In Vivo Dynamic Behavior of the Native and Reconstructed Anterior Cruciate Ligament During Running

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Introduction: The goals of anterior cruciate ligament (ACL) reconstruction are to restore original ligament function and preserve joint health. Non-anatomic placement of graft tunnels may lead to altered graft behavior, but the relationship between tunnel placement and dynamic graft function is not well understood. While previous studies have evaluated ACL behavior in vivo during quasi-static activities [1, 2] or gait [3], in vivo data on ACL native and graft strain during higher-stress functional activities is limited. The purpose of this study was to characterize dynamic graft behavior during downhill running following two different surgical reconstruction procedures, and compare graft function with that of the native ACL. It was hypothesized that graft position and orientation would influence graft function, and specifically that more vertically oriented grafts would behave differently compared to the native ACL.

Methods: Fifteen patients underwent single bundle ACL reconstruction performed by four surgeons using two different techniques for placing graft tunnels. For the transtibial (TT) group (10 subjects), the femoral tunnel was drilled through the tibial tunnel. For the antero-medial portal (AMP) group (5 subjects), the femoral tunnel was drilled independently using an accessory portal. Graft tunnel placement was compared to the native ACL footprint using the 3D ACL insertion of the contralateral limb, assessed with clinical-grade magnetic resonance imaging (MRI). This clinical MRI-based method of detecting native insertion centers was validated to 3.1 ± 1.0 mm accuracy for femurs. To determine tunnel apertures, cylinders were fit to bone tunnels of 3D computed tomography-derived models. The contralateral bone was mirrored about the sagittal plane and co-registered to the operative side, and the intersection of the tunnel cylinder axis with the non-operative cortical bone surface was marked as the tunnel aperture. Functional ACL length was defined as the 3D vector distance between opposing native ACL centers or tunnel apertures during running. The anatomical anterior-posterior component of the functional ACL length was also assessed as a function of time and as a Percentage of the Foot-strike Anterior Length (PFAL) change. Kinematic testing was performed during downhill treadmill running at five months (Day 1) and twelve months (Day 2) after surgery. Knee joint kinematics and ACL behavior were assessed using a previously validated dynamic stereo x-ray (DSX) system [4] in the time interval between footstrike and 100 milliseconds thereafter. Patients' native ACLs from their contralateral, intact limbs were used as experimental controls. Repeated measures analysis of variance was used to assess differences between grafts and native ACLs, and surgical method (TT or AMP) was used as a between-subjects factor (α=0.05).

Results: Non-anatomic tibial tunnels were placed posteriorly (average misplacement 3.8 ± 1.4 mm) relative to native insertion site centers. TT femoral tunnels had more anterior misplacement while AMP femoral tunnels were more proximal and more posterior. Figure 1 shows the distribution of the femoral tunnels relative to the native center (average misplacement 8.4± 2.5 mm).

The difference in 3D functional ACL length between native and reconstructed ACLs over the 100ms time interval was not significant (p=0.251) at 5 months (Figure 2A) and tended towards significance (p=0.123) at 12 months (Figure 2B). On average, both TT and AMP grafts and native ACLs slightly increased in 3D functional ACL length between 5 and 12 months (about 0.6 mm, not significant). At both test dates, grafts went through a greater range of functional ACL length changes than native ACLs. Grafts were on average 7.7 mm shorter along the anterior component than native ligaments (p=0.001) at 5 months (Figure 3A) and 6.6 mm shorter (p= 0.003) at 12 months (Figure 3B).

At 5 months, TT grafts averaged 78.5% PFAL and AMP grafts 45.4% PFAL (Figure 4A). The differences between native and reconstructed ligament PFAL were significant (p= 0.002) at 5 months and nearly significant at 12 months (p= 0.061) (Figure 4B). Grafts were oriented 20.6° more vertically (p=0.001) in the sagittal plane than their native counterparts at 5 months (Figure 5), and this angle did not change significantly at 12 months. No significant interactions were detected between TT or AMP methods and any of the tested variables.

Discussion: This study found differences between dynamic behavior of native ACLs and non-anatomic single bundle grafts during a functional running task. The increase in 3D length (Figure 2) between test dates was not significant, but may be related to alterations in graft stiffness over time. The more vertically oriented (antero-proximal), non-anatomic grafts exhibited increased anatomic anterior component lengthening relative to native ACLs. It has been suggested that higher graft forces are required for more vertically oriented grafts to resist the same anterior translation. The differences in graft and native ACL behavior show a failure of these non-anatomic reconstructions to restore normal ACL function. These shortcomings may increase patient risk to re-rupture, or may alter joint contact mechanics leading to cartilage or meniscal degradation.
This study is limited by the small and unequal group sizes and the non-anatomical and highly variable placement of all grafts. The percentage of relative change calculations should not be considered as true in vivo tissue strain calculations. Assessing the 3D distance between ACL centers does not account for possible motion of the graft within the tunnel or variations in strain patterns along the ligament axis. Nonetheless, this study melded clinical MRI sequences and DSX assessment of knee kinematics to determine and compare in vivo ACL behavior of native ligaments and reconstructed grafts. This allows for patient-specific comparisons of knee and ACL function alterations following reconstruction during demanding activities that place a higher demand on the grafts. The results highlight the importance of anatomic graft placement to mimic the natural behavior of the original ACL.

Significance: This study combined clinical MRI sequences and DSX assessment of knee kinematics to determine and compare in vivo ACL behavior of native ligaments and non-anatomic reconstructed grafts. These data show distinct differences in the behavior of non-anatomic grafts compared to native ACLs.

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Figure 2: 3D functional ACL lengths at 5 months (A) and 12 months (B) after surgery in the interval of foot-strike to 100ms thereafter during downhill running.

Figure 3: Anterior-posterior component functional ACL lengths at 5 months (A) and 12 months (B) after surgery.
Figure 4: Percentage change of the anterior-posterior component of functional ACL length relative to foot-strike length at 5 months (A) and 12 months (B) after surgery.

Figure 5: Sagittal plane ACL angle relative to tibial plateau at 5 months. grafts were significantly higher than native ACLs (p=0.001).