Effect of Lateral Tibial Slope, Frontal Plane Alignment and Medial Tibial Concavity on ACL Strain During a Simulated Jump Landing

INTRODUCTION

Lateral tibial slope, lower limb alignment in the frontal plane and medial tibial concavity are three morphological variables being considered as risk factors for ACL injury. The effect of each variable on ACL strain is not known and it would be difficult to determine this in vivo, even in large prospective field study of injury patterns, because of confounders. Similarly, it would be just as difficult in a laboratory study using stereoradiography because large group sizes would be needed, and the confounders remain. Therefore, we used a 3-D computer simulation of the knee to quantify the role of each of these three variables, one variable at a time. Using a loading pattern combination (i.e., compression, flexion moment, abduction moment, and internal tibial torque) that develops the largest ACL strains during a pivot landing [1], we tested the hypothesis that increases in lateral tibial slope, valgus limb alignment and a decrease in medial tibial concavity would significantly increase peak ACL strain over baseline values.

METHODS

A 3D lower-limb model was constructed using sagittal magnetic resonance (MR) images (T2-weighted, 3D-PD sequence, TR/TE: 1000/35 ms, slice thickness: 0.35 mm, FOV: 160 mm) of a male cadaveric lower-limb (age: 47 yrs, weight: 778 N, height: 1.85 m). The distal femur, proximal tibia, fibula and patella were segmented (SolidWorks 2010, Dassault Systems SolidWorks Corp., Concord, MA; Rhinoceros, McNeel North America, Seattle, WA) and imported into a dynamic motion simulation software (MD ADAMS R3, MSC. Software, Inc., Santa Ana, CA). As previously described [1], eighteen viscoelastic elements were used for the mechanical behavior of the knee joint ligament and capsular structure. The ligament or capsular force was defined according to Shin et al.’s work [2].

Figure 1. Schematic diagrams of (a) the knee model and (b) the in vitro test apparatus.

The knee model was built to replicate the experimental set-up (Fig. 1b) [1], where the quadriceps, medial and lateral hamstrings and gastrocnemius muscles were pretensioned to 180 N for quadriceps and 70 N for each flexor muscle, respectively, with the knee initially in 15 degrees of flexion. Then, the impulsive compressive force, internal tibial torque, and knee abduction moment applied during the experiment drove the knee model.

To validate the knee model, the quadriceps forces, AM-ACL strain, knee flexion angle, internal tibial rotation and knee abduction angle calculated from the simulation were quantitatively compared by Pearson cross-correlation with the time history of values measured from the experiment. After the validation test, sensitivity analyses were performed to identify which morphological factor would most likely cause ACL injury. A proximal segment, which corresponds to the lateral tibial plateau, was separated from the reconstructed tibia. Then, the model simulation was repeated for every 1 deg increment in the lateral tibial slope ranging from 5.5 deg to 13.5 deg with the medial tibial slope unchanged. The frontal plane limb alignment was varied by changing the angle of the femoral shaft (Fig. 1a) from 7.5 deg of varus to 10 deg of valgus in increments of 2.5 deg. The medial tibial concavity was morphed starting from the initially segmented tibia (SolidWorks 2010) so that its depth was varied from 2.0 mm to 5.0 mm in increments of 0.5 mm.

RESULTS

In the model validation test, the quadriceps muscle force, AM-ACL relative strain, knee flexion angle, internal tibial rotation, and knee abduction angle in the simulation were highly correlated with the corresponding values in the experiment (r = 0.988, 0.985, 0.981, 0.976, and 0.817 respectively).

The model simulation predicted that AM-ACL strain was most sensitive to the change in the lateral tibial slope (i.e., 0.8% ACL strain increase per 1.0 deg increase; Fig. 2). On the other hand, the changes in frontal plane limb alignment and medial tibial depth of concavity on ACL strain were less than 2% over the parametric variations described.

DISCUSSION

The most important result is that increasing the difference between medial and lateral tibial slopes accentuates the coupled motion between internal tibial rotation and knee abduction angle, thereby increasing ACL strain during a simulated pivot landing. Although the effect of changing frontal plane limb alignment was smaller than the tibial slope effect, increasing valgus limb alignment did increase ACL strain. This result may help explain the relationship between static frontal plane limb alignment and ACL injury. The increase in the medial tibial concavity depth resulted in decreased anterior tibial translation and internal tibial rotation, thereby reducing ACL strain. We conclude that a larger lateral tibial slope compared to the medial tibial slope, a more valgus limb alignment, and a shallower medial tibial concavity each increase the risk for ACL injury.

SIGNIFICANCE

This study shows that the difference in medial and lateral tibial slopes is the most important morphological variable of the three considered in terms of risk of ACL injury during a pivot landing.

ACKNOWLEDGEMENTS

We thank Dr. Scott G. McLean for focusing our attention on tibial slope and David B. Lipp for providing the MR scans. This work was funded by PHS grant R01 AR 054821.

REFERENCES