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# Anterior cruciate ligament assessment using arthrometry and stress imaging

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**Abstract** Arthrometry and stress imaging are useful clinical tools for the objective assessment of anterior cruciate ligament (ACL) integrity. They are most frequently used for the diagnosis of a complete ACL tear when other workup is equivocal, in conjunction with history and clinical exam findings. Other applications include the diagnosis of partial ACL tears, injury prognosis, and post-operative monitoring. However, further studies are needed to validate these uses. Many different devices and techniques exist for objective examination, which have been compared in recent literature. Reliability and validity measures of these methods vary, and often depend upon examiner familiarity and skill. The KT series of devices is the current gold standard for arthrometry, although the newer robotic GNRB device shows promising early results. Newer methods of data interpretation have been developed for stress imaging, and portable technology may impact this field further.

**Keywords** ACL · Knee · Arthrometry · Stress imaging · Injury · Sports medicine

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## Introduction

Accurate assessment of knee laxity is critical for many steps in the management of anterior cruciate ligament (ACL) injury. Classic physical exam maneuvers, while essential, depend on subjective factors such as clinician experience, muscle relaxation, and inherent knee variability. Advanced imaging such as MRI is expensive and cannot directly evaluate instability. Therefore, objective assessment of joint laxity, or “laximetry,” is often desired to supplement physical exam findings. Broadly, the two types of laximetry are stress imaging and arthrometry, both of which quantify the knee displacement resulting from an applied force.

Both techniques have evolved since their introduction 30–40 years ago. Clinically, laximetry is best defined as a dichotomous tool for diagnostic purposes, used in combination with physical exam maneuvers. In addition, many groups have sought to harness laximetry’s quantitative properties for prognostic purposes or to monitor post-operative laxity. These applications currently have less clear support in the literature, although a recent study suggests that objective evaluation of the uninjured knee can aid in the prognosis of ACL reconstructive surgery. Laximetry is also useful in research, since its quantitative properties allow objective evaluation and comparison of different factors such as surgical techniques or rehabilitation regimens.

Major recent developments include the introduction of a robotic arthrometer, designed to improve the objectivity of arthrometry. There are also ongoing attempts to validate laximetry results in the clinical setting and to systematically compare the many existing techniques and protocols.

## Stress radiography

Stress radiography is a non-invasive method of visual observation and quantification of knee joint laxity in response to an applied stress. For ACL injury, this is typically measured in the anteroposterior plane, although techniques do exist for evaluating rotational and varus/valgus laxity [1••]. Generally, a "baseline" resting lateral knee X-ray (XR) is obtained and compared to an analogous image obtained with force applied to the knee. The level of anteroposterior knee laxity is inferred from the changing tibiofemoral relationship.

The diagnostic value of stress imaging as compared to clinical exam or MRI is unclear, and it is therefore recommended as a diagnostic adjunct rather than a stand-alone tool [2–4]. The highest diagnostic ability is obtained by combining stress imaging with these methods [5].

Several imaging protocols exist, with a recent article reviewing 12 techniques described in the literature [1••]. The Telos device (Austin & Associates, Fallston, Maryland) is a highly reproducible means of producing knee stress for imaging and has achieved widespread use. Clinicians should adopt a consistent testing regimen and should not assume that the results of different protocols are comparable.

### Choice of landmarks

Multiple landmarks can be used to define the tibial and femoral position. Ideally, landmarks should be easily and unequivocally identifiable, and should not be highly dependent on subtle changes in knee rotation or flexion. Theoretically, posterior landmarks are the least dependent on knee flexion, since the center of knee flexion lies posterior to the midshaft axis [6–8]. Central landmarks are the least dependent on axial knee rotation, since they again are nearest to the center of rotational motion. Some investigators choose landmarks which evaluate translation in one knee compartment (i.e., medial or lateral), while others select midline landmarks which represent overall tibial translation. The lateral knee compartment has consistently shown higher anterior laxity in both normal and injured knees, and investigators have found better reliability in measuring the medial compartment [9–12].

Landmarks for defining femoral position include the posterior-most aspect of the lateral femoral condyle (LFC), the posterior-most medial femoral condyle (MFC), or the midpoint between the two as seen on lateral XR. Other studies have used central landmarks, such as the posterior-most aspect of Blumensaat's line, or the central femoral axis. Studies which position the knee in 90° of flexion will often use the anterior-most aspect of the respective femoral condyle. After a femoral landmark is chosen, typically a line is drawn tangential to the landmark and extended distally in a direction perpendicular to the tibial plateau, to allow for comparison to the tibial landmark.

Landmarks for defining tibial position on lateral XR include the posterior-most aspect of the lateral tibial plateau, the posterior-most medial tibial plateau, or the midpoint between the two. Other alternatives include the posterior fibular head, the medial intracondylar eminence, central tibial axis, or the anterior-most aspect of the tibial plateau.

Several studies have compared different landmarks used in stress imaging. In a study by Lee et al., a method using the posterior Blumensaat's line and the anterior tibial plateau showed the best inter-rater and intra-rater reliability, with an intraclass correlation coefficient between 0.891 and 0.963 [6]. Wirz et al. also compared multiple measurement protocols, specifically examining the effect of rotation and flexion on landmark position and reliability, as these represent common positioning errors [7]. They found that a "central-peripheral" method was most consistent despite rotation or flexion—this method used the central tibial axis, compared to a parallel line positioned midway between the posterior aspects of both femoral condyles. The tibial eminence was a relatively inconsistent landmark and was not recommended for use.

### Patient positioning

Knee laxity is dependent on positioning, as the degree of flexion influences the activity of different anatomical restraints. An ideal position should isolate the ACL; this is typically found at roughly 20° of flexion, similar to the position used to perform a Lachman's test. In the majority of studies that describe passive stress imaging, the knee is positioned in 20° of flexion, typically with the patient in a decubitus position lying on the affected side. However, studies have described using knee flexion ranging from 0° to 90°.

Active stress imaging can also be performed using a number of different techniques. The quadriceps contraction technique was first described by DeJour et al. in 1988, and involves positioning the patient supine with the knee initially placed over a triangle [13]. For the image, the patient then fires the quadriceps and extends the leg fully, lifting it into the air. The extensor mechanism, in addition to extending the leg, will translate the tibia anteriorly, and this translation is compared between the two limbs. Another active technique is the lateral monopedal stance, also described by DeJour et al. [14]. The patient stands only on the leg to be imaged, with the knee flexed 20°. In this position, the tibia will translate anteriorly, the degree to which was found to be dependent on the tibial plateau posterior slope. Although this method was initially thought to be desirable due to the physiologically relevant position, it was found to be less sensitive than stress imaging using a manual Lachman maneuver in diagnosing ACL rupture.

### Force application

The force used in stress imaging should be reproducible, gentle to the patient, and adequate to produce maximal translation. This can be performed using passive means, in which an extrinsic force is applied to the patient, or active means, in which the patient produces the translating force through muscle contraction. While active means are attractive due to their physiological mechanism, they generally are more patient-dependent and are less reproducible.

Several passive techniques have been described. Most simply, some authors perform a manual Lachman test during imaging. Another simple technique involves placing a sandbag onto the patient's leg in an appropriate position, typically weighing anywhere from 3 to 9 kg [9, 11, 15]. The Telos apparatus is also commonly used [2, 5, 16–19]. This is a device which holds the femur and tibia in a fixed position, and then applies a reproducible force to the posterior tibia, producing anterior tibial translation. Most authors use 150 N of force, roughly equivalent to 15 kg, but different protocols use anywhere from 50 to 250 N [2, 6, 7, 16].

The baseline for measurement should also be consistent. Some groups simply use the resting knee position, whereas others initially apply a posterior force, thus obtaining the full anteroposterior laxity. PCL integrity obviously can impact this measurement and should always be considered.

Active techniques, as previously mentioned, use the patient's own musculature to produce tibial translation. Typically, this involves a full quadriceps contraction, or enough contraction to position the knee in 20° flexion in a standing position [12, 14]. Obviously these forces cannot be standardized between patients and may be less useful for research purposes. However, they may be more functionally relevant in the clinical setting as they involve the patient's own musculature. Comparative studies have found easier testing protocols and higher diagnostic value using passive methods [18].

### Methods of quantification

Most investigators prefer comparing the affected knee to the unaffected knee, obtaining a "side-to-side difference" (SSD) measurement of increased laxity. Normal SSD is near zero [20]. Different diagnostic thresholds have been reported in the literature ranging from SSD of 2 to 5 mm [14, 17, 21]. In patients with complete ACL tear, Panisset et al. found average SSD to be 7.4 ± 4.3 mm and used SSD >5 mm as their diagnostic threshold using Telos stress imaging (Sn 80.9 %, sp 81.8 %) [5]. Beldame et al. instead used a diagnostic threshold of 4 mm with Telos stress imaging (Son 59 %, Sp 90 %) [2]. Most investigators have found higher diagnostic reliability and validity with medial compartment laxity, as opposed to the lateral compartment [9, 14].

Single-knee absolute translation is the simplest measurement to obtain, and limits overall radiation exposure. However, inherent knee laxity differs between patients, making these results less accurate. A study of normal patients with the Telos device found an average normal knee anterior laxity of 1.76 ± 0.33 mm [22•]. Lerat et al. suggested a 6-mm diagnostic threshold for absolute laxity measurements of the medial compartment using Telos stress imaging [9].

### Rotational stress imaging

Classic stress imaging cannot evaluate rotational instability, a significant criticism of this technique. Although some groups have described rotational stress imaging techniques, this has not yet been well-validated and is not widespread in clinical practice or research [23, 24].

## Arthrometry

Arthrometers are devices designed to apply a reproducible force across the knee and mechanically measure the resulting displacement. Advantages include a relatively simple and quick clinical technique, increased objectivity compared to simple clinical exam, and a lack of radiation exposure. Many devices have been developed, although only a few have entered widespread clinical practice. Testing techniques differ somewhat for each device, and there are also several described methods of data interpretation.

### Devices

*KT-1000/KT-2000*

The KT series of arthrometers are the most highly studied and widely used arthrometers in orthopedic practice, and are largely considered a gold standard for laximetry. The original KT-1000 Knee Ligament Arthrometer (MEDmetric Corp, San Diego, CA, USA) was introduced in 1982 and first reported in 1985 [25, 26]. The patient is positioned supine with the knee flexed, and the KT-1000 is attached to the patient's leg as shown in Fig. 1. Forces can be applied to the tibia either manually or by using a force-quantifying handle. The examiner first "zeroes" the probe at the maximal posterior displacement, and then applies anterior force to the tibia, recording the maximal anterior translation. The KT-2000 adds a two-dimensional display which can produce a force-displacement curve [25].

The diagnostic validity of KT arthrometry has been the focus of much scrutiny and some criticism, although the literature is generally supportive [25, 27–30]. It is important to note that diagnostic sensitivity and specificity vary with the testing protocol, the method of data interpretation, and the diagnostic threshold used. Several groups have found that

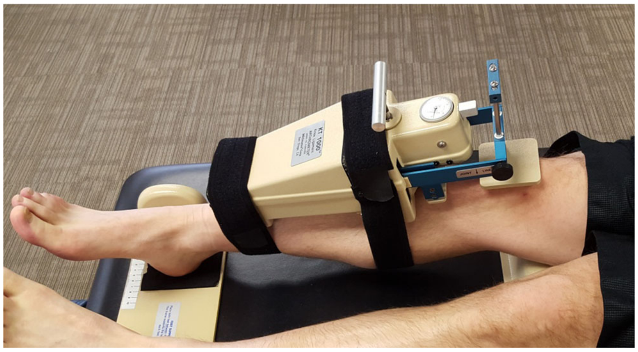

**Fig. 1** The KT-1000 arthrometer as positioned on a subject. The device is centered over the patella, with two straps around the tibia providing stability. Two probes extend to the anterior patella and proximal tibia, recording the tibial position relative to the patella

higher applied forces improve diagnostic ability [31••, 32]. In their comparative meta-analysis, Van Eck et al. found generally good validity measures, with improvement as the applied forces increased from 69 N (Avg Sn 54 % [range 0.24–0.84]), to 89 N (Sn 73 % [60–100 %], Sp 92 % [67–100 %]), to maximum manual force (Sn 93 % [88–100 %], Sp 91 % [87–100 %]) [31••].

The reliability of KT-1000 measurement has also been questioned, and the literature overall is more inconclusive. However, in subjects with an intact ACL, the reliability is generally good, with intra-rater correlations ranging from 0.83 to 0.97 [33–38] and inter-tester correlations ranging from 0.41 to 0.92 [33, 34, 37–40].

In ACL-deficient patients, the literature is more limited and equivocal. Forster et al. initially warned of significant test-retest discrepancies, inter- and intra-surgeon variation, as well as significant differences depending on anesthesia [29]. Measurements are often only reproducible within a few millimeters, which can skew results given that diagnostic thresholds are typically 2–3 mm [41]. Developers of the International Knee Documentation Committee (IKDC) form, designed to be a comprehensive evaluation of knee function, recognized this fact [42]. While their new form required data such as subjective symptoms, manual examination, and functional testing, it only included objective laxity assessment as an optional supplement. The developers cited measurement error, cost, time, and limitation to the anteroposterior plane in their reasoning. Wiertsema et al. were also critical, finding the KT-1000 inferior to the Lachman test in both intra-rater (ICC = 1.0 vs. 0.47) and inter-rater (ICC = 0.77 vs. 0.14) reliability, even with experienced KT-1000 users [43]. The few other published reliability measures vary, with intra-rater reliability ranging from 0.67 to 0.99 and inter-rater reliability ranging from 0.65 to 0.92 [37, 40, 44]. Many factors influence test reliability, including examiner experience, device overtightening, improper positioning, inconsistent force application, leg external/internal rotation, examiner hand dominance, and knee effusions [34, 39, 40, 44–49]. Although only explicitly studied with the KT system, several of these factors could conceivably affect other devices as well.

*GNRB*

The GNRB (Genourob, Laval, France) was first described in 2009 and has been a major focus of arthrometry literature in the past 3 years. It is a robotic arthrometer designed to avoid operator-dependent and relaxation-dependent error. The patient's leg is placed in 20° knee flexion with restraints at the patella and ankle. Pre-defined force is applied to the posterior proximal calf by a mechanical jack, and a probe measures the resulting displacement of the proximal anterior tibia. Electrodes over the posterior thigh are designed to account for the effects of incomplete hamstring relaxation [50].

Several groups have found GNRB reliability to be superior to other arthrometers, which they attributed to the higher-precision translation probe and the automated force application [22•, 50, 51]. However, the literature is not unequivocal, with Vauhnik et al. finding lower intra-rater and inter-rater reliability [52, 53].

Diagnostic validity measures are comparable to other devices, and again depend on the test protocol used. Robert et al. found moderate test sensitivity (Sn 70 %, Sp 99 %) using 134 N force at 20° of knee flexion and a 3-mm SSD diagnostic threshold [50]. Klouche et al. found better sensitivity (Sn 92 %, Sp 98 %) using 200 N force with a 1.9-mm SSD diagnostic threshold. Other groups found more moderate results (Sn 62 %, Sp 76 % at 1.5 mm SSD threshold) [18]. One group also found the GNRB useful for partial tears (Sn 84 %, Sp 81 % at 2.5 mm SSD threshold) [54•].

*Rolimeter*

The Rolimeter (Aircast Europa, Neubeuern, Germany) is another common device used to quantify anteroposterior knee laxity. The device similarly attaches to the patella and the distal tibia, with a probe that rests on the tibial tuberosity. The clinician then performs a manual Lachman test, and the maximal displacement of this probe is recorded [55]. The skill and consistency of the examiner are crucial, as there is no means of standardizing the force or technique applied.

Reliability measures have been moderately high, but possibly dependent on examiner skill. Hatcher et al. found inter-rater reliability of 0.91–0.95 by a range of skill levels [56]. Muellner found reliability of 0.71–0.90 in experienced testers, but worse in novices [57]. Papandreou found varying inter-rater reliability of 0.55–0.96, which they attributed to the inherent subjectivity of the testing method [58].

Intra-rater reliability is also moderately good but variable. Several groups have published their results, ranging from 0.24, 0.55–0.72, to 0.49–1.0 [57–59]. Again, investigators cited inherent subjectivity in explaining this variability.

The little evidence that exists for the Rolimeter's validity is promising. In a study of 50 normal and 46 ACL-deficient knees, sensitivity was 93 % and specificity 87 % in detecting ACL tears [60].

*Other devices*

Several additional arthrometers have been previously developed, but have not maintained widespread adoption.

The Genucom Knee Analysis system (FARO Medical Technologies Inc, Montreal, Canada) is a sophisticated, highly studied arthrometer designed to measure knee laxity in multiple planes [61]. However, reliability and validity were generally inferior, and prohibitively high costs have limited its clinical use [31••, 35–37, 62–68].

The Stryker Knee Laxity Tester (Stryker, Kalamazoo, MI, USA) is an arthrometer conceptually similar to the KT and Rolimeter [69]. Van Eck et al. performed a meta-analysis of studies examining the Stryker device and on average found 81 % sensitivity (range 71–94 %) and 96 % specificity (range 82–100 %) [31••].

The UCLA instrumented clinical knee testing apparatus is also conceptually similar to the KT-1000, with the added ability to evaluate endpoint firmness. Its use is largely limited to that institution; while important in previous research, it has not been featured in recent studies and is not commercially available [46, 70, 71].

The Vermont Knee Laxity Device (VKLD) was designed to evaluate knee laxity under variable levels of lower extremity weight-bearing. Reliability is generally comparable to other devices [72]. This device was useful for literature comparing the knee under variable weight-bearing loads, but is too large and impractical for routine clinical use.

The Edixhoven Mechanic Lachman Device was first described in 1987 and featured a vector-controlled manual handle for force application [73]. Although this theoretically improves reproducibility, the device is quite large and impractical for routine clinical use.

The Acufex Knee Signature System (KSS) consists of a tibial frame and a manual force-applying handle, mounted with transducers to accurately record force and displacement in three dimensions [74]. Limited reports show moderate reliability in injured patients and somewhat inferior reliability in uninjured patients [37].

## Data interpretation

Arthrometry results can be interpreted in a number of ways. The most common data interpretation measure is SSD, using the patient's uninjured knee as a reference. Multiple groups have shown better consistency in SSD measurements as opposed to single-knee measurements, both among different patients, as well as in test-retest analysis of individual knees [25, 29, 38, 68, 75]. Appropriate SSD thresholds vary by device, but are generally 2–3 mm. Some groups do advocate higher or lower values, but this typically comes at a cost of decreased sensitivity or specificity [18, 30, 54•, 69, 71, 76, 77•].

Absolute single-knee translation is a simpler outcome measure, but is confounded by the natural variance in inherent laxity [25]. Daniel et al. showed that average absolute knee laxity increases from 5.8 mm in normal knees to 13.0 mm in ACL-deficient knees using the KT-1000. Subsequent studies have yielded similar results [25, 69, 78].

Another indicator of ACL integrity is the differential laxity produced by increasing forces, visualized by a force-displacement curve. This broad concept has been expressed in several forms, including "stiffness," "compliance index," and "elastic modulus." Daniel et al. recommended their "compliance index," originally defined as the difference in absolute laxity from an applied force of 67 vs. 89 N [25]. They found this to be most sensitive measure of ACL laxity, and other literature has also supported this measurement technique [78]. Alternatively, the "elastic modulus" can be calculated by calculating the slope of the force-displacement curve, which increases in ACL-deficient knees [78, 79]. Wordeman et al. described a "modified compliance index" designed to evaluate the force-displacement slope at relatively higher forces, eliminating the effects of secondary knee stabilizers [79]. Other groups have recommended the use of second-order mathematical derivatives of the force-displacement curve in detecting ACL laxity [80].

## Comparative studies

Stress radiography and arthrometry have distinct advantages and disadvantages when compared to each other. Both are relatively quick with most devices and can be performed in the clinical setting. Stress imaging has the advantages of avoiding measurement error related to soft-tissue effects and the ability to visualize laxity in each knee compartment if desired. Disadvantages include added radiation and cost related to the imaging portion.

Studies comparing diagnostic ability have been mixed, with most finding similar results with both techniques [18, 21, 81•, 82]. Isolated studies have suggested that arthrometry has superior validity to stress imaging when using the KT-1000 or GNRB, but inferior when performed with the Rolimeter [5, 54•, 83]. One group found a higher level of test-retest variability over time with stress imaging, which could impair diagnostic ability [22•]. These findings should be interpreted cautiously as they have not been consistently reproduced and may depend on clinician familiarity. Overall, stress radiography and arthrometry have comparable diagnostic ability, and both appear appropriate in the clinical setting.

Recent comparative studies among arthrometers have shown superior reliability and less operator-dependent error with the GNRB device, likely due to its highly consistent robotic technique [50, 51]. Studies have found comparable results with the KT-1000, Rolimeter, and Stryker devices, and consistently inferior validity and reliability with the Genucom system [36, 55, 59, 60, 64, 84, 85]. It is important to note that each device's results will fundamentally differ, and clinicians must therefore not assume comparability between measurements from different devices [59, 60, 85].

## Clinical application

At this time, laximetry is best-indicated for the diagnostic assessment of complete ACL rupture, alongside a thorough history and clinical exam. Alone, the diagnostic value of laximetry appears comparable to classic exam maneuvers such as the Lachman's or pivot-shift tests, but the combination of both measures is superior [5, 28, 43, 86, 87]. Some literature suggests that this combination exceeds the diagnostic abilities of MRI, thus potentially obviating the need for the added time and cost of advanced imaging [5, 28].

There is limited evidence for laximetry's value in managing partial ACL tears, which can be subtle and challenging to clinicians. Some literature suggests that the majority of partial tears have laxity increases of <3 mm and are undetectable with laximetry [78, 88–92]. However, one group using the GNRB arthrometer found 80 % sensitivity and 87 % specificity with their protocol [50]. Other groups have found good diagnostic ability for laximetry when combined with the pivot-shift test, and there is also suggestion that force-displacement curve analysis could be promising for diagnosis severity [19, 78]. Arthrometry may also be useful for monitoring of conservatively treated partial ACL tears, with some evidence that increasing laxity can predict poorer outcomes and therefore guide treatment [93, 94].

Investigation continues regarding other uses for laximetry. Most recently, it was suggested that increased pre-operative laxity of the uninvolved knee may predict increased involved knee laxity and poorer subjective outcomes following ACL reconstruction [95••]. This could represent an important prognostic marker with which to counsel patients pre-operatively. Other groups have recently attempted to correlate laximetry measurements with functional knee stresses, finding a significant positive correlation between arthrometry results and ACL strain during landing exercises [96•].

Previously, there was much speculation that post-operative laxity of the involved knee could predict outcomes. However, prior research shows poor correlation between involved limb laxity and post-operative subjective or functional outcomes [95••, 97–99]. It is our experience as well that post-operative laxity is not strongly linked to negative outcomes such as re-injury rates. Interestingly, there is limited evidence suggesting that increased laxity following ACL reconstruction may indicate injury to other ipsilateral knee ligaments [100]. However, given the scarcity of data, no conclusive recommendation can be made at this time regarding laximetry for prognosis or post-operative monitoring.

## Conclusions

Laximetry is a useful technique in clinical practice, especially for aiding in the diagnosis of complete ACL tears. It is most strongly proven as a dichotomous diagnostic tool, although there is limited evidence that quantitative results from the involved or uninvolved knee could be useful prognostically. Perhaps the largest recent development in the field is the introduction of the robotic GNRB arthrometer. While the KT series is the existing arthrometry gold standard, the GNRB has received increased attention owing to its automated testing protocol and promising reliability measures.

Stress imaging and arthrometry have comparable diagnostic value and can be chosen according to clinician preference. A consistent regimen should be adopted, and laximetry should always be combined with a thorough history and physical exam for maximal utility. Laximetry devices and methodology are still evolving, and the diagnostic and prognostic power of these methods will improve with further development. Additional research is needed to better define the indications for objective ACL assessment, to cost-effectively integrate it within routine clinical practice, and ultimately improve outcomes for patients.

**Compliance with ethical standards**

**Conflict of interest** Eric M. Rohman declares that he has no conflict of interest.

Jeffrey A. Macalena has served as a consultant for Vericel, Smith and Nephew, and Arthrex within the past 36 months, outside of the submitted work.

**Human and animal rights and informed consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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