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Arthrometric Aspects of Anterior Cruciate Ligament Surgery Before and After Reconstruction With Patellar Tendon Grafts

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Summary: Instrumented arthrometry is an important treatment adjunct for anterior cruciate ligament (ACL)-deficient patients before and after patellar tendon reconstruction, which provides objectivity to other subjective outcome measures and allows for accurate comparison between studies. Increasing numbers of clinical reports are using arthrometry to objectively report anterior displacements. Arthrometry measurements allow the worldwide orthopaedic community to accurately compare and evaluate reported subjective results. It should be noted that patient satisfaction and subjective evaluations by the examiner and patient may overestimate the presumed ligamentous stability, and in these cases, the KT arthrometer provides important objectivity. This objective data may be the only means of early detection of laxity after ACL reconstruction. In this article, a review of the available data regarding arthrometry before and after patellar tendon ACL reconstruction is presented as well as a rationale for selecting a maximum manual side-to-side difference of >3 mm or an absolute laxity of 10 mm as the diagnostic criteria for ACL deficiency. Knee laxity testing data should be incorporated into the objective preoperative and postoperative evaluation of the ACL-deficient patient, and the goal of reconstruction should be to match the contralateral normal knee. Arthrometry data are important to the researcher for objective evaluation and comparison of populations and to clinicians for objective outcomes in individual patients after patellar tendon ACL reconstruction. **Key Words:** Arthrometry—KT—Laxity—Patellar tendon graft—ACL reconstruction—Outcomes.

During the last 4 decades, advances in the understanding and treatment of knee instability have progressed at a rapid rate. Refinements in physical examination techniques, improved radiographic modalities, advances in the principles of ligament healing and rehabilitation, improved surgical techniques, and the constant integration of new technology as it becomes validated have contributed to an improved ability to care for the patient with an anterior cruciate ligament (ACL)-deficient knee. During the 1980s, several ligament testing devices were developed in an attempt to quantitate anteroposterior (AP) displacement of the knee joint. The Lachman, pivot shift, and anterior drawer physical examination tests often vary from examiner to examiner, making comparison difficult. Objective, quantitative ligament testing devices provide the opportunity to compare populations of patients more accurately, and allow for objective evaluation of individual patients before and after ACL reconstruction. Clinical studies that evaluate the results of ACL reconstruction should use objective quantifiable instrumented ligament testing in addition to the subjective clinical grading reported by various authors. This is especially true when evaluating new technology or methods. The KT-2000 and its predecessor, the KT-1000 arthrometer, have most often been reported in the literature and will provide the basis for most of this article.

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OBJECTIVES

This article discusses KT arthrometry and its application to the assessment of knee stability before and after ACL reconstruction with patellar tendon grafts. It in-

FIG. 1. Arthrometer model KT-2000 in place on a patient's right knee.

cludes a description of the device and testing protocol, a review of the literature, a comparison between acute and chronic ACL injuries, and a comparison of data obtained from patients examined while awake and from those under anesthesia. Data evaluating outcomes of patellar tendon allograft and autograft ACL reconstructions is presented. Recent developments in cartilage restoration and meniscus transplantation have been evaluated by instrumented ligamentous laxity testing, and an update on the available data is presented as well.

DEFINITIONS AND TERMINOLOGY

KT-2000 Arthrometer

This instrumented testing machine for quantitating AP knee displacement differs from its predecessor, the KT-1000, only in its data recording capability (Fig. 1).

Passive Lachman Test

Sequential amounts of force are applied through the KT-2000 force handle with the knee flexed to above 30° ± 5°. The direction of force applied may be either anterior or posterior. The amount of the force applied includes 15 lb (67 N), 20 lb (89 N), and 30 lb (133 N).

Maximum Manual Test

With the KT-2000 properly positioned, maximum anterior force is applied by the examiner's hand on the calf, thereby passively displacing the tibia relative to the femur. This test clinically approximates the Lachman test. Estimated forces generated by the maximum manual test range from 135 to 180 N, depending on the examiner's strength.

Compliance Index Determination

Compliance index determination is the difference in millimeters between the 89-N and the 67-N testing results.

Involved–Uninvolved Differences

Also referred to as side-to-side difference (STSD), involved–uninvolved differences quantify the difference between the involved (injured) and the uninvolved knee.

DESCRIPTION OF THE KT ARTHROMETER

The KT-2000 is an instrumented device that was developed to measure anterior and posterior translation of the tibia relative to the femur in a clinical setting. A complete description of the testing protocol was originally described for its predecessor, the KT-1000, provided by Daniel and Malcom and colleagues[17,18,20,48] as well as in the manufacturer's manual. The protocol for use of the KT-1000 and KT-2000 differs only in the ability of the KT-2000 to graphically record output data on an X-Y plotter and an additional signal tone at higher force measurements. Patient positioning, device application, and force generation for the KT-1000 and KT-2000 are identical. Users of this device should review their protocols before use.

The patient is placed into the supine position on the examination table with thighs resting on the provided bolster to maintain the knees at approximately 30° of flexion. The heels are positioned symmetrically on the provided positioning cup to maintain the tibia in symmetric external rotation of approximately 15°. The examiner must make certain that the patient's thighs remain relaxed throughout the examination. The device's 2 force sensing pads are positioned on the patella and the tibial tubercle while the body of the device is secured to the lower leg with straps. When an anterior force is applied to the tibia, relative motion between the 2 properly positioned pads is displayed as AP displacement by the gauge on the KT-2000, which is calibrated to the nearest 0.5 mm. Next, the examiner must determine and set the point at which the knee rests naturally, the zero point. To determine the zero point, the examiner grasps the device's handle, located 10 cm below the joint line, and performs several anterior and posterior translations. After several repetitions, the zero point is determined, and the device is calibrated to reflect this determination. An audible characteristic tone is heard at 15 lb (67 N) and 20 lb (89 N) of anterior force in the KT-1000, and an additional tone has been added to the KT-2000 at 30 lb for larger patients requiring additional force. Newer

KT-1000 and all KT-2000 models feature posterior force tones as well.

The compliance index is the difference between the displacements at 20 lb and 15 lb. This test should be performed at least twice and the results averaged. After each test, the arthrometer must be recalibrated to the zero position. Accurate and reproducible results of KT-2000 testing require an experienced examiner using identical patient and device positioning and force application.

TECHNICAL POINTS AND PITFALLS

Proper technique is necessary to obtain accurate measurements and to ensure reproducibility. The MEDMetric user manual is an important reference guide for KT-2000 and KT-1000 users. An entire section of the manual is devoted to potential pitfalls and technical errors. Ensuring that variables such as knee flexion angle and force vector angles are reproduced and controlled will enhance the accuracy of the measurements.

Patient relaxation must be maintained throughout the entire test to obtain meaningful data. The physician must periodically check the patient's thighs to make certain they are relaxed and that there is no guarding. If the dial needle is noted to "float" or shift erratically, the examiner must reevaluate for patient guarding, because this will confound the results. Maintaining the patient in a comfortable symmetric supine position helps to keep the quadriceps and abdominal muscles relaxed.

Errors in arthrometer placement and the angle of force vector can occur and cause significant variations in measurements. Kowalk et al[45] demonstrated that positioning the device 1 cm proximal to the joint line produced larger anterior translations when measured in vivo than those at the joint line (5.8 vs 5.4 mm), whereas positioning it 1 cm distal produced smaller measurements (4.4 mm), and this difference was statistically significant ($P = 0.05$). In addition, that study demonstrated that changing the angle of force vector by only 10° off the direct perpendicular caused a larger range of measurements.

Soft tissue position and the resulting position of the patella must also be taken into account during testing, particularly in patients with patella alta. In patients with abnormal extensor mechanism tracking or patella height, slight adjustments in the knee flexion angle may allow the patella to sit more concentrically within the trochlea. The examiner must also stabilize the patellar reference pad manually and maintain a consistent pressure while testing.

Tibial rotation errors may also result in testing discrepancies. Anterior force results in anterior displacement and internal rotation of the tibia; posterior force results in posterior displacement and external rotation of the tibia. These AP displacements and rotations of the tibia are coupled motions in the knee joint, which may change dramatically as a result of injury. During KT testing, internal rotation of the tibia will cause decreased translation. Therefore, it is critical to ensure that both tibiae are in proper and symmetric rotation when testing. Under general anesthesia, muscle relaxation will result in excess external rotation of the thigh and thus effectively place the tibia in excessive internal rotation. In this scenario, it is recommended that an assistant hold the thigh internally rotated or that a derotation strap be used. Other technical pitfalls include rotational orientation of the arthrometer, variations in patellar pad pressure, testing reference position (must be reset after each test), and temperature effects on the device itself.

The rate of force application has been demonstrated by Gross et al[31] to affect the compliance and stiffness measurements but not to have a significant effect on the absolute displacement measurements. Slower rates of anterior force application resulted in lower compliance and higher stiffness measurements. These technical points should be remembered to ensure accuracy and reproducibility.

TESTING REPRODUCIBILITY AND DEVICE COMPARISON

The use of instrumented ligament laxity testing is based on the ability to translate and compare reproducible data from study to study and for clinicians to evaluate patients within a reliable reference dataset. To evaluate the reproducibility of KT measurements, Hanten and Pace[33] determined interexaminer, intraexaminer, and intraclass reliability coefficients for KT measurements on 43 uninjured college athletes. The authors noted high reliability coefficients ($r = 0.85$) and intraclass coefficients ($r = 0.92$), and concluded that the KT-1000 had good inter- and intraexaminer reliability. These values were slightly lower than the results obtained by Malcom et al[48] ($r = 0.93$). Using the KT arthrometer, Bach et al[4] reviewed 16 uninjured knees measured by one examiner twice on one day, with repeat examinations performed twice 1 week later. No statistically significant differences in compliance index or displacements at 67 N, 89 N, or maximum manual were noted, illustrating excellent reliability within time and examiner variables. Edixhoven et al[23] noted that reproducibility was directly affected by changes in the subject's positioning when using a rudimentary laboratory testing apparatus, which made it difficult to standardize patient positioning.

There are several other studies that have evaluated other commercially available arthrometers. Neuschwander et al[52] demonstrated no significant difference in STSD at 20 lb and maximum manual results using the KT-1000 and the Acufex Knee Signature System in 21 ACL-deficient patients. Anderson et al[3] prospectively randomized 50 normal and 50 ACL-deficient patients to be measured with the KT-1000, Stryker knee laxity tester, Acufex Knee Signature System, Dyonics Dynamic Cruciate Tester, and the Genucom Knee Analysis System. In normal subjects, the authors noted no significant side-to-side errors within devices, but there was significant variation in the measurements of absolute anterior translation between devices. The Dyonics and Acufex translations were 50% less than the other devices, whereas the Genucom tended to overestimate. Diagnostic accuracy was improved with the maximum manual test for all devices. Overall, the KT-1000 and Stryker devices had the highest diagnostic accuracy. They concluded that measurements cannot be generalized or compared from one device to another.

Steiner et al[59] compared test reproducibility in the KT-1000, Stryker, Acufex, and Genucom in ACL-deficient and normal knees. The Acufex, KT-1000, and Stryker devices were significantly ($P < 0.01$) more reproducible than the Genucom, and capable of correctly identifying normal and abnormal patients approximately 90% of the time, compared with only 60% for the Genucom. Testing sensitivity (65%) and specificity (45%) were lowest for the Genucom, whereas the KT-1000 and Stryker ranged between 75% and 85%, and the Acufex ranged between 85% and 95%. Anderson and Lipscomb[2] demonstrated that although the Genucom was more versatile for collateral and rotatory insufficiencies than the KT and Stryker, the recorded displacements were less accurate. Several other studies have demonstrated superior accuracy and reproducibility of the KT arthrometer[69,37] over the Genucom as a result of the Genucom's day-to-day variance,[68] and between-subject variance,[63] even in controlled cadaver studies.[41] Because the KT-1000 and its successor, the KT-2000, have the most consistent reliability, it has become the most widely used instrumented arthrometer and is the recommended gold standard for outcome-reporting and comparison of knee ligamentous laxity. The majority of this article addresses data from KT devices.

Diagnostic Accuracy of Arthrometry for Evaluating the Injured and Reconstructed Anterior Cruciate Ligament

To better understand the relative accuracy of KT arthrometers, clinicians and researchers should be familiar with studies evaluating this instrument's ability to accurately measure and diagnose ACL injuries compared with magnetic resonance imaging (MRI), clinical examination, stress radiography, and roentgen stereophotogrammetry analysis (RSA).

In 1995, Liu et al[46] reviewed 38 patients with arthroscopically proven complete ACL tears. The results of physical examination, KT-1000 testing, and MRI were analyzed. MRI had an overall sensitivity of 97% for detecting ACL injuries; however, MRI classified 6 of the 38 tears as partial and one as intact with an overall sensitivity for differentiating between complete and partial tears of only 82%. KT-1000 testing based on a 2-mm STSD rather than a 3-mm difference was more accurate than MRI. With a criterion of 2-mm STSD, the sensitivity of the manual maximum test was 100%, whereas at a 3-mm threshold, the sensitivity was 97%. Sensitivity increased with progressive larger amounts of forces used for testing. Lachman test results yielded a sensitivity of 95%, with only 2 being recorded as negative. There were no statistically significant differences between the Lachman and the KT-1000 maximum manual and active displacement testing. This study illustrates the potential of arthrometry and careful physical examination to accurately diagnose an ACL tear. Clearly, MRI imaging, although more expensive, reveals a wealth of information regarding anatomic structures not evaluated by arthrometry.

Flemming et al[26] compared the accuracy KT arthrometry, RSA, and stress radiographs to measure AP laxity after patellar tendon ACL reconstruction. The measurements were significantly different ($P < 0.001$), with the KT-1000 slightly overestimating the absolute AP excursion distance. The KT-1000 ($P = 0.04$) and the RSA techniques ($P = 0.04$) detected significant increases in AP laxity values over time, but the planar stress radiography technique did not ($P = 0.89$). The authors conclude that KT arthrometry and RSA document temporal changes in AP laxity after ACL reconstruction that was not documented by planar stress radiography.

In Vitro Arthrometry Testing

Several cadaver arthrometry studies have allowed direct measurement of the restraining effect of the ACL. Selective sectioning studies[14,17,49] have recorded a mean translation of between 5.8 mm and 6.6 mm with an intact ACL and between 12 mm and 17 mm after sectioning. In another study,[29] a 100-N force caused a mean 7-mm anterior displacement with an intact ACL, which increased to 17 mm after sectioning with maximal values at 30° of flexion. These findings concur with those of Bach et al[10] and others[11,15,17,18,20,29] who noted that anterior displacements at 30 ± 5° were statistically greater than those at 90° as a result of relaxation of secondary stabilizers. This reinforces the importance of proper patient positioning to obtain accurate arthrometry data.

Normal and Anterior Cruciate Ligament-Deficient Knees

In 1985 and 1988, Daniel and colleagues[17–20,48] published several classic articles that introduced the KT-1000 arthrometer to the orthopaedic community. These articles are valuable because they established the parameters of normal and abnormal knees, thus establishing instrumented laxity testers as an important objective component in clinical knee laxity evaluation. In one study, normal (n = 328) and chronic ACL-deficient (n = 89) patients were compared.[17] A second study characterized the KT-1000 measurements in acute ACL-deficient patients (n = 138).[20] Another study compared KT-1000 measurements before and after ACL reconstruction.[48] They reported mean anterior displacement at 89 N of 5.8 mm and 5.5 mm for left and right control knees, respectively. Of interest, the normal knee of chronic ACL-deficient patients was increased with a mean anterior displacement of 7.4 mm. The injured knees had a mean translation of 13 mm. At 89 N, the STSD was noted to be 0.3 mm for control subjects versus a mean of 5.6 mm for chronic ACL-deficient patients. The mean compliance in normal subjects was 0.9 mm. In the normal knees of the ACL-deficient patients, the mean compliance index determination was 1.2 mm, whereas the mean compliance was 2.9 mm in the injured knee. In the group of normal controls, neither gender nor age had an effect on mean displacements. They reported that 92% of subjects with normal knees had a STSD of less than 2 mm, whereas 96% of patients with a unilateral ACL tear had a STSD of greater than 2 mm. Ninety-three percent of the normal subjects had a STSD in compliance of less than 0.5 mm, and 85% of the patients with unilateral ACL tears had a STSD of compliance greater than 0.5 mm.

Daniel's evaluation[20] of acute ACL-deficient knees used 69 N, 89 N, compliance index, maximum manual, and injured–uninjured data in their evaluations. Their normal control knees (n = 120) had a mean translation of 7.2 mm (range, 3–13.5 mm) at 89 N. The contralateral normal knee of the acute ACL-deficient patients had a mean translation at 89 N of 7.3 mm (range, 3–13 mm), and this value was similar to that of the normal knees of chronic ACL-deficient patients reported earlier.[17] The mean maximum manual displacement was 8.5 mm (range, 5–15 mm) in the control knees, and the mean compliance index was 0.9 mm (range, 0–2.5 mm). A key finding was that displacement measurements in normal subjects had a wide range of normal laxity, but with STSD.

In their acute ACL-deficient patients, Daniel et al[20] reported the mean anterior displacement on the injured side was 11.4 mm (range, 6–19 mm) at 89 N. The mean injured–uninjured differences at 89 N were 5 mm (range, 2–12 mm). The authors established a range of equivocal diagnostic laxity and diagnostic laxity ranges for 89 N, maximum manual, compliance index, and STSD. The authors reported that STSD were more important than absolute translations, concluding that a STSD of 3 mm or greater was diagnostic at 89 N or at maximum manual testing. They noted that the STSD in normal knees at 89 N were less than 2 mm in 88% of the patients. The maximum manual differences were suggestive or diagnostic in 91% of the patients. The mean injured–uninjured difference in the acute subjects at 89 N was 3.8 mm (range, 0–8 mm). On maximum manual testing, the mean difference was 5.2 mm (range, 1–10 mm). The mean compliance difference was 1.3 mm (range, 0–3 mm). Daniel also included 26 patients who were examined under anesthesia, and in this population, an increase in the mean 89-N difference and maximum manual difference was noted in patients examined under anesthesia.

Malcom et al[48] prospectively recorded KT-1000 measurements in patients before and after patellar tendon ACL reconstruction. Four different surgical procedures were studied in 43 patients, including semitendinosus reconstruction, the iliotibial band over-the-top reconstruction, the bone–patellar tendon–bone reconstruction, and the patellar tendon over-the-top reconstruction. In the 19 chronically ACL-deficient patients, the authors noted a mean translation of 8.5 mm at 89 N in the contralateral normal knees with a mean STSD of 6.8 mm at 89 N before reconstruction. In the 24 acute patients, the mean displacement of the normal knees was 7.3 mm, and the mean STSD was 4 mm. Under anesthesia before reconstruction, the mean STSD at 89 N was 6.4 mm for the chronic patients and 5.6 mm for the acute patients. After reconstruction, the mean STSD was −1.4 mm for the chronic patients and 0.8 mm for the acute patients, thus indicating that for the chronically ACL-deficient knees, the reconstructed knees were initially tighter than the contralateral normal knees.

Bach et al[4,10] used the KT-1000 to differentiate normal and abnormal ACL populations, to define the differences in translations among acute and chronic ACL-deficient knees, and to assess whether the uninjured knees of patients with unilateral ACL tears differed from those of a control population with normal knees. In this study, 141 controls, 107 acute isolated ACL tears, and 153

TABLE 1. *KT Arthrotomy Data for Normal, Acute, and Chronic Anterior Cruciate Ligament-Deficient Knees (mm)**

	Mean	Range	Standard Deviation
89 N			
Normal (n = 141)	6.3	2–12	1.84
Acute (n = 107)	9.6	4.5–19	3.1
Chronic (n = 153)	11.4	3–21	3.7
Maximum manual			
Normal	7.0	4–11	ND
Acute	13.0	5–22	ND
Chronic	13.5	7–22	ND
Compliance			
Normal	1.1	0.5–2.0	0.4
Acute	2.2	0.5–4.0	0.96
Chronic	2.1	0.5–6.0	1.05

*Measured at 30° of knee flexion.

From Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg* [*Am*] 1990;72:1299.

ND indicates not determined.

TABLE 2. *Comparison of Side-to-Side Differences (mm) in Acute and Chronic Anterior Cruciate Ligament-Deficient Knees**

	Acute (%)	Chronic (%)
67 N		
≤2.0	28	15
≥2.0	72	85
≥3.0	50	69
89 N		
≤2.0	16	12
≥2.0	84	88
≥3.0	69	79
Maximum manual		
≤2.0	10	23
≥2.0	90	77
≥3.0	87	72

*Measured at 30° of knee flexion.

From Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg* [*Am*] 1990;72:1299.

chronic isolated ACL-deficient patients were evaluated. The KT data were recorded for 30° anterior Lachman testing, 69-N, 89-N testing, maximum manual testing, compliance index determination, and STSD. ACL deficiency was confirmed by an abnormal asymmetric Lachman test, a positive pivot shift phenomenon, or by arthroscopy. Table 1 summarizes the authors' reported mean translations and ranges for normal, acute, and chronic ACL-deficient knees. Although the mean translations were greater for acute and chronic knees at 69 N, 89 N, and maximum manual testing than for normal knees, there were wide ranges noted for both normal and abnormal knees, which concurs with Daniel's work. In Bach's series, only 6% of normal subjects exceeded 11-mm displacement at 89 N, leading the authors to conclude that the 10 mm or less of anterior translation at this level of force was a predictor of a normal ACL. It should be emphasized, however, that an ACL-deficient knee may have 10 mm or less of translation. Table 1 demonstrates that at 89 N, 99% of normal subjects had 10 mm or less of translation, whereas 62% of the acute and 56% of the chronic patients had 10 mm or less of anterior translation. On maximum manual testing, 94% of control subjects had 10 mm or less of translation in contrast to 23% of acute and 22% of chronic ACL-deficient patients. Ninety-nine percent of normal subjects had a compliance of 2 mm or less, whereas 43% of acute and 39% of chronic patients had a compliance index of 2 mm or greater.

Bach et al[4,10] also compared control knees with the uninjured knees of acute and chronic ACL-deficient subjects. No significant differences were found between the normal knees of acute subjects versus control subjects. However, statistically significant differences were noted when the normal knees of chronic ACL-deficient patients were compared with those of control subjects at 67 N ($P < 0.003$), 89 N ($P < 0.002$), maximum manual ($P < 0.006$), and compliance index determination ($P < 0.001$). The authors did not have a specific explanation for these observations.

Differences between injured and uninjured knees, so-called STSD, were studied as well. In Bach's study, STSD of 2 mm or less was noted in only 16% of acute and 12% of chronic ACL-deficient subjects (Table 2). Maximum manual testing revealed that 91% of control subjects had 2 mm or less and 99% had 3 mm or less of STSD. Of acute patients, 90% had STSD of 2 mm or greater, and 87% of these patients had differences of 3 mm or greater. The authors also noted that the compliance STSD was 1 mm or less in 99% of the control subjects.[4,10] The mean, range, and standard deviations of STSD in control, acute, and chronic subjects are noted in Table 3. The differences between control subjects and ACL-deficient patients were statistically significant ($P <$

TABLE 3. *Maximum Manual Side-to-Side Difference (mm) in Normal, Acute, and Chronic Anterior Cruciate Ligament-Deficient Knees**

	Mean	Standard Deviation	Range
Normal (n = 141)	0.2	±1.6	−4 to +4
Acute (n = 107)	4.8	±3.7	−7 to +12
Chronic (n = 153)	5.5	±4.5	−6 to +16

*Measured at 30° of knee flexion.

From Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg* [*Am*] 1990;72:1299.

TABLE 4. *Comparison of Maximum Manual and Maximum Manual Side-to-Side Differences (mm) With Lachman and Pivot Shift Grades**

	Maximum Manual	Maximum Manual Difference
Lachman grade		
1	12	3
2	13	4
3	16	8
Pivot shift grade		
1	13	4
2	14	5
3	17	8

*Measured at 30° of knee flexion.

From Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg* [*Am*] 1990;72:1299.

0.001), but there were no significant differences between acute and chronic ACL-deficient patients.

In that same study, Lachman examination and pivot shift grades were compared with the maximum manual test measurements of the KT-1000 in an attempt to correlate objective measurements with clinical grades. A statistically significant difference ($P < 0.003$) was noted when Lachman grades 1, 2, and 3 were compared with the maximum manual test results (Table 4). Mean translations were 12, 13, and 16 mm, respectively, for Lachman grades 1, 2, and 3. For pivot shift grades 1, 2, and 3, statistically significant differences were also noted ($P <$ 0.027). The pivot shift grades 1 through 3 correlated with 13, 14, and 17 mm of anterior translation. In addition, Lachman grades 1, 2, and 3 correlated with 3, 4, and 8 mm of anterior STSD on maximum manual testing. The same trend was noted when compared with pivot shift grades, in which STSD of 4, 5, and 8 mm corresponded to pivot shift grades 1, 2, and 3.

This data allowed for a determination of the sensitivity, specificity, positive predictive accuracy, and negative predictive accuracy for STSD. In summary, the authors found that the most sensitive test was the maximum manual test in acute ACL-deficient patients (90%) when a STSD of ≥2 mm was used. In both acute and chronic patients, a diagnostic cutoff of >2 mm had more sensitivity and a higher negative predictive accuracy but less specificity than when a diagnostic cutoff of ≥3 mm was used. In acute ACL-deficient patients, the authors noted that the maximum manual test was the best screening test (89%). A diagnostic cutoff of ≥3 mm of STSD was found to be highly specific (90–94%) but less sensitive in the acute and chronic ACL-deficient subjects. At that diagnostic cutoff, the maximum manual test was a better screening test in the acute ACL-deficient subjects (84%). When an absolute displacement of 10 mm or less was selected as a diagnostic cutoff, the maximum manual test was determined to be highly specific and highly sensitive for both acute (93%) and chronic (91%) subjects. It also had a high positive predictive accuracy (92% and 94%). On compliance index determination, the authors noted that a diagnostic cutoff of 1.6 mm or less was more sensitive than a cutoff of 2 mm or less. However, the positive predictive accuracy was higher in both acute and chronic patients, using the 2-mm cutoff.

In consideration of these findings, Bach et al used a maximum manual difference of 3 mm and absolute displacement of 10 mm as criteria for diagnosing an ACL tear, and ran these criteria against normal and injured populations. For these parameters, the sensitivity was 99% ($\chi^2 = 65.2$). There was no statistically significant difference in the diagnostic ability of the 3-mm STSD or 10-mm absolute translation criteria to identify ACL deficiency. The maximum manual test was the best factor in differentiating normal from abnormal patients ($P < 0.001$) as determined by a stepwise discriminate analysis, whereas the compliance index determination was the most important testing parameter for differentiating between acute and chronic ACL-deficient knees.

In 1994, Rijke et al[55] reported on the use of instrumented arthrometry for diagnosing partial versus complete ACL tears. They used a KT-1000 equipped with a strain gauge and processor that monitored the required force to increase the anterior displacement by 1-mm increments, which was then read on an external data monitor. They examined 19 patients with the clinical diagnosis of ACL injury using the modified KT-1000 before arthroscopy. The authors reported that the results of the KT testing of partially torn and completely torn ligaments were similar to those obtained by graded stress radiography. Partial tears could be differentiated from complete tears. The sensitivity and specificity for diagnosing a partial ACL tear were 80% and 100%, respectively, whereas complete tears were 100% and 80%. The authors note that, owing to large patient-to-patient variables, only side-to-side comparisons can provide diagnostic distinction and then only in the presence of a normal opposite knee.

Arthrometric Examination: Patients Awake and Under Anesthesia

Several published works have examined the effect of anesthesia on the physical examination and arthrometry of the knee. These studies demonstrate the value of the examination under anesthesia and identify the maximum manual anterior KT arthrometry displacement test as the

TABLE 5. *KT-1000 Data in 50 Contralateral Normal Knees of Patients With Acute or Chronic Anterior Cruciate Ligament Injuries**

	15 lb				20 lb				Maximum Manual			
	Preoperative		Under Anesthesia		Preoperative		Under Anesthesia		Preoperative		Under Anesthesia	
	Mean (mm)	(mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)
Acute (n = 10)	3.0	1–7	4.4	3.0–6.5	3.8	1.5–8.0	5.2	3.5–7.5	4.6	2.0–10.0	6.9	4.0–9.0
Chronic (n = 40)	3.2	1–8	4.1	1.5–8.0	4.0	1.0–9.5	5.0	2.0–9.0	5.1	2.0–10.5	6.8	3.0–12.0
Total (n = 50)	3.2	3.0	4.2	1.0–9.5	4.0	2.0–9.0	5.0	2.0–9.0	5.0	3.0–10.5	6.8	3.0–12.0

*Measured at 30° of knee flexion.

From Bach BR Jr, Warren RF, Flynn WM, et al. Arthrometric evaluation of knees that have a torn anterior cruciate ligament. *J Bone Joint Surg* [*Am*] 1990;72:1299.

single best test to measure anterior displacement in both acute and chronic ACL injuries as well as knees without ligament injuries.

Highgenboten et al[36] used the KT-1000 to measure anterior laxity of the knees of 68 unilateral ACL-deficient patients while they were awake and again while under anesthesia. They reported a significant increase ($P < 0.01$) in the measured displacement in normal and uninjured knees while under anesthesia. In addition, compared with awake measurements, there was an increase ($P < 0.01$) in the STSD in patients when they were under anesthesia. Anderson and Lipscomb's[2] comparison of 50 patients awake and while anesthetized included a mix of testing devices. Nonetheless, using a 3-mm STSD criterion, the correct diagnosis was made in 98% of patients with ACL tears of mixed acuity.

Bach et al[65,70] analyzed KT measurements of ACL patients undergoing reconstruction while awake and while under anesthesia, but unlike Highgenboten et al[36] and others,[22,41,42,71] this study included an analysis of the diagnostic accuracy of the anterior drawer, Lachman, and pivot shift tests as well.[65,70] One hundred patients with surgically confirmed ACL deficiency were evaluated. In acute patients, all demonstrated an abnormal Lachman test preoperatively and under anesthesia. The sensitivity of the anterior drawer test improved from 36% while awake to 76% under anesthesia, and the pivot shift phenomenon improved from 24% awake to 92% under anesthesia. In the chronic subjects, all patients had an abnormal Lachman test awake preoperatively and under anesthesia, the anterior drawer test improved from 61% to 83%, and the pivot shift improved from 71% to 100%.

The mean translations of the acute, chronic, and total populations in this study are shown in Tables 5 and 6. The mean displacements at 89 N increased from 8.4 mm awake to 9.8 mm under anesthesia. The mean maximum manual difference increased from 12 mm to 15.8 mm. The mean compliance index determination did not appear to change significantly from the awake state (2.2 mm) to examination under anesthesia (2.3 mm). The mean STSD increased at 89 N and maximum manual testing, but compliance index differences did not. At 89 N, the mean STSD were 4.4 mm awake and 5 mm under anesthesia. For the combined acute and chronic ACL-deficient populations, mean maximum manual STSD between the injured and uninjured knees was 7 mm while awake and 9 mm under anesthesia.

Bach and coworkers then tested the diagnostic criteria established by Daniel et al,[20] which established a diag-

TABLE 6. *KT-1000 Data in 50 Anterior Cruciate Ligament (ACL)-Deficient Knees**

	15 lb				20 lb				Maximum Manual			
	Preoperative		Anesthesia		Preoperative		Anesthesia		Preoperative		Anesthesia	
ACL Deficiency	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)	Mean (mm)	Range (mm)
Acute (n = 10)	6.0	3.5–8.5	7.2	4.0–9.0	8.0	4.5–10.5	9.2	7.0–12.5	10.8	7.5–14.0	15.2	12.0–19.5
Chronic (n = 40)	6.4	2.5–14.5	7.7	2.5–13.0	8.5	4.0–16.5	9.9	3.5–16.0	12.3	6.0–21.0	16.0	9.5–24.0
Total (n = 50)	6.3	2.5–14.5	7.6	2.5–13.0	8.4	4.0–16.5	9.8	3.5–16.0	12.0	6.0–21.0	15.8	9.5–24.0

*Measured at 30° of knee flexion.

From Wang CW, Bach BR Jr. Clinical diagnosis of ACL-deficient knees. *J Orthop Surg* 1990;7:139.

nostic cutoff of 14 mm or greater for 89 N, of 15.5 mm or greater for maximum manual testing, and of 3 mm or greater for compliance index determination. Equivocal diagnostic cutoffs were 10 to 13.5 mm (89 N), 11 to 15 mm (maximum manual), and 2 to 3 mm (compliance index). With those criteria, the maximum manual test under anesthesia was the only test that was diagnostic in more than 50% of those patients, although the sum of the equivocal and diagnostic patients was 95%. Bach then reanalyzed the data using diagnostic criteria of an absolute translation of 10 mm or greater for either the 89-N or maximum manual test and 2 mm or greater for the compliance index. Using these modified criteria, the diagnostic accuracy in this series increased dramatically; 75% of the patients examined while awake and 98% of those examined under anesthesia were correctly diagnosed using the maximum manual test. Bach's analysis of the criteria included a survey of each patient's dataset to determine if 3, 2, one, or none of the criteria were met. As a result, 53% of the patients met only one diagnostic criterion (chronic; examination under anesthesia), and 45% to 95% of the patients failed to meet any of Daniel's criteria. In contrast, when Bach's criteria were applied, fewer patients failed to meet any diagnostic criteria (0–25%). Seventy-five percent to 100% met at least one diagnostic criterion, and 64% to 74% met at least 2 diagnostic criteria. It should be recalled that the modified criteria were based on the observation that nearly all normal patients have a maximum manual translation of 10 mm or less. These findings support the conclusion that 89 N or a maximum manual testing of 10 mm or greater implies ACL injury until proven otherwise, and that the KT arthrometer instrumented ligamentous laxity maximum manual test is the single best physical examination test for evaluation of ACL injury.

Dahlstedt and Dalen[16] demonstrated the value of the examination under anesthesia by performing KT-1000 evaluations under anesthesia in 41 patients. They noted statistically significant increases ($P < 0.001$) for uninvolved knees in both acute and chronic ACL patients when STSD were performed at 89 N and maximum manual. No statistically significant differences were noted for compliance index in patients examined while awake or under anesthesia for normal or injured knees. At 89 N, the mean anterior displacement in acute and chronic ACL-deficient knees was 9.6 and 12.1 mm, respectively, while awake. This increased to 11.7 and 13.8 mm, respectively, when examined under anesthesia. For the maximum manual test, displacement in acute knees increased from 12.8 mm while awake to 15.9 mm while under anesthesia, whereas in chronic ACL-deficient knees, the displacement increased from 15.1 mm while awake to 17.4 mm under anesthesia. The mean STSD at 89 N while awake was 4.8 mm in acute patients and 7.4 mm in chronic patients. The mean STSD of chronic patients increased while under anesthesia to 7.1 mm at 89 N and 9.1 mm on maximum manual testing. The authors' results led them to conclude that the maximum manual test was the best diagnostic test for ACL deficiency. Their conclusion agrees with those of Bach et al,[5] Daniel et al,[17] and Wang and Bach.[65]

Arthrometric Aspects of Anterior Cruciate Ligament Surgery Pre- and Postreconstruction

Several studies have examined the arthrometric results of surgical treatment of ACL injuries to determine correlations to knee function and outcomes after patellar tendon ACL reconstruction, repair of tibial spine avulsion,[44] and patellar tendon ACL reconstruction combined with cartilage restoration procedures. A familiarity of these studies and their results will help both the clinician and researcher to interpret and record the objective results of their own patellar tendon ACL reconstructions and to critically evaluate published data after ACL reconstruction.

Giannotti et al[30] attempted to correlate arthrometric measurements with functional knee scores. They compared 28 patients who underwent ACL reconstruction with immediate, 1-, 2-, and 3-year postreconstruction KT-1000 maximum manual test results, as well as Tegner, Lysholm, and Hospital for Special Surgery knee scores. The average intraoperative postreconstruction maximum manual STSD was −2.1 mm with the reconstructed side tighter than the uninvolved knee. The 1-year postoperative STSD was 2.3 mm with the reconstructed knee demonstrating more laxity than the uninvolved knee. Evaluation of the various functional knee scores showed uniformly excellent results despite a wide range of laxity at 2 and 3 years. The authors conclude that an increase in arthrometrically determined laxity does not preclude excellent functional results and propose that the follow up STSD are more important than time-dependent increase in laxity. This lack of correlation between subjective outcome reports and objective laxity data are also seen in the work of Harter et al[35] who retrospectively reviewed KT data and subjective patient reported data of 51 patients at an average 48 months after ACL reconstruction with a mix of grafts and techniques. Although the mean anterior displacement of the reconstructed knees had significantly more laxity than the control knee, the subjective outcomes consistently demonstrated postoperative improvement. The authors concluded that static and dynamic clinical tests to assess knee stability and function were independent of the patient's perception of the knee.

Patellar Tendon Autograft Anterior Cruciate Ligament Reconstruction

In 1989, Harter and coworkers[34] used the KT-1000 arthrometer to measure anterior laxity in the knees of 50 patients at a minimum of 2 years after ACL reconstruction by either patellar tendon or semitendinosus autograft reconstruction. The authors reported 67-N, 89-N, and compliance index tests but not the maximum manual test. Although there were significant differences ($P < 0.001$) between uninjured knees and reconstructed knees, no statistically significant differences were noted between the types of grafts used. For patellar tendon reconstructions, the mean translation was 8.1 mm at 67 N and at 89 N, 8.5 at 89 N, and the mean compliance was 0.5 mm. For the semitendinosus graft (combined with an extraarticular tenodesis in 20 patients), the same values were 6.6 mm, 7.3 mm, and 0.8 mm, respectively. There was no significant difference between the their intermediate data at 24 to 40 months and their longer-term follow up at 60 moths, demonstrating durability between 2 and 5 years after reconstruction. In their series, 44% had flexion contractures ranging from 1° to 10°, so they compared the effect of flexion contractures on laxity measurements. They found no statistically significant difference in anterior displacement (89 N) or compliance index determination as a result of flexion contracture. Although the mean differences between normal and reconstructed knees was found to be significant ($P < 0.001$), the magnitude of this postreconstruction STSD was only 2 mm. Daniel et al[17] has reported that 92% of normal subjects have a STSD of 2 mm or less, and Harter et al[34] noted that 66% of their reconstructed patients had STSD of less than 3 mm.

The debate of the relative benefits of patellar tendon graft versus hamstring autograft continues. Freedman et al[28] performed a metaanalysis of 34 studies evaluating KT arthrometer data of 1976 patients at a minimum of 2 years after either patellar tendon or hamstring autograft ACL reconstruction. In the cumulative analysis of KT data, 79% of the patellar tendon autograft patients had a maximum manual STSD of less than 3 mm, whereas only 73% of the hamstring patients had a STSD of less than 3 mm. This difference was statistically significant and led the authors to conclude that the patellar tendon graft choice resulted in greater static stability at 2 years compared with the hamstring group. In this metaanalysis, the improved arthrometer scores correlated with improved patient satisfaction for the patellar tendon graft at 2 years, despite a higher incidence of anterior knee pain.

Another recent KT arthrometer comparison of patellar tendon and hamstring grafts was performed by Feller et al.[24] Sixty-five patients were evaluated at a minimum 36 months after being randomized to receive either a patellar tendon autograft or a quadrupled hamstring autograft for a primary ACL reconstruction. This analysis revealed a greater STSD in anterior laxity at maximum manual for the hamstring autograft group compared with the patellar tendon autograft. This increased laxity in the hamstring autograft group was associated with increased femoral tunnel widening, but there were no statistically significant differences in Cincinnati outcome scores, IKDC ratings, and return-to-play rates between the patellar tendon and hamstring groups.

Tibone and Antich[62] reviewed 11 patients at a minimum of 2 years after intraarticular patellar tendon reconstruction and extraarticular augmentation. The patients were studied objectively using gait analysis, Cybex, and KT-1000 arthrometer assessment. No patients demonstrated a pivot shift, but instrumented arthrometry testing revealed the operated knee to be significantly looser only during maximum manual (7.2 mm vs 5.3 mm, $P < 0.01$). For all other KT measurements, there was no significant difference between the normal and surgical knees. The mean STSD were 1 mm (67 N), 1.1 mm (89 N), 0 mm (compliance index), and 1.9 mm (maximum manual).

Andriacchi et al[13] reported on the functional results after ACL reconstruction using gait analysis to assess function. At a mean of 22 months after patellar tendon ACL reconstruction, patients underwent gait analysis. KT data were collected before and after reconstruction. All patients demonstrated a preoperative clinical evaluation consistent with ACL deficiency. The mean maximum manual STSD, the mean displacements at 89 N and maximum manual, and the compliance indexes were significantly reduced ($P < 0.001$) compared with preoperative KT-1000 measurements. These data paralleled their clinical evaluation in which 90% of the patients had a negative pivot shift.

O'Brien et al[54] reported on 80 patients at a minimum of 2 years after open ACL reconstruction using patellar tendon autograft with extraarticular augmentation in 32 (40%) patients. The authors reported 61 (76%) patients had STSD of 3 mm or less on maximum manual testing, 16 (20%) had 3- to 5-mm differences, and 3 (4%) had greater than 5 mm. No statistically significant differences were noted between their subgroups of augmented and unaugmented patients.

In 1995, Bach et al[6] reported on 62 of 75 patients who underwent ACL reconstruction using autologous patellar tendon through an arthroscopic technique without extraarticular augmentation. Patients were evaluated pre-

TABLE 7. *Comparison of Preoperative and Postoperative KT-1000 Arthrometer Results (mm)**

Test	*N*	Mean	Standard Deviation	Range
Preop 20 involved	52	8.6	±2.4	4–14
Preop 20 uninvolved	52	4.2	±2.0	1–9.5
Postop 20 involved	62	4.0	±2.4	1–15
Postop 20 uninvolved	62	3.4	±1.5	0.5–7.5
Preop mm involved	52	12.7	±3.1	7–21
Preop mm uninvolved	62	5.6	±2.3	2–10.5
Postop mm involved	62	5.5	±3	1.5–20
Postop mm Uninv	62	4.8	±1.7	1.5–9.5
Preop 20-D	52	4.4	±2	−1–8
Postop 20-D	62	0.5	±2.6	−5–11.5
Preop mm-D	52	7.1	±2.9	2–14
Postop mm-D	62	0.7	±3.2	−6–16

*Measured at 30° of knee flexion.

From Bach BR Jr, Jones GT, Hager CA, et al. Arthrometric results of arthroscopically assisted anterior cruciate ligament reconstruction using autograft patellar tendon substitution. *Am J Sports Med* 1995;23: 179.

operatively and at a minimum of 2 years and an average of 3.1 years postoperatively. Preoperatively, 94% of the patients had a maximum manual STSD of 3 mm or greater. Postoperatively, 56 patients (90%) had a maximum manual STSD of 3 mm or less, 3 (5%) had 3 to 5 mm, and 3 (5%) had greater than 5 mm. Of the 3 patients with a STSD of greater than 5 mm, 2 had a demonstrable pivot shift. Arthrometric parameters were statistically reduced ($P < 0.0001$) from preoperative values and were consistent with the diagnostic criteria established for normal knees. Table 7 summarizes the pre- and postoperative KT-1000 data for the involved and uninvolved knees. Of note is the significant reduction in translations from the preoperative examination under anesthesia testing, with a plateau in the translations between 6 months and at final follow up, indicating durability in laxity at 6 months.

In 1998, Bach et al[8,9] published 2 articles on surgical results of ACL reconstructions using patellar tendon autografts. The first was a retrospective 2-year minimum follow-up evaluation on single incision technique and included arthrometric evaluation.[8] In this study, 103 patients were evaluated with a mean follow up of 36 months (range, 24–55 mm). KT-1000 results were recorded on 86 patients preoperatively and on all patients postoperatively. These results showed statistically significant reductions in maximum manual anterior translation and STSD ($P < 0.0001$). The mean maximum manual translation preoperatively was 11.9 mm (range, 5.0–23 mm), and the mean STSD preoperatively was 6.5 mm (range, −5–15 mm). Postoperative results showed the mean maximum manual translation reduced to 6.3 mm (range, 2–16 mm), and the mean STSD reduced to 1.1 mm (range, −6–7 mm). Eighty-six patients (83%) had STSD of 3 mm or less, 14 patients (14%) had differences between 3 and 5 mm, and 3 patients (3%) had differences of 5 mm or more.

Bach et al[9] also retrospectively reviewed their results of patellar tendon autograft ACL reconstructions using an arthroscopically assisted 2-incision technique at an interval intermediate follow up of 5 to 9 years postoperatively. Preoperative KT-1000 data were recorded on 76 patients. Preoperatively, the mean maximum manual translation was 13.1 mm, and mean STSD was 7.6 mm. Postoperatively, the mean maximum manual translation was 6.3 mm, and mean STSD was 1 mm. At the final follow up in 94 knees, the maximum manual STSD was less than 3 mm in 66 patients (70%), 3 to 5 mm in 24 patients (26%), and more than 5 mm in 4 patients (4%). The anterior maximum manual translation of the injured knees was significantly reduced postoperatively ($P < 0.001$). The average decrease in STSD from pre- to postoperatively was 6.6 mm, and the reduction in maximum manual translation was 6.8 mm. These reductions in absolute translation and STSD were statistically significant ($P < 0.001$).

Allograft Reconstruction

Noyes and Mangine[53] prospectively reported on the effects of early motion after open and arthroscopically assisted allograft patellar tendon ACL reconstructions. Patellar tendon allografts were used in all but one patient. The authors incorporated KT-1000 data into their objective evaluation of patients and reported STSD at 89 N. In this small series of 10 acute and 8 chronic ACL-deficient knees, the mean involved knee had 5.4 mm greater anterior displacement than the uninjured knee preoperatively. At 1 month postoperatively, the surgical knee had −1.9 mm less anterior displacement, and at 3 months, the knees were nearly symmetric at a −0.6-mm difference. At 6 months, 15 patients had a STSD at 89 N of 3 mm or less. At 1-year follow up, 3 patients had a STSD of 5.0 mm.

Bach et al[5] recently reported the results of 59 patients evaluated at a mean follow up of 51 months (range, 26–170 months) after primary ACL reconstruction using patellar tendon allograft. The indications for using patellar tendon allograft for primary ACL reconstruction were: 1) patients greater than 40 years of age, 2) radiographic evidence of mild degenerative joint disease, 3) moderate patellofemoral crepitation or pain symptoms, 4) petite stature, with graft donor tissue of questionable quality, or 5) patient request for allograft reconstruction. The fresh-frozen, nonirradiated allografts were all obtained from the same tissue bank (Allosource Tissue Bank, Denver, CO). A 10-mm, middle third patella tendon allograft was fashioned with 25-mm bone plugs. In this study, patients were evaluated before and after reconstruction by comprehensive physical examination, functional testing, radiographic evaluation, and patient questionnaire in addition to KT arthrometry. Anterior maximum manual and maximum manual STSD were calculated. An arthrometric failure was defined as a STSD of 5 mm. Results were stratified into ≤3 mm, 3.1 to 4.9 mm, and ≥5 mm. Knee rating questionnaires included the 2000 International Knee Documentation Committee (IKDC) Subjective Knee Evaluation Form, KOOS, Noyes Sports Activity Scale, Tegner, Lysholm, and SF-12. The questionnaire also included a visual analog scale (VAS) for pain ratings. The average age of the 21 male and 38 female patients at the time of reconstruction was 41 years (range, 18–61 years; standard deviation [SD], 10).

KT arthrometric testing was recorded on 39 patients preoperatively. The mean maximum manual translations of the injured knees were 14 mm (range, 6–21 mm; SD, 3) before surgery and 7.5 mm (range, 4–13 mm; SD, 2) for the uninjured knee. These differences were significant ($P < 0.001$). Stratification of STSD preoperatively revealed that 15% had <3 mm, 26% had 3.1 to 4.9 mm, and 59% had >5-mm differences. Postoperatively, the mean maximum manual translation was 7.6 mm (range, 4–16 mm; SD, 2) for the affected knee and 6.9 mm (range, 2–15 mm; SD, 2) for the unaffected knee, reflecting a significant improvement compared with preoperative translations of the affected knee ($P < 0.001$). Stratification of STSD postoperatively revealed that 95% had ≤3 mm STSD and 5% had greater than 3 mm but less than 5 mm STSD. The reductions in STSD were statistically significant ($P = 0.001$). There were no statistically significant differences between the affected and unaffected knees postoperatively with regard to arthrometric testing, and high patient satisfaction rates correlated with excellent KT measurements. Ninety-four percent of the patients were completely or mostly satisfied with the results of their surgical procedure. Sixty-five percent were completely satisfied, 30% were mostly satisfied, 5% were somewhat satisfied, and no patients were dissatisfied. Ninety-six percent of the patients stated they would have the surgery again if the injury occurred to the opposite knee.

In this study, graft failure was defined as the presence of a pivot shift of any grade or KT-1000 maximum manual test of ≥5 mm of STSD. Five patients had a grade I pivot shift, and one had a grade III pivot shift (10%). The overall failure rate was 10%. There were no infections, no evidence of any acute or chronic rejection of the grafts, and no evidence of disease transmission. No patients had chronic effusions or synovitis. No patients had significant tunnel expansion (>20 mm) on radiographic evaluation.

In Bach's series from Rush Medical Center,[4–9] the results of autograft and allograft patellar tendon graft ACL reconstruction have been comparable. Patients' rating of success was 92% mostly or completely satisfied in their autograft group versus 94% in the allograft group. The positive pivot shift (grade I and higher) was present in 9% in the autograft group and 10% in the allograft group. In the autograft group, 74% had a negative Lachman versus 72% in the allograft group (Table 8). These results after primary allograft patellar tendon use are significantly better than previous experience using nonirradiated allograft for revision ACL surgery for a failed primary patellar tendon autograft.[27] The authors conclude that the use of allograft tissue for ACL reconstruction is a viable alternative to autograft in certain patient populations. Patients in this population of ACL-deficient patients often include older athletes or patients with preexisting chondral disease. These patients must be counseled about realistic expectations of pain and functional outcome despite successful ACL reconstruction confirmed by KT arthrometry.

Siebold et al[58] compared the outcomes of 251 patients at a minimum of 2 years after primary ACL reconstruction with either patellar tendon allograft or Achilles tendon allograft. In this study, the patellar tendon group stability measured with the KT-1000 showed an average STSD difference of 2.1 mm and 2.0 mm in the Achilles tendon group. Despite these equivalent laxity measurements, there was a higher failure rate ($P < 0.001$) in the patellar tendon group, with a 10% retear rate of the patellar tendon reconstructed ACL, compared with 5% of the Achilles tendon group. The authors conclude that as a result of the higher failure in both allograft tissues, that autograft tissue be used routinely for primary ACL reconstruction, and that the allograft tissue use be reserved for revision reconstructions or multiple ligament injury scenarios. The results in this series do not agree with those of Bach et al with respect to allograft patellar tendon, nor with the results of Indelli,[40] who reported a mean STSD of 2.3 mm at 3 to 5 years after Achilles tendon allograft ACL reconstruction. It should be considered, however, that the KT data in these studies serve well to offer objective comparison specifically concerning anterior laxity after ACL reconstruction. The good KT arthrometry results obtained by Siebold et al mitigate concerns of allograft tissue laxity and suggest that there may be other reasons for the ACL failures in that study.

TABLE 8. *Primary Allograft Patellar Tendon Anterior Cruciate Ligament Reconstruction Outcomes Compared With Primary Autograft ACL Reconstructions: The Rush Medical Center Experience**

	Bach et al[5]†	Bach et al[7]‡	Bach et al[8]§	Bach et al[9]^
Age (range)	41 (18–61)	27 (16–45)	25 (10–52)	26 (12–53)
MMD-STS postoperatively				
<3 mm	95%	92%	83%	70%
3–5 mm	5%	4%	14%	26%
>5 mm	0%	4%	3%	4%
Negative pivot shift	90%	92%	91%	84%
Pain with stairclimbing				
Mild/moderate	46%	NA	14%	13%
Severe	2%	NA	0%	0%
Tegner	6.3 (2–10)	6.3 (1–9)	6.5 (2–9)	6.3 (2–9)
Lysholm	82 (43–100)	88 (52–100)	89 (43–100)	87 (34–100)
Noyes sports activity scale	71 (20–100)	90 (50–100)	90 (33–100)	89 (27–100)
Would repeat surgery	96%	95%	95%	94%
Mostly or completely satisfied	94%	90%	92%	97%

*Measured at 30° of knee flexion.

†Minimum 2-year retrospective follow up (allografts).

‡Two- to 4-year retrospective follow up (autografts).

§Minimum 2-year retrospective follow up (autografts).

^Five- to 9-year retrospective follow up (autografts).

MMD-STS indicates maximum manual difference side to side.

NA, not available.

From Bach BR Jr, Aadalen KJ, Dennis MG, et al. Primary anterior cruciate ligament reconstruction using fresh-frozen, nonirradiated patellar tendon allograft: minimum 2-y follow-up. *Am J Sports Med* 2005;33:284–292.

Revision Anterior Cruciate Ligament Reconstruction

KT arthrometry has permitted increased precision in the quantitative assessment of outcomes of revision ACL reconstruction. Taggart et al[61] retrospectively reviewed 20 patients after ACL revision reconstruction using varied graft sources, including patellar allograft. In this study, patients underwent a thorough clinical evaluation and arthrometry measurement. There was a significant maximum manual STSD after the revision ACL reconstruction, but these results did not correlate with high patient subjective ratings. The results of this study indicate that although there is residual AP laxity on clinical assessment and KT-1000 instrumentation after revision ACL reconstruction, the majority of patients subjectively rated the results as good or excellent. The finding of a poor correlation between objective KT measurements and patient subjective rating of the surgery correspond with the findings of Harter et al[35] and others[30,44,610] who found that postoperative laxity measurements did not correlate with patients' perception of knee function.

In another study from Rush Medical Center, Fox et al[27] retrospectively reviewed a cohort of 39 patients 2 to 11 years after revision ACL reconstruction with nonirradiated fresh-frozen patellar tendon allograft. In this review, Tegner, Lysholm, Noyes, KOOS, IKDC, and SF-12 rating scales were used in addition to the KT arthrometry. KT data revealed that 84% had a maximum manual STSD of <3 mm and 6% had greater than 5 mm STSD. With the use of the KT data to objectively evaluate the status of the anterior knee laxity after ACL reconstruction, this study demonstrates that the results for a revision ACL reconstruction with a nonirradiated patellar tendon allograft are less favorable than a primary ACL reconstruction, and the authors concluded that it should be considered a salvage procedure.

SPECIAL CIRCUMSTANCES

The KT arthrometer has become an important adjunct for evaluating various techniques of knee reconstruction. Recently, the arthrometer has been used to evaluate special circumstances that go beyond the realm of strict ligament reconstruction. Its use in these areas is critical to making careful objective measurements and rational comparisons of the outcomes of various techniques, allowing for techniques to be improved after scrutiny of data that is translatable from one study to another.

A tibial spine fracture is considered the pediatric equivalent of an ACL injury.[38] After fixation of type III tibial spine fractures in children, Kocher et al[44] evaluated 6 patients at a minimum of 2 years after arthroscopic reduction and 3.5 mm screw fixation of Meyers and

McKeever[50] type III tibial spine avulsion fractures. Patients were evaluated by comprehensive physical examination, knee outcome questionnaires, and KT arthrometry. Arthrometry showed greater than 3-mm manual-maximum STSD in 4 of 6 patients. Functional assessment, however, revealed excellent function, with a mean Lysholm score of 99.5 (range, 98–100), mean Marshall score of 49.0 (range, 47–50), and mean Tegner score of 8.7 (range, 7–9). The authors concluded that arthroscopic reduction and internal fixation of type III tibial spine fractures in skeletally immature patients results in persistent laxity but excellent functional outcome.

Meniscus transplantation has moved into mainstream orthopaedics over the last decade. In the setting of combined meniscus and ACL deficiency, combined meniscus transplantation and ACL reconstruction is indicated. Sekiya et al[57] evaluated 28 patients retrospectively at a mean of 2.8 years after combined simultaneous patellar tendon allograft ACL reconstruction and meniscus transplantation. Patients were evaluated by physical examination, IKDC scores, SF-36, and KT-1000 arthrometry. Eighty-six percent of patients had normal or near-normal IKDC scores, with 90% rated as normal or near-normal Lachman and pivot examinations. At both 30 lb and maximum manual, there was an average STSD of 1.5-mm anterior laxity. The authors concluded that concomitant meniscal transplantation and ACL reconstruction could restore meniscal function, protect articular cartilage, and by restoring the meniscus as a key secondary stabilizer, protect the ACL reconstruction. Using KT arthrometry measurements, future studies may be able to compare the results of revision ACL reconstruction with or without meniscal transplantation.

Osteochondral implantation for the treatment of focal chondral defects has become more commonplace in the last decade.[1] In the setting of combined ACL deficiency, treatment of a symptomatic focal chondral defect with osteochondral implantation must be combined with ACL reconstruction. Klinger et al[43] prospectively reviewed 21 patients for greater than 32 months after osteochondral implantation of cartilage defects with a mean area of 3.5 cm^2. KT arthrometry revealed a decrease in the STSD of 5.9 mm before reconstruction to 1.9 mm after combined osteochondral implantation and ACL reconstruction. All but 2 patients had returned to full activities without restriction and were asymptomatic. The authors concluded that symptomatic full-thickness articular cartilage defects associated with ACL instability can be effectively treated by performing ACL reconstruction and osteochondral grafting in one procedure.

NONANATOMIC VARIABLES AFFECTING MEASUREMENTS

The KT arthrometer's ability to make accurate comparisons is rooted in its ability to standardize objective data to support or refute subjective evaluation by clinicians, patients, and researchers. Despite considerable efforts to standardize positioning, technique, and anatomic considerations, it remains challenging to control for the multitude of nonanatomic variables that can affect ligament laxity testing. An understanding of the magnitude and direction of variation caused by certain biologic and social conditions will allow for more accurate interpretations of the arthrotomy data.

Worker's Compensation

A general perception exists that outcomes of orthopaedic procedures in patients with worker's compensation claims fair worse than those of patients without such claims. Bach et al[66] evaluated the KT-2000 arthrometry of 22 patients with worker's compensation claims who underwent ACL reconstruction between 1987 and 1995. They showed a mean maximum manual difference of 1.9 mm with 15 patients (68%) having a maximum manual difference of <\/3 mm and 7 patients (32%) from 3 to 5 mm. This data compares comparably with historic data at Rush.[4–9] This study found that the presence of a workers' compensation claim has no negative affect on the outcome of patellar tendon ACL reconstruction does not significantly alter KT measurements.

Gender

The higher incidence of ACL tears in women has been proposed to be the result of multiple factors, among them hormonal and ligamentous laxity differences.[51] Neuromuscular gender differences include less total muscle mass, delayed muscle activation, and slower force generation when compared with men[12] as well as decreased ability to generate muscle force in female athletes when compared with male athletes, even when corrected for differences in size.[32] In addition, female athletes have altered muscle recruitment patterns than men, with a tendency to recruit quadriceps muscles, rather than hamstrings or gastrocnemius muscles,[39] a pattern that places the female ACL at additional risk. Estrogen and progesterone receptors have been found within the ACL,[47] and female athletes are at greater risk of ACL injury during their ovulatory phase of their menstrual cycle.[67] It is reasonable to predict that female knee laxity would fluctuate with hormone cycles that affect the ACL.

VanLunen et al[64] examined ACL laxity by arthrometry during women subjects' menstrual cycle. In this study, 12 college-aged women not currently on hormone therapy with regular cycles for 12 months before initiating the study underwent KT measurement of normal knees at the onset of menses, near ovulation, and on day 23 of the midluteal phase of the menstrual cycle. At each measurement, blood draws monitored hormone levels. There were no differences noted in KT measurements relative to hormone changes during their cycles. This study found no associations between hormone concentrations during any phase of the menstrual cycle and ACL laxity as measured on the KT-2000 arthrometer.

More recently, however, Romani et al[56] examined normal knees in 20 college-aged women with normal cycles and not taking oral contraception. Each woman donated regular blood draws to assay for estradiol, estrone, and progesterone levels, and their normal knee underwent KT-2000 arthrometer measurements. This study identified a significant correlation with estradiol and estrone levels and ACL laxity during the ovulation phase of the cycle. Deie et al[21] examined the normal knees of 16 college-aged women experiencing normal cycles. In addition to hormone levels, basal body temperatures were recorded to assist in identifying the follicular, ovulatory, and luteal phases of the menstrual cycle. In addition, normal knees of 8 college-aged men were measured for comparison. For the women, there were significant changes in the anterior displacement at the 89-N and 134-N force levels during the follicular and luteal phases, but no change in laxity during the testing period for the male subjects. It is possible that hormone changes that occur in conjunction with ACL laxity fluctuations occur in a narrow window of time around the ovulation event, and VanLunen's investigation did not draw blood during the correct window of hormone level changes. Each of these studies is limited by the small number of subjects and the complex physiological variables present during the normal menstrual cycle. Notwithstanding these limitations, the KT-2000 data presented in these studies present compelling evidence that cyclical hormone-driven ACL laxity fluctuation is one of many factors that explain gender differences in rates of ACL injury.

To investigate gender differences after ACL reconstruction, Bach et al presented KT data for matched populations of men and women undergoing ACL reconstruction with patella tendon grafts. In that study, 200 patients comprised of 137 men and 63 women were evaluated by physical examination, questionnaire, functional testing, and radiographic evaluation and KT-1000 arthrometry at a mean of 5 years after ACL reconstruction with patellar bone–tendon–bone autograft. Male patients had a significantly greater mean KT-1000 maximum manual STSD (0.76 vs 1.73 mm, $P = 0.014$) than women. However, no differences were noted in the percentage of patients with greater than 5-mm STSD, with 5 men (4%) and 2 women (3%) classified as arthrometric failures.[25] This study illustrates that despite significant physiological differences between the ACL in male and female knees, good long-term outcomes after ACL patellar tendon reconstruction can be obtained in both men and women.

Exercise

Steiner et al[60] studied the immediate effect of exercise on AP laxity of the knee on college-aged athletes. A displacement force of 30 lb (133 N) was applied using a Stryker knee laxity testing device. Four groups were evaluated (sedentary, squat powerlifter, basketball players, and distance runners). For the distance runners and basketball players but not the power lifters, up to 20% increased laxity was demonstrated after exercise ($P < 0.01$). This study incorporated the use of a knee laxity tester to demonstrate that exercise that involves repetitive physiological stresses at a high strain rate can cause a transient immediate increase in laxity measurements, whereas exercises involving a relatively few number of large stresses at a low strain rate do not significantly change laxity measurements.

Generalized Ligamentous Laxity

The extent to which a patient's inherent generalized ligamentous laxity will affect a KT measurement is important to understand. In the patient population reported by Bach et al,[4,10] generalized ligamentous laxity was assessed in normal controls and ACL-deficient populations to determine if this affected the KT-2000 displacements. Thumb-to-forearm laxity (TFL), metacarpophalangeal extension (MPE), elbow recurvatum, and knee recurvatum were measured and graded. The grades of these various parameters of ligamentous laxity were summarized in a total laxity score (TLS), and an attempt was made to correlate increased KT arthrometer displacements with generalized ligamentous laxity in the test population.

In injured patients with TFL, statistically significant differences were noted at 67 N and 89 N ($P < 0.001$). For example, at 89 N, patients without TFL had a mean anterior displacement of 11.3 mm, whereas those with TFL had a mean anterior displacement of 14.6 mm. In addition, increased KT measurements correlated with higher grades ($P < 0.01$) of generalized ligamentous laxity as reflected by higher combined TLS scores. For injured knees, patients with a TLS score of zero had a mean translation of 10.7 mm; TLS of one, 11 mm; TLS of 2, 13.1 mm; TLS of 3, 14.3 mm; and TLS of 4, 15 mm. For uninjured knees, increased TLS score correlated with increased displacement at both 89 N and at maximum manual test levels. At 89 N of force, patients with a TLS of zero had a mean displacement of 5 mm; TLS one, 6.2 mm; and TLS 3, 7.5 mm. For maximum manual testing, a similar increased trend of displacements was noted: TLS zero, 12.6 mm; TLS one, 13.8 mm; and TLS 2, 16.3 mm; but only 2 patients had a TLS score of 3 = 12.2 mm, and for this reason, the trend did not reach statistical significance. The trend witnessed in displacement and the correlation with higher TLS scores was also seen with respect to the compliance calculations. Patients with a TLS = zero, the mean compliance was 2.0 mm; TLS 1, 1.9 mm; TLS 2, 2.4 mm; TLS 3, 2.6 mm; and TLS 4, 3.6 mm. Compliance was the only statistically significant testing parameter ($P < 0.001$) in chronic patients with knee recurvatum on the involved or uninvolved side. Similarly, compliance was the only statistically significant testing parameter in chronic patients with elbow recurvatum ($P < 0.001$).

In summary of laxity findings, it appears that MPE and TFL are the most important parameters of the 4 tested. It has been observed by many surgeons that the patient with generalized ligamentous laxity is analogous to a "double-edged sword" in that this patient often fails conservative treatment yet is at some risk for failing autograft patellar tendon reconstruction, possibly as a result of the biologic composition of autograft tissue, as well as the composition of the secondary restraints. Future ACL outcome studies should consider quantifying ligamentous laxity and incorporating this nonanatomic biologic feature of laxity into the analysis.

SUMMARY

Instrumented laxity testers, particularly the KT-1000 and -2000, have been used to evaluate the normal and ACL-deficient knee in both in vitro and in vivo studies. Objective quantification of knee laxity in ACL-deficient patients before and after patellar tendon reconstruction is an important treatment adjunct. Increasing numbers of clinical reports are using arthrometry to objectively report anterior displacements. Future reports should include 89 N, maximum manual, compliance index, and STSD, because variation in testing parameters has been highlighted in the previously reviewed papers. KT arthrometry (KT-1000 or KT-2000) allows the worldwide orthopaedic community to accurately compare and evaluate reported results because these measurements provide objectivity to the subjectively graded clinical tests. It should be noted that in several studies[30,34,,35,44,61] patient satisfaction and subjective evaluations by examiner and patient tended to overestimate the presumed ligamentous stability, and in these cases, the KT arthrometer provides important objective information regarding the integrity of the ligament stability. This objective data may be the only means early detection of laxity after ACL reconstruction. Knee laxity testing data should be incorporated into the objective preoperative and postoperative evaluation patients after patellar tendon ACL reconstruction, and the surgeon should strive to match the stability of the contralateral normal knee. These testing devices are important tools for the researcher recording and comparing outcomes of populations, but also for clinicians evaluating an individual patient's progress after ACL reconstruction.

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