Instrumented Measurement of the Multiple-Ligament-Injured Knee: Arthrometry, Stress Radiography, Rotationometry, and Computer Navigation

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Introduction

The multiple-ligament-injured knee presents a variety of unique challenges. Among the many significant challenges are the accurate clinical diagnosis and classification of the ligamentous and soft-tissue injuries. The history (i.e., mechanism) and clinical exam are the most important elements of assessment of the knee. Instrumented ligament laxity measurement is an important adjunctive diagnostic tool available to the clinician.

The most important application of instrumented examination in the dislocated knee is for confirmation of the clinical diagnosis determined from history and physical examination. This quantitative information used in conjunction with appropriate diagnostic imaging can lead to a more accurate diagnosis of the anatomical structures affected and, in turn, more effective and safer treatment of the patient's knee injury. Any application of physical stress to the knee joint, however, should take place only after the patient has been deemed to be in stable condition and a possible vascular lesion has been ruled out. In addition, appropriate analgesia is of paramount importance, as many of the instrumented measurements require some level of stress on the joint and therefore can lead to significant pain. Muscular "guarding" by the patient due to discomfort can lead to erroneous measurements being obtained.

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Indications and Reasons for Instrumented Measurement

While not essential for diagnosis, there are a number of advantages to using instrumented measurements of knee ligament laxity to enhance the standard physical examination. Objective measurements are helpful to the clinician when documenting the extent of injury and are essential to the researcher. They can also be helpful when communicating with the extended health care team in certain cases, including the primary care sports medicine physician, physiatrist, physiotherapist, or athletic trainer.

Diagnosis

Accurate diagnosis of the multiple-ligament-injured knee is crucial, as it ultimately defines the type and extent of surgical intervention necessary to restore function. X-ray and magnetic resonance imaging (MRI) form an indispensable part of the clinical workup but MRI, in particular, should not be relied upon in isolation to determine the correct medical treatment. For instance, the difference between a partial and a complete ligamentous rupture may be difficult or impossible to determine using MRI imaging alone, but that difference could have a profound effect on surgical planning.

Instrumented testing can provide a more objective and dependable measure of laxity, and, therefore, assist with differentiation of complete versus partial ligament injuries, leading to a safer and more effective treatment.

Although advanced soft-tissue imaging is now relatively standard, there are cases and situations where these evaluations may not be diagnostically helpful. Patients may have significant artifact secondary to previous injury or surgery rendering the examinations uninterpretable.

Some patients will have a contraindication for MRI, such as indwelling ferrous metallic material, pacemaker, or defibrillator. Another growing problem is the difficulty encountered in imaging patients who are morbidly obese, a patient

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group that also happens to be at greater risk for multiligament knee injury.

Postop

By comparing instrumented measures pre- and postoperatively, one can quantify the clinical effect of the surgical intervention. A direct comparison with the same measurement tool using the same technique can provide immediate postoperative information to the surgeon on the effect of the repair or reconstruction.

Follow-Up/Rehab

In follow-up, either post-injury or postoperatively, repeated instrumented measurement can provide insight into the integrity of the repair or reconstruction, or reveal residual clinical instability. This can be especially beneficial after a reinjury, as postoperative changes may make imaging-based diagnosis more challenging. Having an objective measurement to compare against can lead to a clearer clinical picture.

Methods of Measurement

Stress Radiography

Posterior Stress

Stress radiographs are most indicated and most helpful in defining the posterior displacement of the tibia relative to the femur [1]. The degree of that displacement reflects the integrity of the posterior cruciate ligament (PCL) and the posterolateral or posteromedial corners (PMCs) of the knee. There are numerous described techniques for stressing the posterior structures, and the four most common are presented below.

Hamstring Contraction

The active resisted hamstring contraction radiograph is performed by having the patient assume the lateral decubitus position with the index knee dependent, and flexed 90°over an X-ray cassette to obtain a true lateral view. The patient is then asked to actively contract their hamstrings against resistance at the heel, while knee flexion is maintained at 90° (Fig. 5.1). The resultant lateral radiograph of the knee can then be measured, assessing the posterior tibial displacement. In one comparative study, the hamstring contraction stress view showed similar results to the Telos stress device, and far greater accuracy than the axial stress view [2].

Fig. 5.1 The active resisted hamstring contraction stress X-ray. The patient is performing an active maximal hamstring contraction against resistance in the lateral position. The X-ray is done during the maximal contraction. (From Carsen and Johnson 2013 [36]. Reprinted with permission)

Axial View

A modified axial patellofemoral radiograph has been described as a quick and easy form of stress view to assess the integrity of the posterior structures of the knee. The patient is positioned supine with the knees flexed to 70°, feet flat on the table in moderate plantar flexion, and the tibia in neutral rotation. The X-ray beam is then directed from distal to proximal and parallel to the longitudinal axis of the patella, at an upward angle of 10° to the X-ray table. Early results of the technique were promising [3]. However, more recent multi-technique comparisons have shown it to be a less reliable technique compared to the alternative stress views [2, 4].

Posterior Sag/Gravity View

The patient is positioned supine on the X-ray table, and both the hip and knee are flexed to 90°. The tibia is held in place in neutral rotation. A true lateral radiograph of the knee is then obtained. The method is quick and easy, but has not compared favorably to other stress views [4].

Kneeling Stress View

The stress view yielding the best and most reliable results thus far is the kneeling stress view. The patient kneels on a bench or similar structure with the knee over the edge of the bench (i.e., the femoral condyles are past the bench, while the tibial tubercle is supported by it). The knee is maintained at 90° of flexion. A true lateral radiograph of the knee is then taken. Measurement of displacement is then performed using the posterior cortex of the tibia and posterior cortex of the

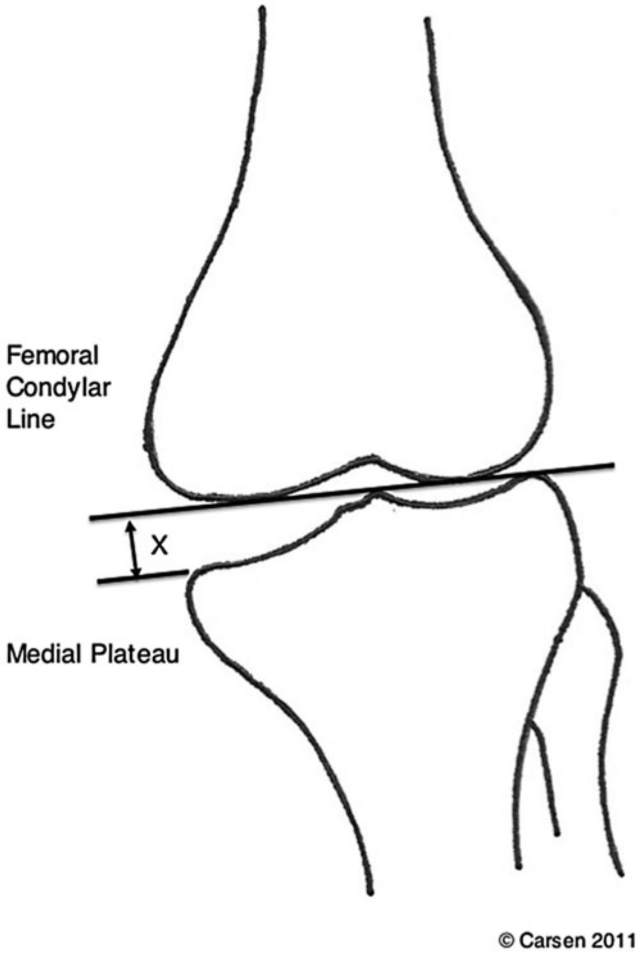

Fig. 5.2 The opening of the medial joint space is measured in millimeters. (From Carsen and Johnson 2013 [36]. Reprinted with permission)

distal femur. The kneeling stress view was found to have very high inter- and intra-observer reliability [5], and to be reliable evaluation of posterior laxity [6].

Of note, however, a recent study comparing Telos stress views to kneeling stress views showed significantly different displacement measurements—both pre- and post-reconstructive surgery [7]. This has been hypothesized to likely be due to the difference in force placed on the anterior tibia with the two techniques. Further study will therefore be required to better define normative displacement measurements for the kneeling exam. Moreover, a larger comparative study to other available methods is necessary to determine the value of the kneeling stress view in quantitating the posterior instability.

Valgus Stress

A valgus force applied to the knee will put stress on the medial collateral ligament (MCL) opening the medial compartment and allow for grading of MCL injury. The patient is positioned supine on a radiolucent table, and their knees bound together. The examiner is then able to apply valgus stress to both knees by attempting to separate the patient's feet from the foot of the bed. The knees should be maintained in approximately 10–15° of flexion, and the feet slightly externally rotated while performing the stress. An anteroposterior (AP) radiograph is then taken of the knee at the endpoint of displacement. Displacement is measured from the medial plateau to the femoral condylar line [8] and the uninjured knee is used as the control (normal) value (Fig. 5.2).

Varus Stress

Varus stress radiography has been found to correlate well with MRI findings and be helpful in determining which lateral/posterolateral corner injuries should be surgically repaired or reconstructed [9]. Gawthmey et al. found that a lateral joint opening averaging 18.6 mm (range 10.0–36.5 mm) was associated with a complete posterolateral corner (PLC) disruption on MRI while an opening of 12.8 mm (range 7.5–17.0 mm) was reflective of a partial tear. Opening in operative cases that underwent PLC stabilization was, on average, 16.5 mm (11.0–36.5 mm) versus 11.0 mm (range 7.5–13.5 mm) in those that were treated nonoperatively [9].

Advantages

- Cost-effective
- Some protocols have very good reliability and effectiveness

Disadvantages

- Training for clinicians and radiation technologists
- Standardization of protocols is necessary to obtain comparable data

Instrumented Stress Radiography

Telos Stress Radiography

The Telos Stress Device (Austin and Associates Inc. Fallson MD) is a commercially available system that allows for the application of consistent and reproducible stress forces to the index knee joint, while radiographs are obtained (Fig. 5.3). Measurement of displacement on the radiograph can then be performed. Depending on the patient's position and device's orientation, it can be used to stress the tibiofemoral joint

Fig. 5.3 The stress X-ray examination of the PCL-deficient knee with the Telos device. (From Carsen and Johnson 2013 [36]. Reprinted with permission). *PCL* posterior cruciate ligament

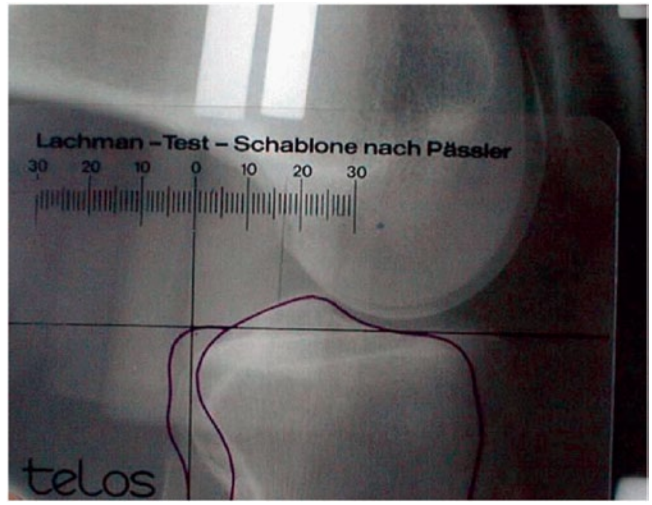

Fig. 5.4 The Telos stress X-ray with the measuring template. (From Carsen and Johnson 2013 [36]. Reprinted with permission)

anteriorly, posteriorly, medially, or laterally, thereby assessing the ACL, PCL/PLC/posteromedial corner (PMC), MCL, and lateral collateral ligament (LCL), respectively.

Posterior Stress

To perform a posterior stress X-ray utilizing the Telos device, the patient is positioned in the lateral decubitus position, index knee dependent on the radiolucent table. The knee is positioned at 90° of flexion inside the Telos device (Fig. 5.3). The knee must be in neutral rotation. A 15-kPa force is exerted on the anterior tibial tubercle, and a lateral X-ray is performed. The knee must be positioned in a true lateral position, which should be confirmed by superimposition of the lateral and medial femoral condyles on the radiograph.

Measurement of displacement is performed by using the Telos template, aligning the inferior horizontal line parallel to and overlying the tibial plateau. The perpendicular "zero" line is then lined up with the posterior border of the tibial plateau. The measurement of posterior displacement is then made in millimeters between the posterior border of the tibial plateau and the posterior border of femoral condyles.

The degree of posterior displacement is measured with a template on the lateral stress X-ray (Fig. 5.4). In this example, the posterior displacement is 17 mm.

The difficulties with this method are:

- It is essential to have a true lateral X-ray with the femoral condyles overlapping as shown in Fig. 5.4.
- The template must be accurately positioned to ensure reproducible measurements.

One of the most significant challenges with the Telos system is ensuring standardized measurement. Following a standardized protocol when performing the radiographs produces reliable and reproducible measurements [10].

A recently published study conducted over 12 years using the Telos device for the evaluation of knee instability in more than 1000 patients found it to be reliable and effective at diagnosing posterior laxity [11]. They found that a measurement of greater than 8 mm of posterior displacement was diagnostic for complete PCL rupture, while a measurement of greater than 12 mm was indicative of injury to secondary supporting structures as well (PLC and/or PMC).

Anterior Stress

The Telos system has not been as helpful in assessing the magnitude of anterior laxity of the knee. Rijk et al. found that an anterior displacement of more than 7 mm was abnormal, with a false-negative rate of 12% [12]. The patient and device positioning for anterior stress testing is essentially identical to the posterior stress exam, with the position reversed.

Recently, Dejour et al. demonstrated that the Telos device in conjunction with clinical examination (pivot shift test) was helpful in differentiating partial from complete ACL ruptures [13].

Advantages

- Accurate measurement of the posterior displacement with a template.

Disadvantages

- The use of X-rays/radiation.
- The radiological technician must be trained in the correct use of the device.
- Expense of the Telos device.

Knee Ligament Arthrometers

KT-1000/2000

The KT-1000 and KT-2000 (the KT-2000 is essentially the same as the KT-1000 but with an added graphic plotting interface) are arthrometers that measure anterior–posterior tibiofemoral translation (i.e., translation in the sagittal plane only).

Anterior

The KT-1000 knee ligament arthrometer (MEDMetric Corp., San Diego, CA), developed by Dale Daniel and Larry Malcolm [14], has become the standard for the measurement of ACL laxity. Starting from its introduction in the early 1980s, it has continued to be found to be accurate and reliable in the measurement of anterior translation of the tibia on the femur [15]. It has proven to have strong reliability, with good inter- and intra-rater performance [16]. It has recently performed equally compared with intra-operative computer-assisted surgery/navigation [17]. The device is used with the patient supine and a support platform placed under both thighs to maintain approximately 25–35° flexion of both knees. The feet are supported on the lateral aspects by a second platform to ensure the same relative rotation of both lower legs. This position is ideal for the performance of an instrumented Lachman test on both knees. The arthrometer is placed secured with Velcro straps on the knee and lower leg such that the force pad is located over the tibial tubercle, and the patellar pad is resting on the anterior surface of the patella. The patella pad is gently stabilized while the force handle is pushed and pulled to achieve tibiofemoral translation readings (Fig. 5.5). The maximum manual test has been found to have the highest diagnostic value for the determination of ACL laxity and is performed by using a hand behind the calf to produce a maximal anterior translation force [18].

The best results with the KT-1000 are obtained when comparing side-to-side difference within the same patient, and when the same examiner performs the repetitive exams. Though the KT-1000 arthrometer is simple to use, there is still an association of increased accuracy and reproducibility with the experienced user.

Posterior

The KT-1000 has not, however, achieved the same level of acceptance for the quantitative measurement of posterior instability. Daniel [19] described the method of measuring posterior laxity by first determining the quadriceps neutral point.

The principle of the measurement as described by Daniel is to determine the four levels of anterior-to-posterior motion:

- Anterior
- Quadriceps neutral
- Posterior sag
- Posterior displacement

Initially, the patient contracts the quadriceps muscle sufficiently to bring the tibial forward to the "quadriceps neutral" position.

The posterior motion from this point is then recorded as the posterior sag, and then the posterior displacement with 20 pounds of posterior force is measured and noted as the posterior displacement (Fig. 5.6). The total amount of posterior motion is determined when these two later values are added.

In our experience, it is often difficult to get the patient to contract their quadriceps sufficiently to bring the tibia fully forward to the neutral position. This amount of forward displacement is often underestimated. Johnson presented a study to the PCL study group in 1995, comparing the KT value against the stress X-ray [20]. The results were:

When the millimeters of displacement of the KT is expressed as a percentage of the Telos:

Fig. 5.5 This photo shows the KT-1000 device used to measure the anterior tibial displacement

Fig. 5.6 This photo demonstrates the KT-1000 device positioned to measure posterior tibial translation

> 10 mm of posterior displacement—the KT is 65 % of the Telos
< 10 mm of posterior displacement—The KT is 72 % of the Telos

The KT-1000 measurement underestimates the degree of posterior instability when compared with the Telos stress X-ray, and this difference is more pronounced when the posterior displacement is greater than 10 mm. The PCL-deficient knee is, therefore, best quantitatively evaluated with stress X-rays.

This underestimation of displacement by the KT-1000 was also confirmed by Noyes et al. [21], who found that stress radiography was superior to both arthrometer and clinical posterior drawer testing. His group determined that 8 mm of posterior displacement was the cutoff for complete PCL rupture [21].

This study confirms that the measurement of the posterior displacement is more accurate with the stress X-ray, especially in cases where the posterior displacement is greater than 10 mm.

Another study by Harner et al. [22] compared a novice and an experienced user of the KT-1000 device and found that the device was a moderately reliable tool to evaluate PCL laxity. This was a small group of patients, most having less than 10 mm of posterior laxity.

Advantages

- Widely used and accepted method of measurement of anterior displacement in the ACL-deficient knee
- Widely available

Disadvantages

- Underestimates the degree of posterior instability, especially when more than 10 mm of posterior displacement is present.

Knee Laxity Tester

The use of the knee laxity tester (KLT) arthrometer (Orthopedic Systems Inc., Hayward CA) or Stryker Knee Laxity Tester (Stryker Inc., Kalamazoo, MI) likely hit its peak in the 1990s, and though the arthrometer is no longer available, it is still used by some and was highly tested. Like the KT-1000, the KLT measures tibiofemoral translation in the sagittal plane.

Anterior

The technique is similar to the KT-1000, and has produced similar results [23].

Posterior

The measurement of posterior laxity has been described by Cannon [24]. The patient is positioned sitting with the knee flexed to 90° over the end of a table. The patient actively contracts the quadriceps. At this quads' neutral point, the instrument is set to 0. The tibia is then displaced posteriorly with a 20- and 40-pound force. The displacements are recorded. The authors [25] found that the arthrometric measurements correlated well with the clinical examination. The arthrometer was also able to detect subtle grade 1 injuries.

Advantages

- The knee is held in the 90° position and it may be easier for the patient to perform the quads active test

Disadvantages

- The instrument is not widely available
- The 71° position was determined by Daniel to be the optimum position to measure the quads active position.

Rotationometer/Laxiometer

The ligament augmentation and reconstruction system (LARS) rotational laxiometer (LARS, Dijon France) was developed specifically to measure the degree of rotation of the tibia relative to the femur. It is a simple device, which can be strapped externally to the subjects' tibia and measures rotation in a noninvasive manner. Objective measurement of external and internal rotation of the tibia at 30 and 90° of knee flexion provides an indication of clinical PLC and PMC laxity (Fig. 5.7).

This device has been validated by measuring the normal variation of tibial rotation [26]. Baseline values of the degree

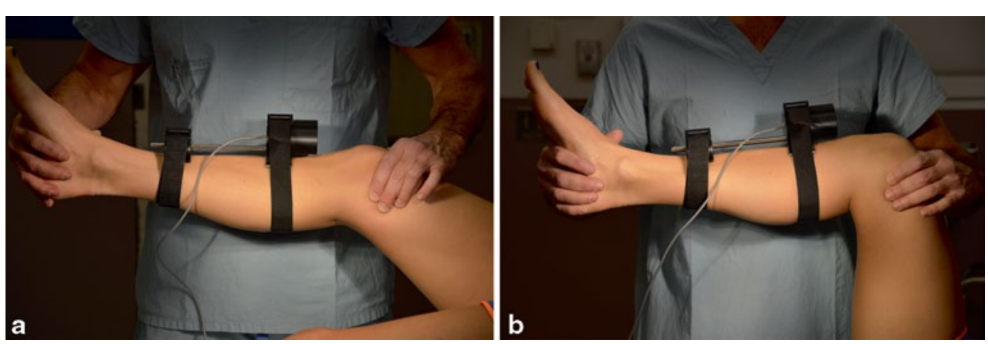

Fig. 5.7 The rotational laxiometer used to measure the external rotation of the tibia at 30° (**a**) and 90° (**b**) of knee flexion

of normal external rotation of the tibia at 30 and 90° have also been established. Three authors each examined 30 asymptomatic patients to determine the side-to-side difference. At 90°, the side-to-side difference was 4.4° (range 3.7–5.1) and at 30° the difference was 5.5° (range 4.7–6.3) [26].

It can be extrapolated that any measurement above these numbers is abnormal and indicative of pathological posterolateral corner laxity. The LARS rotational laxiometer is also a useful device to assess the rotational stability of reconstructed knees postoperatively. One caveat to the use of the rotational laxiometer, as pointed out by the validating authors [26], is that the device is not able to measure the moment applied by the observer during testing or to cancel out the coupled motion of the femur. It is also important to note that when using this device in the presence of PCL deficiency, it is necessary to correct for the posterior sag of the tibia by first performing a quadriceps contraction neutralization prior to evaluating tibial rotation.

Advantages

- Measures external/internal tibial rotation

Disadvantages

- The device requires two people to operate properly when posterior sag is present.
- The device is expensive and not widely available

Computer-Assisted Navigation

Recently, there has been significant progress in the area of computer-assisted surgery (CAS). The role of computer navigation in soft-tissue knee reconstruction surgery has largely focused on accurate tunnel and fixation positioning. However, with increasingly accurate mapping and navigation technology, many of the CAS systems, such as the OrthoPilot system (Aesculap Implant Systems, Center Valley, PA), are now able to intraoperatively measure knee kinematics in multiple planes.

With growing interest in CAS, there have been a number of groups studying the accuracy of various systems in accurately mapping and plotting the kinematics of the knee. Results thus far have been promising, with accuracy measured within 1 mm or 1–2° [27–29]. A recent study comparing computer navigation to the KT-1000 in determining the degree of ACL deficiency found the two approaches to yield comparable results [17]. The keys to obtaining accurate measurements with CAS are familiarity with program (each system has its own learning curve), accurate placement of bony navigation markers, and proper system calibration.

The future of CAS holds great promise, and it should allow for improved accuracy and reproducibility in the measurement of laxity of the knee in all planes and, in particular, in complex multiplanar movements. It is likely to be of value in assessing immediate pre- and post-reconstruction kinematic alterations in complex multiligament reconstructions. However, there are still a number of hurdles for computer navigation to overcome. The systems are still very costly, and most centers will not have access to them. They require appropriate training and support. Computer navigation is an important tool for instrumented measurement, but will not negate the need for other instrumented measures, as it currently is only used in the operative setting. CAS has also not been shown to be of clinical benefit over traditional surgical approaches in the performance of ACL reconstruction [30]. Given these limitations, at this time, computer navigation does not have a significant role to play in preoperative diagnosis or in follow-up.

Advantages

- Accuracy
- Immediate post-reconstruction measurement

Disadvantages

- Costly
- Facility availability
- Only currently used in the operating room (OR) setting

Future Directions

The use of instrumented measurements of ligament laxity in the multiple-ligament-injured knee is currently undergoing somewhat of a renaissance. The development of arthrometers and measurement tools to quantitate knee instability became prevalent in the early 1980s when a number of devices were designed and produced. Among these, the KT-1000 arthrometer has been proven to be the device of choice in evaluating anterior tibiofemoral translation and has now been utilized in well over 500 published peer-reviewed studies. As our ability to restore knee function through surgical stabilization has improved, our interest has increased in obtaining more accurate preoperative and postoperative knee laxity measurements. A better understanding of the soft-tissue anatomy and kinematics of the knee, the advent of anatomic ligament reconstruction including multiple-bundle reconstructions, and the wider introduction and adoption of computer navigation have all led to an increased interest and need for accurate and reproducible objective measures. Recent general reviews have highlighted the current state of instrumented measurement, the most recent outcomes and evidence for their use, and also experience with new techniques and devices [31, 32].

One of the remaining challenges is the accurate determination of rotational laxity. Rotational instability has proven itself to be more difficult to reliably assess than linear translation and displacement, and its clinical importance over the long term is still to be fully appreciated. There are several tools that have been recently developed by respected research groups attempting to better characterize and define ligamentous laxity [32–35]. Most of these systems incorporate electromagnetic markers that are placed on surface landmarks on the lower extremity as well as some form of standardized force applied in rotation and translation. While these systems will be unlikely to play a role in the average clinician's practice, they will help to continue to shed light on the complex kinematics of the knee and lead us to better understand the various soft-tissue deficiencies that must be addressed in the multiple-ligament-injured knee, and their relative importance.

Conclusion

The cornerstone of assessment of the multiple-ligament-injured knee is obtaining a thorough history and performing a detailed clinical exam. History and physical exam along with advanced soft-tissue imaging provide much of the information necessary for initial assessment and management. Instrumented measurement can provide a useful adjunct, and allows for more objective clinical testing and more reliable measurements that can be used to analyze outcomes of a single patient or groups of patients. Familiarity and experience with the instrumented measure being used is essential to gathering accurate reproducible measurements.

The choice of instrumented measurement systems should be based on both the ligaments being tested and the resources available.

In the setting of computer-assisted surgery, very accurate measurements can be taken intraoperatively both pre- and post-reconstruction. Unfortunately, these systems are still not widely available, are expensive to purchase, and do not create measurements that are interchangeable with other instrumented means. The use of computer navigation for the purpose of instrumented measurement is still in its infancy.

The KT-1000 arthrometer is widely available and has proven itself reliable and accurate in the measurement of anterior tibial translation, but is not nearly as effective at gauging posterior laxity. The KT-1000 is the tool of choice for objectively assessing the ACL. The posterior structures, the PCL and PLC, are best assessed using the Telos Stress Radiography system. However, the system's cost and limited clinical adoption make it an unlikely option for many clinicians. The LARS rotational laxiometer can be an objective adjunct to a clinical exam of tibiofemoral rotation, and is of benefit in assessing and following PCL injuries. Recent renewed interest in stress radiography has produced a number of comparison trials of stress radiography, and thus far it appears that kneeling stress radiographs show great promise as a reliable measure of posterior laxity.

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