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Orthopaedics

Analysis of Three-Dimensional In Vivo Knee Kinematics Using Dynamic Magnetic Resonance Imaging

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Patients continue to develop premature arthritis despite good subjective and objective evaluations of anterior cruciate ligament (ACL) reconstructed knees. Current objective evaluations have been limited to muscle strength examination, radiographic imaging, and laxity measurements. Anterior–posterior laxity measurements were originally developed to diagnose ACL insufficiencies; however, their application has been broadened to evaluate the success of ACL reconstructions. Although we recognize the importance of the meniscal function in preventing osteoarthritis, we do not have any means to evaluate meniscal kinematics after ACL injuries and reconstruction. In this article, we will highlight the importance of developing new methods in evaluating in vivo tibiofemoral and meniscal kinematics under dynamic conditions. We will also present our recent work on magnetic resonance analysis of knee kinematics under simulated weight-bearing conditions. We hope that we can extend this technique in dynamic evaluation of cruciate ligament injured knees. With better quantification of three-dimensional tibiofemoral and meniscal kinematics, we hope that we can improve our ability to diagnose, treat and critically evaluate our reconstructions for the cruciate ligament injured patients.

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Short-term follow-up studies of anterior cruciate ligament (ACL) reconstructions have documented high success rates; however, long-term follow-up studies have been less encouraging. ACL reconstructions can still lead to premature osteoarthritis despite good objective stability measurements. The clinical experience clearly demonstrates a lack of understanding and basic science knowledge regarding knee kinematics after ACL deficiency and reconstruction.

Currently, clinicians rely mostly on stability examinations on evaluating ACL-deficient knees. There are no current means that allow dynamic testing of the knee during various motions when the patients are symptomatic. The lack of detection severely hampered our ability to stratify patients after ACL deficiency. Moreover, all our treatment modalities, such as bracing, primary repair, and reconstructions are evaluated based on examinations such as radiographs, muscle strength, and laxity measurements. These are not "dynamic" tests that can detect pathology or symptoms that are usually present during activities. All our current stability measurements have been on tibiofemoral translations. Although we know the importance of the meniscus in preventing premature osteoarthritis and the interdependence between the medial meniscus and ACL, we have failed to focus on the significance of changes in meniscus kinematics after ACL injuries.

Three-Dimensional Knee Kinematics

Various techniques have been used to quantify the motion that occurs at the knee joint. These include the use of goniometers, 6-degrees-of-freedom linkage systems, optical tracking systems, the application of roentgen-stereophotogrammetry, and robotic technology. Goniometers have been

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used in the past; however, these are fairly imprecise and difficult to characterize motion that has 6° of freedom.[1,2] The accuracy depends highly on the interface between the skin and the linkage itself.[3] Modifications have include cortical pins that enable fixation of the linkage system to bone; however, this modification is only applicable to cadaveric specimens.[4-6] Optical tracking systems have evolved significantly over the years and have been used extensively to study knee kinematics in those patients who have ACL-deficient knees and in those who have undergone total knee-replacement surgery. They are versatile systems that allow the investigation of knee kinematics throughout various knee motions, such as stair-climbing, gait analysis, and cutting motion.[7-9] Roentgen-stereophotogrammetry has been used to characterize knee motion by determining the amount of translation between bony landmarks. Biplanar photography has to been used to characterize the complex 6-degree-of-freedome knee motion.[10-12] This method is more time-consuming and requires long exposure to radiation.

Robotic technology is an innovative methodology that has been used to study kinematics in cadaveric knees.[13-16] Combining the robotic manipulator, a highly accurate spatial linkage device, with a force moment sensor, the system consists of a feedback loop between knee kinematics and force vector measurement. Extensive research has been performed using robotic technology to study variables in ACL and posterior cruciate ligament (PCL) reconstructions, in situ forces in ligament grafts,[17,18] and the significance of multiligament injuries.[19,20] However, this current technology has been limited to the use in only cadaveric specimens.

All the above systems have allowed accurate measurements of knee kinematics; however, these methods are limited to measuring kinematics of the whole knee joint, namely the relative position between the femur and the tibia. Until recently, there has been no existing device that allows measurement of in vivo kinematics of intra-articular structures. Determining in vivo kinematics of intraarticular structures is difficult and challenging secondary to their inaccessibility within the knee.

Magnetic resonance imaging (MRI) has revolutionized the field of radiology. It provided a noninvasive method in evaluating soft tissue structures. Its application in the field of orthopaedics has changed the management of various common orthopaedic ailments. Injuries to intraarticular structures, such as the menisci, cruciate ligament, and collateral ligaments, can be accurately identified preoperatively using MRI.[21-24] Menisci motion in the cadaveric knee has been evaluated using MRI.[25,26] Even though this study was performed in cadaveric specimens, it was one of the early studies on kinematic MRI of the knee joint in evaluating motion of an intraarticular structure. Dynamic imaging can provide insights on injury mechanisms as well as treatment protocols. Currently, limited dynamic or kinematic MRI has been used in the analysis of patellofemoral joint mechanics, ligament insufficiencies and shoulder instability.[27-30]

Logan and coworkers[30] examined tibiofemoral kinematics in ACL-deficient knees by using an open MRI system under weight-bearing conditions and found anterior subluxation of the lateral tibial plateau. Scarvell and coworkers[31] compared tibiofemoral contact with movement of the femoral condylar centers in ACL-deficient knees by using a closed MR scanner under weight-bearing conditions. Both studies have shown that MRI can be used to study tibiofemoral kinematics. Although the open MR scanners used in some of the previous studies allow for greater knee flexibility, they are generally limited by lower magnetic field strength and poorer image quality. Moreover, to investigate the knee stability and the risk of injury in meniscus after rupture of the ACL, a simultaneous analysis of tibiofemoral and meniscal kinematics under weight-bearing conditions is necessary.

ACL Reconstructions

ACL reconstructions are now routinely performed after ACL injuries. The results of ACL reconstructions have improved tremendously with the evolution of a more anatomic and functional reconstruction. Reconstruction of the ACL using biologic grafts is now considered the “gold standard” for ACL reconstructions. Many studies have reported 85% to 95% success rate in short-term follow-up studies.[32-50] Even though most of the patients can return to their previous sporting activities, there are still a high number of re-ruptures, persistent pain, and early arthritis recorded in long-term follow-up studies.[51,52] A bone scan of the ACL reconstructed knee shows abnormalities even years after the reconstruction.[53,54] These reports have stimulated researchers to improve their reconstructive techniques and also search for means of better evaluating the ACL reconstructed knee.

ACL-reconstructed knees are currently being evaluated using subjective criteria, such as the patients’ symptoms with daily activities and functional tests. Objective evaluations focus mainly on laxity examinations, quadriceps strength, and radiographic findings.[55,56] These information are useful; however, they do not address the direct question on whether the ACL-reconstructed knee can restore the normal biomechanics of the knee joint itself. As mentioned earlier, laxity measurements only address anterior–posterior translations but do not account for rotational stability. Although the ACL is a primary restraint for anterior translation, it is also plays a key role in rotatory stability of the knee. Currently, there have been no studies on whether ACL reconstruction can restore in vivo kinematics of the menisci and cruciate ligaments and normal tibiofemoral kinematics during motion. Despite having high subjective knee scores and stable laxity measurements after ACL reconstructions, some patients can still develop premature arthritis. A more comprehensive and detail objective evaluation of the knee is crucial to determine the success of current treatment of ACL insufficiencies.

ACL reconstructions have traditionally been reconstructed using the “single-bundle” technique, with one femoral and one tibial tunnel. The intact ACL consists of 2 bundles, namely the anteromedial and posterolateral bundle, which tightens and loosens at various flexion angles.[57,58] Concerns have been voiced on whether a “single-bundle” ACL reconstruction is able to duplicate the complex biomechanical be-

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