INTRODUCTION: Anterior cruciate ligament (ACL) injury can lead to knee instability, functional deficits and long-term joint degeneration (osteoarthritis). Surgical reconstruction of the ACL is typically effective at restoring static knee stability (i.e. as measured with a knee arthrometer such as the KT-1000), reducing or eliminating episodes of gross instability during physical activity ("giving way" episodes), and restoring lost function. However, current methods for ACL reconstruction do not appear to reduce the risk of osteoarthritis associated with ACL injury.

There are several plausible explanations for this, such as damage to other joint structures at the time of injury or during the interval between injury and reconstruction. Given the differences in geometry, origin/insertion location and material properties between the original ACL and the replacement graft as well as the neuromuscular alterations associated with ACL loss, it also possible that the reconstruction fails to restore normal knee kinematics. These differences may be subtle and activity-dependent. Thus, they may be difficult to detect with conventional motion analysis techniques.

The goal of this study was to compare kinematics between the ACL injured limb and the contralateral (uninjured) limb for a series of patients who have undergone ACL reconstruction. A high-accuracy cine-radiographic method was employed to evaluate 3D knee kinematics during a mildly stressful sports activity (downhill running).

METHODS: Tibial-femoral kinematics were assessed in-vivo for five subjects between 4 and 9 months after ACL reconstruction (using bone-patellar tendon-bone or quadrupled hamstring grafts with interference screw fixation). The injured/reconstructed limb was on the right side for 3 subjects and the left for 2 subjects. All subjects were free of injury or disease in their contralateral limb. After obtaining informed consent, 1.6mm tantalum beads were implanted in both tibias and femurs of all subjects at the time of their ACL reconstruction surgery. A minimum of 3 markers was placed in each bone to enable full six-degree-of-freedom motion tracking. All procedures were approved by the appropriate Institutional Review Board for human research.

Knee motion was assessed during downhill treadmill running (10% slope, 2.5m/s). This activity was selected since it is known to be at least mildly stressful to the ACL but is not likely to put the subjects at significant risk of injury, even relatively early in their rehabilitation course. Kinematic data was collected using a biplane radiographic system (Figure 1) capable of tracking implanted radiopaque markers in 3D at 250 frames/s with a dynamic accuracy of ±0.11mm. Data was acquired from approximately 0.1s before to 0.4s after landing impact (foot-strike) for 3 trials for each leg. For each trial, 3D coordinates of implanted markers were determined using standard stereo-photogrammetric methods (DLT) and lowpass filtered (20 Hz). Translations between marker-based and anatomical coordinate systems were determined using 3D bone models generated from subject-specific CT scans. Three-axis rotations of the tibia relative to the femur were calculated for each trial using the conventions proposed by Grood and Suntay. 3D translations were determined relative to ACL origin/insertion locations on the tibia and femur (estimated from CT-based subject-specific bone models), and expressed in an anatomical coordinate system fixed to the tibia. Ensemble average curves were generated from all trials for each subject, after synchronizing to footstrike timing. Kinematic variables were extracted at 0.0, 0.025, 0.05, 0.075 and 0.10 s after footstrike for statistical analysis.

Within-subject differences between the intact and reconstructed limbs were evaluated with a repeated measures ANOVA (significance set at p=0.05).

RESULTS: Curve shapes were similar across subjects for all 6 degrees of freedom. Anterior tibial translation curves were nearly identical for the intact and reconstructed limbs (see Figure 2). For all subjects, reconstructed knees were more externally rotated (average 3 deg) and adducted (more varus; average 2 deg) on the reconstructed side relative to the intact side. Though these differences were small, they were consistent and statistically significant (repeated measures ANOVA; int/ext rotation p=0.029, varus/vaLgus p=0.035). No significant differences were found in the remaining rotations/translations. Rotation motion curves were consistent across individuals, with between-subject standard deviations of 2.5 deg or less for internal/external and varus/vaLgus rotations. Translations were somewhat more variable, with between-subject standard deviations ranging from 2.6 mm. This was due in part to geometric differences (e.g. size) between the joints, creating baseline shifts in the translation curves. Since bone shape and size were consistent across the two limbs of each subject, these geometric differences did not affect the paired statistical analysis.

DISCUSSION: The primary clinical goal for ACL reconstruction surgery is the elimination of instability created by loss of the ACL. Prior studies using static measures of stability (e.g. KT-1000) have shown that the surgery is generally successful at reducing or eliminating anterior/posterior (AP) laxity. The data presented here suggest that these results may translate into dynamic stability as well. The patterns and magnitude of translation in the reconstructed limbs were nearly identical to those in the intact limbs for all three directions of motion.

Translational stability does not, however, necessarily imply restoration of normal knee function. Consistent shifts towards external rotation and varus were found, suggesting that common reconstruction techniques may not restore normal rotational motion. This is potentially important, since abnormal rotational motion would alter the nature of the interaction of the articulating joint surfaces. Increased varus rotation is of particular interest, as even small shifts in varus/vaLgus position can significantly alter joint contact forces and stresses. Though the effects of these abnormal motion patterns are not known, they could have important implications for long-term joint health.

The combination of a somewhat stressful task, high-accuracy skeletal kinematics (free of skin motion artifact), subject-specific 3D bone models, and within-subject side-to-side comparisons employed for this study appears to be well suited for reliably detecting even subtle differences in dynamic joint behavior. It is hoped that further applications of this technique may be helpful for improving long-term outcome after ACL reconstruction.

Figure 1. Experimental setup for downhill treadmill running in high-speed stereo-radiographic imaging system

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