulation model of the knee designed to evaluate the influence of deceleration forces during running to a stop (single-leg landing) on ACL strain. This work tested the conceptual development of the model by simulating a physical experiment that provided direct measurements of ACL strain during vertical impact loading (peak value 1294 N) with the leg near full extension. The properties of the soft tissue structures were estimated by simulating previous experiments described in the literature. A key element of the model was obtaining precise anatomy from segmented MR images of the soft tissue structures and articular geometry for the tibiofemoral and patellofemoral joints of the knee used in the cadaver experiment. The model predictions were correlated (Pearson correlation coefficient 0.889) to the temporal and amplitude characteristic of the experimental strains. The simulation model was then used to test the balance between ACL strain produced by quadriceps contraction and the reductions in ACL strain associated with the posterior braking force. When posterior forces that replicated in vivo conditions were applied, the peak ACL strain was reduced. These results suggest that the typical deceleration force that occurs during running to a single limb landing can substantially reduce the strain in the ACL relative to conditions associated with an isolated single limb landing from a vertical jump.

Keywords: Anterior cruciate ligament strain; ACL injury; Knee model; Single-leg landing; Deceleration force

1. Introduction

Anterior cruciate ligament (ACL) injury is very common during sport activities and frequently occurs in the absence of contact with another player or object (Boden et al., 2000; Griffin et al., 2000). While it is reported that noncontact ACL injuries often occur during landing or deceleration prior to a change of direction (Boden et al., 2000), the mechanism of ACL injury is not well understood. Anterior forces on the tibia, internal/external rotational torque, and valgus torque contribute to strain in the ACL in controlled in vitro and in vivo studies with low-magnitude quasi-static loads (Markolf et al., 1995; Woo et al., 1999; Fleming et al., 2001). However, a recent study of individuals performing a single-leg run-to-stop revealed that anterior translation of the tibia may not occur during this activity (Chaudhari et al., 2004). Instead, posterior forces on the tibia were observed during the first 100 ms after foot strike, due to the deceleration forces acting at the foot. These forces caused posterior tibial translation in most subjects, which would seem to protect the ACL from injury. However, the effect of this observed combination of loads on ACL strain remains unknown.

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To understand the mechanism of ACL injuries, estimating the strain of the ACL is essential. ACL strain has mainly been measured using in vivo measurement with implanted displacement transducers (Beynnon et al., 1992; Fleming et al., 2001) or in vitro measurement using various techniques (Markolf et al., 1995; Woo et al., 2006). Computer simulations have also predicated ligament forces (Pandy and Shelburne, 1997; Song et al., 2004).

Simulation studies have provided considerable insight into the biomechanics of the knee joint (Crowninshield et al., 1976; Andriacchi et al., 1983; Garg et al., 1990; Blankevoort et al., 1991; Shelburne and Pandy, 1997; Yu et al., 2001; Chen et al., 2001; Caruntu and Hefzy, 2004). However, most of these models use generic anatomical geometry and are designed only to predict static or quasi-static characteristics of the knee joint such as passive flexion and rotational stiffness. Predictions of ACL strain during dynamic landing motions have not been performed using a model validated for the estimation of ACL strain. Thus there is a need for a knee model that predicts ACL strain under dynamic loading conditions that occur in vivo during sports activities similar to those that result in ACL injuries.

The purpose of this study was to develop, test, and apply a 3D specimen-specific dynamic simulation model of the knee designed to test the influence of deceleration forces on ACL strain during run-to-stop single-leg landing.

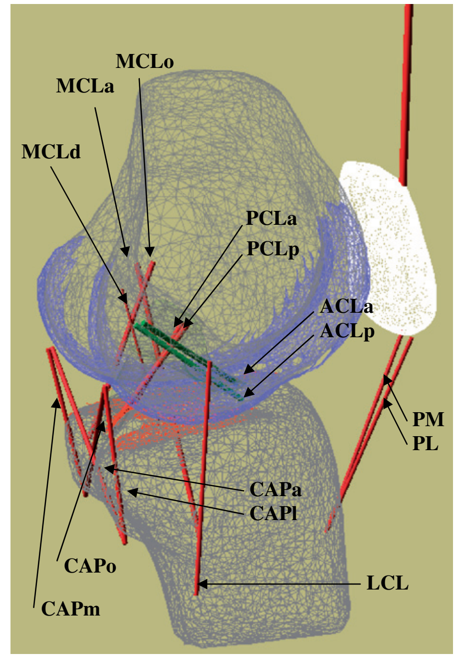

Fig. 1. Schematic of the knee model showing 14 ligament bundles. ACL bundles are shown green. The anterior and posterior bundle of ACL (ACLa and ACLp); the anterior and posterior bundle of PCL (PCLa and PCLp); the LCL; anterior, oblique, and deep bundle of MCL (MCLa, MCLo, and MCLd); the medial, lateral, oblique popliteal, and arcuate politeal bundle of posterior capsules (CAPm, CAPl, CAPo, and CAPa); and the medial and lateral patellar ligament (PM and PL).

2. Methods

A 3D dynamic specimen-specific knee model (Fig. 1) and the simulated experimental apparatus were created to investigate the influence of various loading configurations on ACL strain during landing motions. The knee model was constructed from the MRI of a cadaver specimen that was used in an experimental study (Fig. 2a and b) to replicate vertical impact loading during single limb landing (Withrow et al., 2006). Soft tissues were modeled as nonlinear elastic elements with properties obtained from the literature. The experimental apparatus (Fig. 2b) was simulated with similar dimensions, mass, and the same musculotendinous properties as the physical experimental apparatus (Fig. 2a). A specimen-specific validation of ACL strains was performed by comparing predicted ACL strains to experimental measurements under identical loading and limb alignment. No parameters in the knee model were adjusted for the validation test; finally, physiological levels of external posterior force were applied to investigate the effect of deceleration force on ACL strain.

Model anatomy was obtained from MRI (3D-SPGR sequence, FOV $140 \times 140\,\text{mm}^2$, matrix 256×256, slice

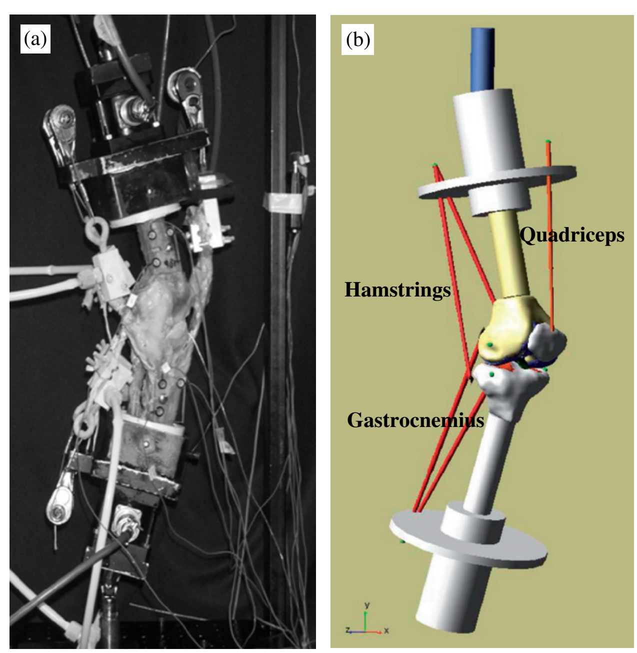

Fig. 2. (a) The experimental apparatus used for validation (photo by courtesy of Dr. Withrow). (b) The simulated dynamic single-leg landing apparatus with the specimen-specific knee model showing five musculotendinous bundles.