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ACL UPDATE: OBJECTIVE MEASURES ON KNEE INSTABILITY (V MUSAHL, SECTION EDITOR)

Functional knee assessment with advanced imaging

Keiko Amano[1] · **Qi Li**[1,2] · **C. Benjamin Ma**[1]

Abstract The purpose of anterior cruciate ligament (ACL) reconstruction is to restore the native stability of the knee joint and to prevent further injury to meniscus and cartilage, yet studies have suggested that joint laxity remains prevalent in varying degrees after ACL reconstruction. Imaging can provide measurements of translational and rotational motions of the tibiofemoral joint that may be too small to detect in routine physical examinations. Various imaging modalities, including fluoroscopy, computed tomography (CT), and magnetic resonance imaging (MRI), have emerged as powerful methods in measuring the minute details involved in joint biomechanics. While each technique has its own strengths and limitations, they have all enhanced our understanding of the knee joint under various stresses and movements. Acquiring the knowledge of the complex and dynamic motions of the knee after surgery would help lead to improved surgical techniques and better patient outcomes.

Keywords ACL · Anterior cruciate ligament · Reconstruction · Advanced imaging · Knee joint · Knee assessment

Introduction

The anterior cruciate ligament (ACL) has an important function in knee stability. ACL tears can lead to injuries to other structures, and ACL reconstruction should prevent further injuries to the nearby structures such as the meniscus and cartilage. The reconstructed ACL, regardless of technique or graft type, is meant to restore the function of the native ligament, preventing the pivot shift, which is characterized by anterior translation and internal rotation of the tibia with respect to the femur during weight-bearing and cutting activities [1]. The overall outcomes of ACL reconstruction have been good, but failures such as persistent instability, discomfort, graft tear, and early cartilage degeneration still frequently occur [2–6]. It is thought that the lack of stability contributes to these complications; therefore, an effective biomechanical measurement as a method of identifying knee laxity is essential for improving the outcomes after ACL reconstruction [7]. Clinical exam maneuvers such as the Lachman, anterior draw, and pivot shift tests have helped clinicians diagnose and guide treatment. The pivot shift test, which combines both translational and rotational movements, has been shown to be most valuable [8] but requires experience and can often be inhibited by pain. It is also subjective, or semi-quantitative measurement at best, and dependent on patient cooperation.

The difference between transtibial and transmedial tunnel creation of the ACL graft raised new discussions surrounding the importance of restoring rotatory laxity, and since then various biomechanical studies, both in vitro and in vivo, have evaluated the effectiveness of the surgical techniques. The debate between single bundle (SB) versus double bundle (DB) has joined this discussion on accurately describing the static and dynamic function of the knee. Currently, there are a number of ways to measure biomechanical parameters, each with various advantages and disadvantages. Clinical exam

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✉ C. Benjamin Ma
MaBen@ucsf.edu

[1] Department of Orthopaedic Surgery, University of California, San Francisco, San Francisco, CA, USA

[2] West China Hospital, Orthopaedic Department, Sichuan University, Sichuan Province, China

maneuvers such as the pivot shift test, Lachman test, and the KT-1000, while relatively simple to use, have not produced the most reliable and reproducible results [9]. While other modalities such as computer-assisted surgery may be more reliable and precise, these procedures are invasive, labor intensive, and require a trained examiner. To address these challenges, some researchers have turned to imaging, as many of these protocols can be noninvasive and reproducible. Imaging also allows in vivo evaluation, accounting for other intra-articular structures such as ligament, meniscus, and cartilage. In this article, we will discuss some of the emerging methods of measuring biomechanics and laxity in ACL injured knees using advanced imaging, the advantages and disadvantages, and their use and potential in expanding to the clinical setting.

Radiography

Different radiographic techniques are widely used to research stability in ACL deficient and reconstructed knees. Stress radiography in particular has been used as a diagnostic tool to assess knee instability in all directions, but because it only provides two dimensional (2D) and static images, its use is limited in measuring dynamic functional knee assessment. Combining radiography with magnetic resonance imaging (MRI) and computed tomography (CT) can provide three dimensional (3D) geometry and motion of the knee, but most of them are often limited to static conditions. Despite these limitations, radiographic techniques such as fluoroscopic imaging techniques can still provide a dynamic way of measuring joint kinematics.

Passive stress radiography

Passive stress radiography offers an objective, quantifiable, noninvasive, and retrievable data for the diagnosis and assessment of knee ligamentous injuries. To date, numerous stress radiographic techniques have been reported for assessing knee instability. A systematic review of literature showed at least 16 stress techniques described for passive stress radiography of the knee, and the diagnosis of ACL injury showed excellent reliability and correlation with results of the pivot shift test [10]. Several techniques were used for measurements involving more than one plane of stability, such as the Telos device (Metax, Hungen-Obbornhofen, Germany) [11]. But there is still a lack of consensus as to which technique is best for assessing multiple knee instability parameters including rotational instability, one of the main concerns addressed in ACL surgery. The fact that passive stress radiography can only provide 2D, and static images would limit its further use for the functional assessment of knee kinematics unless newer techniques are explored.

Dynamic stereo-radiographic and fluoroscopic imaging techniques

Dynamic stereo-radiographic and fluoroscopic imaging techniques have also been used to measure human knee joint motion in vivo. All of these techniques are more complex, expensive, and invasive, including radiation exposure, but can provide high-precision measurement of knee kinematics which may be better than surface marker techniques [12, 13].

A number of these techniques require metallic marker implantation such as tantalum markers in both the femur and tibia bones prior to testing [14, 15]. These fixed markers are visible on X-ray images, helping to determine the joint positions and orientations during knee motion. This technique can evaluate tibial rotation and tibio femoral translational data in knee joint motion with relatively high accuracy. Using implanted tantalum markers and high-speed dynamic stereo X-ray images, altered landing kinematics were observed in ACL-reconstructed knees, including decreased flexion angle (20.9° vs 28.4°), increased tibial external rotation (12.2° vs 6.5°), and increased tibial medial translation (3.8 vs 2.3 mm) noted during single-legged hopping 5 months after ACL reconstruction when compared to the contralateral knees. These differences decreased over time, due to changes in both the ACL-reconstructed and contralateral ACL-intact limbs [10]. The invasive procedure of metallic marker implantation, however, may limit its wide clinical use.

Other new techniques without implanted markers have been set up for measuring dynamic motion of the knee, most of which include the 2D–3D image matching method [13, 16–18]. This method has been proposed for the accurate reproduction of the positions and orientations of the knee by registering the known 3D surface models of the femur and tibia to the captured dynamic fluoroscopic images during actual activities. 3D knee models could be based on 3D-MRI [16–19, 20•, 21, 22] or 3D-CT [23, 24•, 25] images, and a local coordinate system is created for each bone. Some of the more commonly used techniques are described below.

The dual fluoroscopic imaging techniques are widely used to examine ACL-related knee kinematics for higher accuracy and precision. Most recent dual fluoroscopic imaging techniques include an automatic 2D–3D image matching method that can automatically register the 3D surface models of the knee onto fluoroscopic images [17, 19, 20•]. When there is large range of motion about the knee joint, the fluoroscope may not be able to capture the entire knee joint image because of its limited image size. These incomplete fluoroscopic images may affect the reproduced joint positions. But with automatic matching method, even if only parts of the knee joint are available from fluoroscopy, it can still accurately reproduce knee joint positions. The dynamic spatial positions of the femur and tibia could be determined with an accuracy and precision of less than 0.15–0.23 mm in translation and 0.40°–0.43° in orientation [17, 26]. Using 3D MRI-based dual fluoroscopic technique, DeFrate et al. found that the ACL-deficient knee demonstrated an anterior shift (approximately 3 mm) and an internal rotation of the tibia (approximately 2°) at low flexion angles during a quasi-static lunge, as well as a medial translation of the tibia (approximately 1 mm) between 15 and 90° of flexion [16]. Chen et al. also found that ACL-deficient knees showed higher flexion angles and higher anterior tibial translation compared to the intact contralateral knees during the stance phase of the gait [22]. Using this technique, Hosseini et al. obtained images at different flexion angles as the patient performed a single-leg quasi-static lunge before and after transtibial bone-patellar tendon-bone (B-PT-B) ACL reconstruction. The results showed that reconstruction of ACL restored some of the in vivo cartilage contact biomechanics of the tibiofemoral joint back to normal. However, an abnormal posterior and lateral shift of cartilage contact location to a thinner tibial cartilage area at lower flexion angles persisted in ACL-reconstructed knees, a finding which had been described previously in ACL-deficient knees [18, 21]. Another study by Hosseini et al. demonstrated that combined ACL/meniscus injuries could alter the kinematics of the knee in a different way compared to isolated ACL injuries depending on the different patterns of meniscus tears [16].

The principle of the dynamic stereo-radiography with 2D–3D image matching method is similar with the dual fluoroscopic imaging technique and also widely used in ACL-related knee kinematics studies [24•, 25]. The main difference between these two techniques may be that dual fluoroscopy is mostly used for relatively low-demand tasks while dynamic stereo-radiography can provide short imaging times and high frame rates for more strenuous activities (Fig. 3) [13, 25]. With 3D-CT bone model-based dynamic stereo X-ray, Hoshino et al. found that greater tibial internal rotation was associated with larger magnitude of sliding motion in the medial compartment during downhill running [21]. They also observed that although anterior tibial translation was reduced in ACL-reconstructed knees, knee rotation increased compared to the contralateral knees in both SB and DB groups; therefore, the authors concluded neither SB nor DB ACL reconstruction restored normal knee kinematics or medial joint sliding [20•].

Thus far, most of the findings described by dynamic radiographic studies suggest abnormal kinematics in both ACL deficient and reconstructed knees, such as different flexion angles, excessive rotation either externally or internally, increased medial translation of the tibia, and abnormal cartilage contact areas during running or walking. These results suggest that kinematics is only partially restored after ACL reconstruction, and this may contribute as one of the causes of subsequent cartilage degeneration. These radiographic methods are becoming more widely available and are likely to provide further answers for better dynamic joint function and stability in ACL-related studies.

Computed tomography

3D reconstructions of CT scans are often combined with stereo-radiographic and fluoroscopic imaging techniques such as those in studies described above. 3D-CT-based bone shape analysis has also shown reliability in repeated measurements, which is required when measuring relevant morphologic features in clinical assessment and further research. Through knee 3D-CT analysis, Hoshino et al. found that femoral condyle offset ratio (COR) is a unique morphological feature that is measureable by 3D-CT. COR is larger in women and could be a possible risk indicator for ACL injury in the female population [27]. ACL studies using 3D-CT of the knee are mostly related to bone morphology and ACL injury risks and rarely involve kinematics [28, 29]. Possible reasons may be the limitation to static conditions, the lack of soft tissue visibility by CT scan, and more radiation exposure. Further utilization of 3D-CT imaging in knee kinematics assessment related to ACL research could be considered with higher resolutions.

Magnetic resonance imaging

MRI is used routinely to evaluate ACL tears and for pre-surgical planning, allowing visualization and evaluation of soft tissues that act to stabilize the joint, such as the meniscus and the other ligaments. It also allows good visualization of bone. Like CT scans, MRI can provide 3D reconstructions of the joint, but this can be expanded to include the soft tissues, offering additional ways of evaluating the functional stability of the knee. Both static and dynamic measures are possible using closed and open MRI.

Closed MRI scanners can provide measurements for anterior translation and rotation of the tibia with respect to the femur that may not be easily detected by physical examinations alone. Because of the details available in multiple slices, biomechanical measurements lower than 5 mm, which may be difficult to assess manually on exam, can be taken. There are several ways of calculating these biomechanical parameters. One is to take measurements on individual slices [30, 31], while others create a 3D model of the joint to estimate the bony positions. As such, anterior translation and rotation of the tibia can be evaluated in various ways. Tanaka et al. used a method of estimating tibial translation by taking measurements on single individual slices in the sagittal plane, selecting specific slices from the medial and lateral compartments that meet certain criteria. They found significant differences in the anterior subluxation of tibia between normal knees, ACL-deficient knees, and failed ACL-reconstructed knees [32]. On the other hand, in addition to measuring tibial subluxation, Vassalou et al. used axial images to measure tibial rotation to

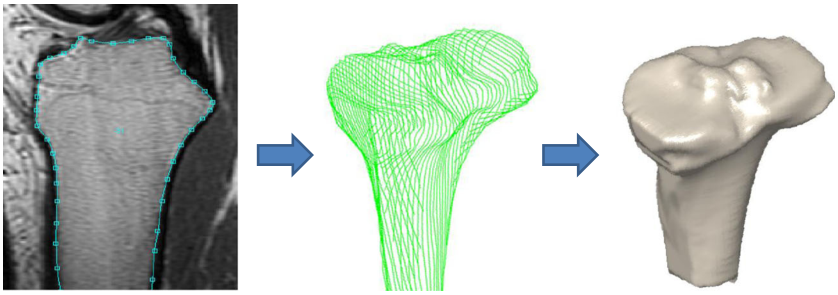

Fig. 1 3D cloud points are generated from semi-automatic segmentations on T2 FSE images to generate a 3D representation of the tibia. Image courtesy of Musculoskeletal Quantitative Imaging Research, University of California, San Francisco

compare ACL-deficient knees with a control group [33]. These single slice measurement techniques have also been useful in the evaluation of different surgical techniques. Yau et al. used both axial and sagittal sequences to estimate the femoral tunnel position and found that transportal technique showed better results than transtibial technique at 1 year follow-up [34]. In another study, Noh et al. also used sagittal images but used a different method to determine the femoral tunnel aperture and position [35]. These methods of using individual slices for measurements are relatively simple, inexpensive, repeatable, and reproducible, but anatomic variability between individuals may potentially introduce inaccuracies into the measurements.

3D reconstructions of MRI is another option, often using modeling and bony landmarks as reference [36–38, 39•, 40, 41]. These models can be used on various anatomical variants, albeit to different degrees depending on the method, and can offer a series of comprehensive measurements in various planes (Fig. 1). Scanlan et al. used 3D surface modeling from MRI segmentations to estimate the anterior translation of tibia and correlate this with loss of extension after ACL reconstruction using the transtibial technique [40]. Lansdown et al. introduced a method of measuring tibial translation and rotation using a semi-automatic segmentation method with high reliability [42]. A limitation of using closed MRI is that the patient is supine during the scan, and this may represent an inaccurate estimation of biomechanical measurements in a weight-bearing limb. However, these groups have addressed this limitation by creating MRI compatible devices, such as a pulley system to apply axial force, as substitutes for ground reaction force present during weight-bearing activities [42]. Devices are also used to place anteriorly directed force on the tibia to measure anterior translation, although this may differ from simulating weight-bearing conditions [30].

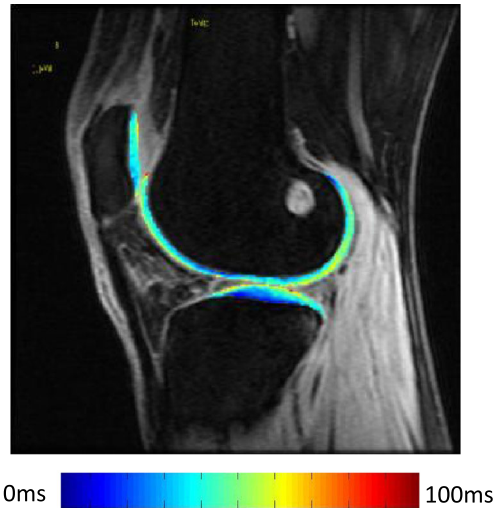

Fig. 2 Color map of $T_{1\rho}$ relaxation times which correlate with proteoglycan content within the articular cartilage. Image courtesy of Musculoskeletal Quantitative Imaging Research, University of California, San Francisco

Open MRIs offer the advantage of acquiring images at various positions, including standing positions during actual weight-bearing, referred also as upright MRIs. Tracking methods are employed to collect consecutive images from the same knee, allowing motion by the subject. Apparatuses designed to apply standardized forces across the joint may at times be employed as well [43, 44]. Patients may be upright and gradually flex their knees while the scanner acquires images at set flexion angles [45, 46]. Open MRIs, however, have the disadvantage of lower spatial resolution, but Olender et al. was able to combine data from open MRI with closed MRI with much higher resolution using a cadaver knee [47]. As mentioned above, fluoroscopy could also provide valuable details that cannot be acquired by open MRI. Lenhart et al. used data from static MRI and closed MRI while combining these imaging data with dynamic musculoskeletal modeling, while also using an apparatus to mimic weight-bearing [48•]. While this may be a very comprehensive method of

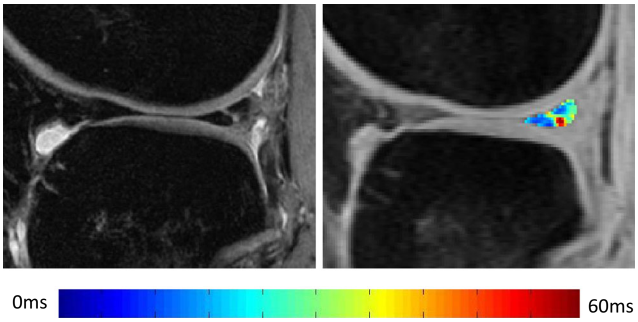

Fig. 3 *Left image* shows high-resolution 3D FSE showing meniscus tear in the posterior horn of the lateral meniscus. *Right image* shows $T_{1\rho}$-weighted image shows a color map overlay of $T_{1\rho}$ relaxation times corresponding to the tear. Image courtesy of Musculoskeletal Quantitative Imaging Research, University of California, San Francisco

understanding knee dynamics and multiple interactions between the knee structures, the study was limited to one subject. Despite the use of these semi-dynamic MRIs, these active movements may not reflect the complexities of higher level activities such as cutting. Likewise, studies that combining MRI measurements with other data such as motion analysis and physical exam maneuvers like pivot shift tests may bridge the imaging measurements with more complex, real-life movements.

MRIs offer additional options of studying biomechanics by visualizing the soft tissues. The menisci, which are also stabilizers of the knee joint, can be assessed to evaluate laxity. Shefelbine et al. used 3D modeling to estimate the position of the menisci using manual segmentation on sagittal slices and interpolation in ACL-deficient knees [49]. More recently, Nagazaki et al. analyzed changes in meniscus positions after ACL reconstruction. By taking measurements on individual slices, they found significant differences between pre- and postoperative measures [50, 51]. Other studies have focused on soft tissue characteristics as surrogates that can be correlated to knee laxity described by physical exams. The position and status of the reconstructed ligament itself has been explored as indicators of laxity [52, 53]. ACL characteristics such as signal intensity and graft obliquity were correlated to physical exam findings from the Lachman test [54]. In addition to meniscus and ligaments, cartilage compression and deformation may also be viewed as surrogates of unusual loading patterns. Sutter et al. used compression seen in cartilage to understand the mechanics involved in hopping activities by creating a 3D surface model [55].

Quantitative MR (qMR) adds further ability to assess soft tissues of cartilage and meniscus by measuring quantifiable parameters of the extracellular matrices themselves. The changes seen within cartilage or menisci have been studied in its relationship to biomechanical findings under the hypothesis that development of early cartilage degeneration seen in ACL-injured patients is due to altered biomechanics [56, 57]. Various qMR techniques have been applied. Neuman et al. used gadolinium-enhanced magnetic resonance imaging of cartilage (dGEMRIC) to compare cartilage of ACL copers to normal individuals [58]. Zaid et al. used $T_{1\rho}$ and T_2 relaxation times and found moderate correlation between these measurements in cartilage and altered biomechanics (Fig. 2) [39•]. In addition to cartilage, Wang et al. also found elevation of $T_{1\rho}$ and T_2 in the menisci of ACL-injured knees (Fig. 3) [59]. While these measurements themselves may not be considered "functional" in the traditional biomechanical sense, this may provide an alternative to estimate joint laxity and the its proceding consequences. Perhaps, one of the greatest advantages of MRI is the acquisition of numerous data at the same time. Different sequences can offer information on different tissues and measurements from multiple planes, and this can be performed in one sitting.

Conclusions

This article has focused on measuring the functionality of the knee with emphasis on changes in biomechanics seen after ACL injuries. The use of advanced imaging is very exciting, but there are currently no standardized methods between the various techniques. In addition, imaging equipment and image processing software may vary between institutions, making standardization and comparisons difficult. The cost is also a factor that could influence the availability of these modalities. As 3D data and soft tissue details can be acquired by advanced imaging, laxity measurements using these methods can provide comprehensive information regarding the knee joint. An establishment of uniform measurements may help expand this technology to wider use and perhaps to routine clinical practice. We do believe that advanced imaging of joint kinematics have and continue to lead to improvement in management of ACL injuries.

Compliance with ethical standards

Conflict of interest Keiko Amano and Qi Li declare that they have no conflict of interest.

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