Published in final edited form as:

Am J Sports Med. 2013 June ; 41(6): 1330–1339. doi:10.1177/0363546513483269.

Contact Stress and Kinematic Analysis of All-Epiphyseal and Over-the-Top Pediatric Reconstruction Techniques for the Anterior Cruciate Ligament

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Abstract

Background—Anterior cruciate ligament (ACL) injuries are an increasingly recognized problem in the pediatric population. Unfortunately, outcomes with conservative treatment are extremely poor. Furthermore, adult reconstruction techniques may be inappropriate to treat skeletally immature patients due to the risk of physeal complications. “Physeal-sparing” reconstruction techniques exist but their ability to restore knee stability and contact mechanics is not well understood.

Purpose—(1) To assess the ability of the all-epiphyseal (AE) and over-the-top (OT) reconstructions to restore knee kinematics; (2) to assess whether these reconstructions decrease the high posterior contact stresses seen with ACL deficiency; (3) to determine whether the AE or OT produce abnormal tibiofemoral contact stresses.

Hypothesis—The AE reconstruction will restore contact mechanics and kinematics similarly to that of the ACL intact knee.

Methods—Ten fresh-frozen human cadaveric knees were tested using a robotic manipulator. Tibiofemoral motions were recorded with the ACL intact, after sectioning the ACL, and after both reconstructions in each of the 10 specimens. The AE utilized an all-inside technique with tunnels exclusively within the epiphysis and fixed with suspensory cortical fixation devices. The OT had a central and vertical tibial tunnel with an over-the-top femur position and was fixed with staples and posts on both ends. Anterior stability was assessed with 134N anterior force at 0, 15, 30, 60, and 90° of knee flexion. Rotational stability was assessed with combined 8 Nm and 4 Nm of abduction and internal rotation, respectively, at 5, 15, and 30° of knee flexion.

Results—Both reconstruction techniques offloaded the posterior aspect of the tibial plateau compared to the ACL deficient knee in response to both anterior loads and combined moments as demonstrated by reduced contact stresses in this region at all flexion angles. Compared to the ACL intact condition, both the AE and OT had increased posteromedial contact stresses in response to anterior load at some flexion angles and the OT had increased peripheral posterolateral contact stresses at 15° in response to combined moments. Neither reconstruction completely restored the

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mid-joint contact stresses. Both reconstruction techniques restored anterior stability at flexion angles less than or equal to 30°. In contrast, neither reconstruction restored anterior stability at 60° and 90° flexion. Both reconstructions restored coupled anterior translation under combined moments. Additionally, the AE over-constrained internal rotation in response to the combined moments by 12% at 15° flexion.

Conclusions—Both reconstructions provide anterior and rotational stability, and decrease posterior joint contact stresses compared to the ACL deficient knee. However, neither reconstruction restored the contact mechanics and kinematics of the ACL intact knee.

Clinical Relevance—Since the AE reconstruction has clinical advantages over the OT, our results support the hypothesis that the new AE technique is a potential candidate for use in the skeletally immature athlete.

Key Terms

pediatric; ACL reconstruction; kinematics; contact stress; all epiphyseal; over-the-top

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common in active, young patients accounting for 6.7% of total injuries and 30.8% of all knee injuries in soccer players age 5 to 18 in the US.³⁹ Furthermore, ACL injury has been reported in between 10% and 65% of pediatric knees with acute hemarthroses.^{9, 20, 40, 42}

Unfortunately, the outcome of non-operative treatment for ACL injury is extremely poor in the skeletally immature population. Overall, chronic ACL deficiency can lead to instability, meniscal injury, chondral damage, osteoarthritis (OA), and decreased activity levels. Clinical^{11, 32, 35, 44} and animal² studies have documented a link between ACL rupture and subsequent development of OA of the knee within 10 to 15 years. Development of OA over this period in the skeletally immature population would have devastating consequences in light of the high rate of failure and unsatisfactory outcomes of total joint replacement in young individuals.

Historically, ACL reconstruction in skeletally immature patients was not recommended because of potential iatrogenic physeal injury resulting in growth arrest, limb length discrepancies, and angular deformities.^{14, 16, 24} However, surgical treatment of ACL injuries in this age group has risen secondary to the increased injury rate and as a result of the poor natural history of non-operative treatment.^{10, 15, 22, 23, 31} A variety of surgical procedures for ACL reconstruction have been developed but no single technique predominates.²³ Two of the techniques to avoid crossing the physes and thus mitigating chances of injury to the physes, termed “physeal-sparing” techniques, include the all-epiphyseal reconstruction (AE) and the transtibial over-the-top femur reconstruction (OT).^{1, 3, 6, 12, 17, 25} These are two of the more commonly used techniques at our institution.

Given the relationship between altered knee joint kinematics, abnormal contact stresses, and development of OA^{4, 37, 38}, it is critical to evaluate the ability of any reconstruction technique to restore articular contact mechanics. Despite their importance in the progression

of OA, no studies have been performed to evaluate the ability of “physeal-sparing” reconstructions to restore native contact mechanics. Therefore, we defined three objectives for this study: (1) to assess the ability of the AE and OT reconstructions to restore knee kinematics, (2) to assess whether these reconstructions decrease the high posterior contact stresses seen with ACL deficiency, and (3) to determine whether the AE or OT produce abnormal tibiofemoral contact stresses. We hypothesize that the AE reconstruction more closely replicates the ACL intact knee kinematics and contact mechanics compared to the OT reconstruction.

MATERIALS AND METHODS

Ten fresh-frozen human cadaveric knees were utilized. The specimens were thawed at room temperature over 24 hours before testing. The average age of the specimens was 55.1 years (range 45 to 61 years). A medial arthrotomy was performed prior to testing to confirm the status of the cartilage and ligaments. Specimens were excluded if any gross joint abnormalities, prior surgery, instability, or cartilage degeneration was observed. Skin and soft tissues were removed with care taken to avoid damage to the ligamentous structures. Semitendinosus and gracilis tendons were harvested for use in the ACL reconstruction. The tibial and femoral shafts were potted in bonding cement (Bondo/3M, Atlanta, Georgia) with the use of two 3.5 mm screws drilled transversely in each shaft to ensure fixation between bone and cement. The fibula was stabilized with a 3.5 mm syndesmotic screw at the level just above the potting cement.

The knees were loaded using a six-degrees-of-freedom robotic arm (ZX165U; Kawasaki Robotics, Wixom, Michigan)^{33, 45} (Fig. 1). A universal force-moment sensor (Theta; ATI, Apex, North Carolina) was mounted to the end of it to measure the forces acting across the knee joint. The femur was rigidly fixed in place and the tibia was attached to the robotic arm. A 3D digitizer (MicroScribe; Immersion, San Jose, California) was used to define anatomic landmarks on the tibia and femur to create clinically-meaningful descriptions of knee motion.¹³ The medial and lateral femoral epicondyles were used to define the orientation of the flexion-extension axis. The long axis of the tibia was used to define internal-external rotation. The common perpendicular of the flexion-extension and the axial rotation axes was posterior and defined adduction/abduction and anterior/posterior translation.

Testing began by determining the path of passive flexion of the knee with the ACL intact from full extension to 90° of flexion in 1° increments. These flexion angles served as the starting positions for the application of loads in the tests that followed. The ACL was preconditioned by determining the position and orientation required to achieve an anterior force of 134N at 30° flexion and repeating this pathway between the loaded and unloaded positions for 10 cycles. Anterior force at this flexion angle loads both bundles of the ACL, hence it was a convenient position for preconditioning this ligament.³⁶ In addition, the medial collateral ligament was preconditioned by applying combined moments of 8Nm and 4Nm abduction and internal rotation, respectively, at 15° flexion and repeating this pathway for 10 cycles. The MCL is a primary contributor to knee stability under this loading condition and flexion angle; thus they were selected for preconditioning the MCL.³⁴ To

assess anterior stability, a 134N anterior force was applied at 0, 15, 30, 60 and 90° of knee flexion.⁷ To assess rotational stability, combined moments of 8Nm and 4Nm in abduction and internal rotation, respectively, were applied at 5, 15, and 30° flexion simulating the pivot shift exam.¹⁸

The knee was left unconstrained in all other directions but flexion. This enables measurement of primary and coupled motions during each test. The position and orientation of the tibia relative to the fixed femur that was required to achieve these loading conditions was recorded with the ACL intact, deficient, and after both AE and OT reconstruction. The order of testing was randomized following assessment of the intact knee for the ACL-deficient state, and both AE and OT reconstructions. After the first reconstruction, the tibial tunnel was back-filled with an allograft OATS (Arthrex, Naples, Florida) osteocartilagenous plug harvested from a separate cadaveric lateral femoral condyle to mitigate the possibility of tunnel break through.

The graft for the AE was a quadrupled semitendinosus autograft using the Arthrex Graftlink device for suspensory cortical fixation (Arthrex, Naples, Florida). The graft for the OT was a two-tendon semitendinosus and two-tendon gracilis construct. Four-tendon grafts were used for the OT to generate a graft diameter of 10mm, which was equal to that of the AE reconstruction. Graft length for the AE ranged from 50 to 60mm, while graft length for the OT ranged from 200 to 225mm. We maintained consistent graft diameter across reconstructions to minimize this factor as a source of variability between the reconstruction methods. The ACL was exposed through a medial parapatellar arthrotomy, which was sutured closed prior to testing each condition. All reconstructions were performed by the senior surgeon (FAC) assisted by the orthopaedic resident (MMM) to minimize variability in technique.

The AE (Fig. 2A) contained all-epiphyseal sockets on both the femur and the tibia.³⁰ The footprints of the native ACL were clearly identified and debrided. An outside-in femoral guide was placed at the center of the femoral ACL footprint such that the resulting tunnel was 1 to 2 mm from the posterior wall on the medial aspect of the lateral femoral condyle. The guide, set at 95°, was placed on the lateral epicondyle. The appropriately sized FlipCutter (Arthrex, Naples, Florida) was used to drill from the lateral cortex to the guide in the notch. The FlipCutter was then activated and used to drill the femoral socket to approximately 20 to 25 mm with at least a 7 mm bone bridge. The tibial socket was placed at the center of the ACL footprint on the tibia with the anterior horn of the lateral meniscus and tibial spine used as landmarks. The guide was set at approximately 60°, 15 mm medial to the tibial tubercle, and 20 mm distal to the joint line (proximal to the physeal scar). The FlipCutter was used to drill a socket approximately 20 mm long with at least a 7 mm bone bridge. The graft was then passed into the joint, retrograde into the femur and antegrade into the tibia. Fixation was through the TightRope Reverse Tensioning (RT) devices (Arthrex, Naples, FL) with self-tensioning suspensory cortical fixation in both epiphyses reinforced in the epiphysis with SwiveLocks (Arthrex, Naples, Florida) due to the risk of fracture in cadaveric bone. The graft was cycled ten times between 0 and 90° flexion under 89N (20lbs) of tensile load before fixation under tension at 30° knee flexion.

The OT (Fig. 2B) began with the tibial tunnel. The tunnel was more vertical and central than the AE tibial sockets used in this study and those that are currently advocated in the adult ACL reconstruction. The tunnel was drilled with the FlipCutter using the tibial alignment guide at 60°, 10 mm medial to the tibial tubercle, and 40 mm distal to the joint line (distal to the physeal scar). The over-the-top position on the femur was dissected and the graft passed through the tibial tunnel to the posteromedial aspect of the lateral femoral condyle and around the posterolateral condyle to the lateral aspect of the femur. It was secured to the femoral metaphysis with a staple (Synthes, West Chester, Pennsylvania) and with sutures tied over a post. The graft was cycled ten times between 0 and 90° flexion under 89N (20lbs) of tension before fixation to the tibial metaphysis at 30° flexion.

All kinematic pathways were determined for each state (ACL intact, ACL deficient, AE, OT) and each testing condition. Once the kinematic pathways were determined, a pressure sensor (4010N; TekScan, South Boston, MA) was placed beneath the menisci and each of the pathways were rerun for each condition. The pressure sensor was calibrated by loading it to 200 and 800N, and then fitting the output at these loads to a two-parameter power function. The calibration accuracy was verified by loading the sensor in an MTS loading system (MTS Systems, Eden Prairie, Minnesota). All positions and orientations required to achieve the prescribed loading conditions were replayed, and the contact stresses in the medial and lateral compartments were continuously recorded. Contact stress was characterized regionally on the medial and lateral compartments by dividing each compartment into six sectors (Fig. 3). Mean contact stress was calculated in each sector at the position and orientation of the knee corresponding to the maximum applied load. Sensors were recalibrated if a second acquisition of contact data yielded a change in contact stress > 10%.

Statistical Methods

A sample size of ten was required to detect differences of 1.5 ± 1.0 mm with 80% power in our primary outcome measure: anterior translation in response to combined valgus and internal rotation moments. Our sample size estimate included adjustment for our alpha value by the number of conditions in our study ($\alpha=0.05/4=0.0125$). This was selected as our primary outcome measure because it represents a clinically acceptable level of anterior subluxation of the tibia relative to the femur in response to a pivot shift exam following ACL reconstruction. The dependent variables are primary and coupled motions, and mean contact stresses in each sector of the medial and lateral compartments. Differences between all test conditions in knee kinematics and regional contact stresses for all loading parameters were assessed using generalized estimating equations (GEE) with post-hoc alpha adjustment by the number of comparisons ($0.05/6=0.0083$) using the Bonferonni correction. All analyses were performed using SAS version 9.2 (SAS Institute, Cary, NC).

Source of Funding

This investigation was supported in part by grant KL2RR024997 of the Clinical and Translational Science Center at Weill Cornell Medical College, by the Clark and Kirby Foundations, and by the Surgeon in Chief Fund at Hospital for Special Surgery. Donation of

surgical equipment by Arthrex is gratefully acknowledged. Special thank you to Sean Hazzard.

RESULTS

There was no evidence of graft failure in any of the specimens that were tested.

Kinematics

No significant differences in anterior translation were detected following the AE and OT reconstructions in comparison to the ACL intact knee between 0 and 30° flexion in response to anterior loads. The AE reconstruction resulted in 39% and 59% greater anterior translation than the intact knee in response to an anterior load at 60° and 90° flexion, respectively ($p<0.0001$) (Fig. 4). Similarly, the OT reconstruction led to 37% and 63% greater anterior translation compared to the intact knee in response to an anterior load at 60 and 90° flexion, respectively ($p<0.0001$) (Fig. 4). Anterior translation in response to the combined moments (simulated pivot shift) resulted in no significant differences between the ACL intact knee and either reconstruction at all flexion angles ($p>0.008$) (Fig. 5). Internal rotation in response to combined moments following the AE reconstruction decreased by 12% compared to the intact condition at 15° ($p=0.006$) (Fig. 6).

Posterior Contact Stresses

Following ACL sectioning, contact stress increased in both the posterocentral and posteroperipheral sectors of the medial compartment following ACL sectioning in response to an anterior load at all flexion angles tested ($p<0.001$) relative to the intact knee (Table 1, Fig. 7). With combined moments, contact stress increased in the posteroperipheral sector of the lateral compartment after ACL sectioning compared to the intact knee at 5 ($p<0.001$), 15 ($p<0.001$), and 30° ($p=0.005$) flexion, and in the posterocentral sector at 5 and 15° flexion ($p<0.001$).

Both the AE and the OT reconstructions acted to reduce posterior contact stresses in the central and peripheral sectors of the medial compartment relative to the ACL deficient knee in response to an anterior load at all flexion angles tested ($p=0.001$, Fig. 7). In response to combined moments the AE and the OT reconstructions also acted to reduce posterior contact stresses in the central and peripheral sectors of the lateral compartment relative to the ACL deficient condition at all flexion angles tested ($p=0.006$, Fig. 8).

Following the AE reconstruction, contact stress in the peripheral posteromedial sector remained elevated by 42% at 15° ($p=0.006$) and by 115% at 90° ($p=0.006$) (Fig. 7) relative to the intact condition in response to an anterior load. Contact stress in the central posteromedial sector also increased by 7% ($p=0.001$) and by 14% ($p=0.008$) at 30° and at 90°, respectively, with AE reconstruction compared to the intact condition in response to an anterior load (Fig. 7). The OT reconstruction had increased central posteromedial contact stresses by 27% at 15° ($p=0.008$) compared to the intact condition with an anterior load. No differences between the ACL intact condition and the AE reconstruction were detected in the posterolateral compartment in response to the combined moments. The OT reconstruction resulted in a 21% ($p=0.002$) increase in contact stress in the peripheral

posterolateral sector at 15° flexion in response to combined moments relative to the intact knee (Fig. 8).

Mid-Joint Contact Stresses

In response to an anterior load, the AE reconstruction increased midperipheral contact stress on the medial compartment compared to the OT by 22% ($p=0.004$), by 19% ($p=0.003$), and by 21% ($p<0.001$) at 30°, 60°, and 90° flexion, respectively (Fig. 7). The AE increased midperipheral stresses compared to the ACL deficient condition by 23% at 60° and the ACL intact by 43% at 90° ($p<0.005$). The AE decreased midperipheral and midcentral medial stresses compared to the ACL intact knee by 24% and 43%, respectively, at full extension ($p=0.005$). No other differences were detected in the remainder of the mid-joint contact stresses between either reconstruction and the intact condition in response to anterior load. No differences were detected in midcentral contact stresses on the medial compartment between the two reconstruction in response to an anterior load.

In response to the combined moments, the AE caused midperipheral and midcentral lateral contact stresses to increase by 24% and 14%, respectively, at 15° ($p<0.005$), (Fig. 8) compared to the intact knee. The OT also had increased midcentral lateral contact stresses by 25% at 5° ($p<0.005$). No differences in mid-joint contact stress were detected between the AE and OT reconstructions in response to the combined moments.

DISCUSSION

This study was designed to evaluate the ability of two commonly performed “physseal-sparing” ACL reconstruction techniques to restore regional contact stress and kinematics in response to clinically relevant tests of anterior and rotational stability. Both reconstruction techniques restored anterior stability at flexion angles less than or equal to 30° flexion. However, anterior translation remained above intact levels in both reconstructions, at 60 and 90° flexion. The AE reconstruction also reduced internal tibial rotation beyond intact levels under combined moments at 15° flexion to a small extent (12%). Some over-constraint to rotation may change the tibiofemoral compartment contact areas as Van De Velde et al⁴³ showed with ACL deficiency. However, this small change in constraint (12%) may not be clinically significant. Both reconstruction techniques offload the posterior aspect of the tibial plateau in response to both anterior loads and to combined moments as demonstrated by reduced contact stresses in this region compared to the ACL deficient condition. Neither the AE nor the OT completely restored the posterior joint contact stresses seen in the ACL intact condition. In the medial mid-joint the AE had increased contact stresses compared to the OT reconstruction between 30 and 90° flexion but it also decreased the medial mid-joint contact stresses compared to the intact knee at full extension. Neither reconstruction restored the lateral midjoint contact stresses completely in response to the combined moments.

Both the AE and the OT reconstructions restored anterior stability at flexion angles closer to full extension but were unable to restore anterior translation at higher flexion angles (between 60 and 90° flexion). Clinically, most cutting and pivoting activities occur closer to full extension; therefore, both of these reconstructions may be effective in preventing the instability associated with ACL deficiency. Both more closely restore the constraint

provided by the posterolateral (PL) bundle, which is the primary restraint to anterior forces at 0, 15, and 30°. ³⁶

The ability of the AE and OT reconstructions to reduce posterior contact stresses observed in the ACL deficient knee is important because abnormal contact stress may contribute to the development of osteoarthritis. ^{4, 37, 38} Decreasing elevated posterior contact stresses may also be important for preserving the menisci in juvenile patients because meniscal damage following ACL injury is an important determinant of joint degeneration. ^{4, 37, 38, 43} Biomechanically, meniscal preservation is important for stabilizing the knee, ²⁹ and reducing joint contact stress and increasing joint contact area. ^{5, 26} Neither the AE nor the OT completely restored native contact stresses in the medial and lateral compartments. However, both were an improvement over the stresses measured in the ACL deficient knee. This is important because it may prevent the degeneration of the chondral surfaces and menisci seen with ACL deficiency. However, long-term clinical studies are required to support this assertion with the AE technique.

Our findings suggest that the AE reconstruction could be a treatment option because it reduces posterior contact stresses, stabilizes the knee, and because it has several clinical advantages over the OT reconstruction. Specifically, the AE eliminates risk of growth disturbance, arrest, and angular deformities by avoiding transphyseal drilling. The OT technique requires an additional lateral arthrotomy for the passage and femoral fixation of the graft. This AE technique has no risk of physeal tethering; graft fixation distal to the tibial physis or proximal to the femoral physis may serve as a tether on the physis and may cause growth disturbances. ⁸ Furthermore, the AE reconstruction eliminates the need for postoperative hardware removal because it involves fixation that is entirely within the epiphyses. Since the entire AE reconstruction is distal to the femoral physis and proximal to the tibial physis, the graft should not be stretched as the individual grows. In addition, we speculate that this all-inside technique with blind-ended sockets may provide a better biologic environment for healing than the OT by avoiding the creation of tibial and femoral tunnels that communicate with the fascial and subcutaneous tissues. However, further research into tendon to bone healing in a blind socket is necessary.

Maintaining a constant graft diameter across specimens and reconstructions was a strength of this study because it eliminated this factor as a source of variation in our results. This strategy enabled better isolation of the effects of graft length and orientation, and fixation method across surgical techniques. To maintain equal diameters, the graft we used for the OT was made of four tendons (two gracilis tendons and two semitendinosus tendons) to obtain the desired 10mm diameter, whereas the AE graft was quadrupled. The OT technique used by Kennedy et al ¹⁹ used a doubled hamstring autograft. Clinical use of the four-tendon OT graft is not common since it would necessitate bilateral harvests. Since a smaller two-tendon graft is used clinically, our results likely over-represent the ability of the OT to stabilize the knee. Interestingly, we observed minimal differences in stability between the two reconstructions even though the graft length for the OT was about four-times greater than that of the AE. Given that increased graft length would decrease stiffness, we would expect the AE graft to provide more stability than the OT. Multiple factors may explain the similarities in stability between the two reconstructions. Specifically, more compliant

fixation in the AE technique could decrease stiffness of this construct and thus decrease knee stability. However, stability of the OT could be increased due to capturing of the graft as it wrapped around the posterior aspect of the femoral condyle. This could shorten the effective length of the graft, thereby increasing graft stiffness and thus increasing stability toward that of the AE.

A previous study on the biomechanical evaluation of “physeal-sparing” ACL reconstruction techniques reported that no single technique restored native knee kinematics.¹⁹ Similar to our findings, this group also observed that both the all-epiphyseal and the over-the-top reconstructions could not restore anterior stability to that of the native knee under an anterior load at deeper flexion angles.¹⁹ In addition, both our study and that of Kennedy et al., found that the AE and the OT techniques restored axial rotation to native levels at most flexion angles from 30° to full extension.¹⁹ However, we observed overconstraint of the AE under combined moments, which was not reported previously.¹⁹ This may be explained by differences in surgical technique including our use of a larger diameter graft for the AE (10mm versus 8mm). Furthermore, we applied different loads and enforced different boundary conditions than the previous work. In particular, we applied a combination of valgus and internal rotation moments simulating a pivot shift exam¹⁸ while Kennedy¹⁹ applied a moment in internal rotation. This provides additional support for assessment of knee function under combined valgus and internal rotation moments (i.e., a simulated pivot shift maneuver), not only because of their importance as a predictor of knee function and clinical outcome,²⁷ but because of their ability to differentiate between the biomechanical performance of the native and reconstructed knee.²⁷ Our study agrees with previous work reporting that ACL deficiency shifts medial tibiofemoral contact pressures posteriorly.⁴³ Van de Velde et al.⁴³ also reported in their in vivo work that the contact area decreased and the contacting cartilage was thinner in this posterior region. These may be important biomechanical factors that contribute to OA progression in those with ACL injury. Similar to our work, others also reported that AE reconstruction offloads the posterior aspects of the medial and lateral compartments of the tibia.⁴¹ Unfortunately, the previous work failed to include data from a control group with an intact ACL; therefore, they could not assess the ability of the AE to restore native articular contact patterns, despite potential implications of such comparisons in long-term OA development. The OT technique also did not restore loading patterns of the native ACL at 60 and 90° flexion in response to an anterior tibial load.²⁸ Similar to our work, these data suggest that the OT technique is unable to restore the mechanical behavior of the native knee at deeper flexion angles.

There are several limitations to this study. We utilized a time-zero cadaveric model, which provides no information on the effects of the reconstruction on knee joint biomechanics as healing progresses and rehabilitation ensues. *In vivo* clinical testing of knee stability is required to assess changes with time. While we are optimistic that decreasing the high posterior joint contact stresses seen with ACL deficiency is beneficial for preservation of the menisci and chondral surfaces, we currently have no clinical evidence on the long-term effect of either reconstruction. We utilized adult knees due to difficulty in obtaining juvenile donor tissue. Morphological differences between skeletally mature and skeletally immature knees including notch size²¹ may alter stability and contact mechanics.

Both reconstructions provide anterior and rotational stability, and decrease posterior joint contact stresses compared to the ACL deficient knee. However, both reconstructions exhibited some deficiencies in contact stress patterns and kinematics relative to the ACL-competent knee. Given that the AE reconstruction has clinical advantages over the OT, these results indicate that the AE technique is a potential candidate for use in the skeletally immature patient. Comparative clinical studies in juvenile ACL patients geared towards identifying the benefit of one reconstruction technique over the other are required to further substantiate our assertion. Such studies should incorporate both clinical and biomechanical measures to identify the best predictors of long-term outcome in juvenile patients.

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What is known about this subject?

There is an increasing prevalence of ACL injuries in skeletally immature patients and no consensus as to which ACL reconstruction technique provides the best outcome. At least one prior study examined the biomechanics of some of the ACL reconstruction techniques used in patients with open physes, but none looking at our particular all-epiphyseal physeal-sparing technique or the changes in tibiofemoral contact pressures with ACL deficiency and all-epiphyseal reconstruction.

What this study adds to the existing literature?

This study documents the biomechanical changes as well as the contact pressure changes in the knee joint when employing our all-epiphyseal ACL reconstruction technique. This technique provides both anteroposterior and rotational stability as compared to the ACL deficient state and comparable stability to the ACL intact state at certain flexion angles.

Figure 1. Testing Apparatus

The robotic manipulator allowed six-degrees of freedom measurement of knee kinematics in response to loads simulating clinical tests of knee stability.

Figure 2. ACL Reconstruction Techniques

A. All-epiphyseal ACL reconstruction with blind epiphyseal sockets on the femur and tibia secured with suspensory cortical fixation. B. Transtibial and over-the-top femur ACL reconstruction secured with staples and over a post.

Figure 3. Compartment sectors for contact stress measurements

Contact stress was measured using Tekscan stress transducers, which were sutured to the tibial plateau (left). The sensing area of the stress transducer was divided into medial and lateral compartments (right). Each compartment of the contact stress map was divided into posterior (Post), middle and anterior (Ant) rows and central and peripheral (Periph) columns. This yielded total of six sectors in each compartment. Mean contact stress was calculated in each sector at the maximum externally applied load for each loading condition and each flexion angle.

Figure 4. Simulated Anterior Drawer: Anterior Translation in Response to Anterior Load

Mean anterior translation in response to an anterior load at each flexion angle tested in the intact and ACL-deficient knee, and following the all epiphyseal (AE) and the over the top (OT) reconstructions. * $p < 0.05$ for comparison of the ACL intact and deficient conditions; § $p < 0.05$ for comparison of the AE or OT and deficient conditions; † $p < 0.05$ for comparison of the ACL intact and either AE or OT; ¶ $p < 0.05$ for comparison of AE and OT.

Figure 5. Simulated Pivot Shift: Anterior Translation in Response to Valgus – Internal Rotation Moment

Mean coupled anterior translation in response to combined valgus and internal rotation moments at each flexion angle tested in the intact and ACL-deficient knee, and following the all epiphyseal (AE) and the over the top (OT) reconstructions. * $p < 0.05$ for comparison of the ACL intact and deficient conditions; § $p < 0.05$ for comparison of the AE or OT and deficient conditions; ‡ $p < 0.05$ for comparison of the ACL intact and either AE or OT; ¶ $p < 0.05$ for comparison of AE and OT.

Figure 6. Internal Rotation in Response to Valgus – Internal Rotation Moment

Mean internal rotation in response to combined valgus and internal rotation moments at each flexion angle tested in the intact and ACL-deficient knee, and following the all epiphyseal (AE) and the over the top (OT) reconstructions. * $p < 0.05$ for comparison of the ACL intact and deficient conditions; § $p < 0.05$ for comparison of the AE or OT and deficient conditions; † $p < 0.05$ for comparison of the ACL intact and either AE or OT; ¶ $p < 0.05$ for comparison of AE and OT.

Figure 7. Anterior Load Contact Stress Patterns

The average for all specimens of the mean contact stress generated on the tibial plateau in response to an anterior load at 30 and 90° for the intact and ACL-deficient knee, and following ACL reconstruction using the all epiphyseal and over- the-top techniques. Anterior loads at 30 and 90° flexion simulated the Lachman and anterior drawer exams, respectively.

Figure 8. Valgus – Internal Rotation Moment Contact Stress Patterns

The average for all specimens of the mean contact stress generated on the tibial plateau in response to combined abduction and internal rotation moments simulating the pivot shift exam at 15° flexion for the intact and ACL-deficient knee, and following ACL reconstruction using the all epiphyseal and over- the-top techniques.

Table 1

Measurements

Angle (°)	Anterior Load											
	Posterior						Medial Compartment					
	Peripheral			Central			Peripheral			Mid-Joint		
	Intact	Deficient	AE	OT	Intact	Deficient	AE	OT	Intact	Deficient	AE	OT
0	0.39±0.38	1.1±0.93*	0.28±0.14§	0.51±0.50§	0.26±0.21	0.79±0.41*	0.20±0.16§	0.30±0.24§	0.25±0.11	0.24±0.37	0.19±0.14†	0.22±0.16
15	0.16, 0.61	0.51, 1.70	-0.16, 0.73	0.16, 0.87	0.14, 0.39	0.51, 1.07	0.00, 0.41	0.10, 0.51	0.18, 0.31	-0.03, 0.52	0.09, 0.30	0.10, 0.34
30	0.50±0.42	0.60±0.99*	0.71±0.58§†	0.76±0.76§	0.30±0.26	1.01±0.44*	0.32±0.22§	0.38±0.30§†	0.33±0.18	0.25±0.37	0.31±0.19	0.29±0.19
45	0.25, 0.75	0.95, 2.26	0.31, 1.11	0.28, 1.24	0.15, 0.46	0.66, 1.37	0.10, 0.53	0.17, 0.59	0.22, 0.43	-0.10, 0.59	0.15, 0.47	0.11, 0.47
60	0.53±0.51	0.82±0.97*	0.96±0.96§	0.85±0.92§	0.25±0.26	0.83±0.28*	0.33±0.27§†	0.36±0.38§	0.31±0.18	0.28±0.32	0.39±0.26†	0.32±0.22
75	0.23, 0.84	0.13, 2.50	0.33, 1.60	0.26, 1.43	0.10, 0.41	0.51, 1.15	0.13, 0.53	0.12, 0.60	0.20, 0.42	0.02, 0.35	0.13, 0.66	0.08, 0.56
90	0.55±0.44	0.53±0.88*	1.03±0.90§	0.95±0.92§	0.24±0.20	0.52±0.17*	0.28±0.16§	0.27±0.18§	0.35±0.16	0.35±0.25	0.43±0.24†§	0.36±0.21
105	0.29, 0.81	0.86, 2.20	0.37, 1.70	0.30, 1.60	0.12, 0.36	0.31, 0.74	0.12, 0.45	0.08, 0.45	0.26, 0.45	0.14, 0.56	0.26, 0.61	0.21, 0.52
120	0.40±0.33	0.70±0.87*	0.86±0.62§†	0.87±0.75§	0.21±0.17	0.49±0.18*	0.24±0.14§†	0.27±0.18§	0.28±0.12	0.38±0.23	0.40±0.20††	0.33±0.17
135	0.20, 0.59	0.65, 1.96	0.34, 1.39	0.30, 1.44	0.10, 0.31	0.27, 0.71	0.11, 0.37	0.10, 0.44	0.21, 0.35	0.18, 0.58	0.24, 0.56	0.19, 0.46
150												
165												
180												
Angle (°)	Combined Moments											
	Posterior						Lateral Compartment					
	Peripheral			Central			Peripheral			Mid-Joint		
	Intact	Deficient	AE	OT	Intact	Deficient	AE	OT	Intact	Deficient	AE	OT
0												
15												
30												
45												
60												
75												
90												
105												
120												
135												
150												
165												
180												

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		Combined Moments											
		Lateral Compartment											
		Posterior						Central					
		Peripheral						Central			Peripheral		
		Intact	Deficient	AE	OT	Intact	Deficient	AE	OT	Intact	Deficient	AE	OT
Mean, SD CI	5	0.37±0.22	0.71±0.40*	0.40±0.16§	0.41±0.20§	0.26±0.16	0.38±0.19*	0.25±0.12§	0.24±0.14§	0.55±0.32	0.62±0.39	0.59±0.40	0.51±0.27
		0.24, 0.50	0.44, 1.00	0.21, 0.60	0.21, 0.61	0.16, 0.36	0.23, 0.53	0.10, 0.41	0.08, 0.39	0.36, 0.74	0.28, 0.96	0.28, 0.89	0.23, 0.78
		0.48±0.28	1.10±0.58*	0.53±0.21§	0.58±0.27§†	0.31±0.16	0.54±0.15*	0.33±0.09§	0.31±0.13§	0.54±0.27	0.70±0.41*	0.67±0.36†	0.61±0.25
Mean, SD CI	15	0.31, 0.65	0.63, 1.57	0.24, 0.83	0.35, 0.81	0.22, 0.41	0.34, 0.73	0.18, 0.49	0.18, 0.44	0.38, 0.70	0.39, 1.00	0.40, 0.95	0.35, 0.87
		0.79±0.37	1.39±0.82*	0.75±0.24§	0.75±0.33§	0.42±0.16	0.63±0.25	0.39±0.10§	0.36±0.12§	0.56±0.48	0.55±0.45	0.64±0.35	0.61±0.34
Mean ± SD (95% CI)	30	0.58, 1.01	0.76, 2.03	0.41, 1.10	0.48, 1.03	0.33, 0.51	0.36, 0.89	0.24, 0.55	0.21, 0.52	0.28, 0.85	0.12, 0.99	0.21, 1.06	0.18, 1.04

Mean ± SD (95% CI)

Mean contact stress (MPa) ± one standard deviation of the intact, ACL deficient, All-Epiphyseal ACL reconstruction (AE), and over-the-top femur ACL reconstruction (OT) in response to combined abduction and internal rotation moments at 5, 15, and 30° flexion. 95% confidence intervals are in parentheses.

* p<0.05 for comparison of the ACL intact and deficient conditions;

§ p<0.05 for comparison of the AE or OT and deficient conditions;

† p<0.05 for comparison of the ACL intact and either AE or OT;

‡ p<0.05 for comparison of AE and OT.