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SYMPOSIUM: MANAGEMENT OF THE DISLOCATED KNEE

Stress Radiography for the Diagnosis of Knee Ligament Injuries: A Systematic Review

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Abstract

Background Stress radiography is a widely used diagnostic tool to assess injury to the anterior and posterior cruciate ligaments and the medial and lateral structures of the knee. However, to date, numerous techniques have been reported in the literature with no clear consensus as to which methodology is best for assessing ligament stability.

Questions/purposes The purpose of this review was to identify which stress radiographic techniques have support in the literature for the diagnosis of acute or chronic knee ligament injuries, to define which technique is most accurate and reliable for diagnosing knee ligament injuries, and to compare the use of stress radiography with other diagnostic tests.

Methods Two independent reviewers performed a systematic review of PubMed (MEDLINE), the EMBASE library, and the Cochrane Controlled Trials Register for English language studies published from January 1970 to August 2013 on the diagnosis of knee ligament injuries using stress radiography. Information describing the ligament(s) investigated, stress radiographic technique, magnitude of force, measures of accuracy and reliability, and comparative diagnostic tests were extracted. Risk of bias was assessed using the QUADAS-2 tool.

Results A total of 16 stress techniques were described for stress radiography of the knee. The diagnostic accuracy of stress radiography including the sensitivity, specificity, and positive and negative predictive values varied considerably depending on the technique and choice of displacement or gapping threshold. Excellent reliability was reported for the diagnosis of anterior cruciate ligament, posterior cruciate ligament, varus, and valgus knee injuries. Inconsistencies were found across studies regarding the efficacy of stress radiography compared with other diagnostic modalities.

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Conclusions Based on the multitude of stress techniques reported, varying levels of diagnostic accuracy, and inconsistencies regarding comparative efficacy of stress radiography to other diagnostic modalities, we are not able to make specific recommendations with regard to the best stress radiography technique for the diagnosis of knee ligament injuries. Additional comparative studies using consistent methodology and appropriate blinding are necessary to further define differences in accuracy and reliability both among stress radiography techniques and between stress radiography and other diagnostic tests.
Level of Evidence Level III, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Stress radiography is a widely used diagnostic tool that provides objective quantification of knee ligament stability. Its applications include diagnosing acute and chronic injuries [1, 21, 30, 32], comparing instability preoperatively and postoperatively [20, 24, 39, 55], and monitoring stability in nonoperatively treated patients [17]. A variety of stress techniques have been described that assess ligament stability using an anteriorly, posteriorly, varus-, or valgus-directed force to the knee [10, 14, 17, 28, 29, 37, 40, 41, 43, 45]. Side-to-side differences in the amount of displacement (anterior or posterior) or gapping (varus or valgus) increase suspicion of a functional deficit in knee ligament stability. Compared with physical examination, stress radiographs provide a quantifiable and retrievable record of instability. Physical examination alone has often been reported to be inaccurate, subjective, and poorly reproducible for assessing anterior knee laxity [3, 23, 49, 53]. Clinician experience, a patient's pain, tolerance of the examination, and concurrent ligamentous injuries may skew physical examination interpretation, detracting in certain situations from its clinical use [22, 25, 27]. Previously reported discrepancies in the reliability and reproducibility of the physical examination have created a niche for objective and quantifiable assessments of ligament stability such as stress radiography that augment diagnostic power and enhance management decision-making [33, 35, 36].

Many factors influence the results of stress radiography in a clinical setting, including the position of the patient, knee position, muscular tone, the degree of muscular relaxation, gravity, the testing procedure, and the orientation, magnitude, direction, and amplitude of the force applied [4, 47]. In addition, viscoelastic properties, functional competence, secondary ligamentous restraints, and the inherent accuracy and reproducibility of the measurement device contribute to the degree of displacement [8, 37, 47]. The ideal stress radiographic technique is inexpensive, efficient, reproducible, accurate, and examiner-independent. Techniques described in the literature attempt to control for these variables with varying degrees of success. Despite more than four decades of use in the clinical setting, no clear consensus has emerged as to which stress radiography techniques are best for diagnosing knee ligament injuries.

This systematic review of the knee stress radiography literature therefore was designed to answer the following questions: (1) What stress radiographic techniques have support in the literature for the diagnosis of acute or chronic knee ligament injuries? (2) Which technique(s) is/are most accurate and reliable for diagnosing knee ligament injuries? (3) How does the use of stress radiography compare with other diagnostic tests?

Materials and Methods

A systematic electronic literature search was conducted in PubMed (MEDLINE), the EMBASE library, and the Cochrane Controlled Trials Register for studies published from January 1970 to August 2013. The following Boolean terms were used in the title and abstract fields: Stress Radiographs Anterior Cruciate Ligament ("Stress" AND "Radiographs" AND "Anterior" AND "Cruciate" AND "Ligament"); Stress Radiographs Posterior Cruciate Ligament ("Stress" AND "Radiographs" AND "Posterior" AND "Cruciate" AND "Ligament"); Varus Stress Radiographs ("Varus" AND "Stress" AND "Radiographs"); and Valgus Stress Radiographs ("Valgus" AND "Stress" AND "Radiographs").

Individual searches were also conducted to screen for articles published in 2013 and not yet searchable in the databases. The following journals were searched: *The American Journal of Sports Medicine, The Journal of Bone & Joint Surgery, The Bone & Joint Journal, Journal of Orthopaedic Research, Clinical Orthopaedics and Related Research,* and *Knee Surgery, Sports Traumatology, and Arthroscopy*. No restrictions were placed on study type during the initial search. Citations were exported to an Excel spreadsheet (Microsoft Corp, Redmond, WA, USA). Six hundred seventy-one studies were identified and 266 unique studies remained after duplicates were manually removed (405 studies excluded) (Fig. 1).

Two independent reviewers (EWJ, BTW) assessed the eligibility of each study based on the information presented in the title and abstract. Inclusion and exclusion criteria were developed to best answer our research questions. Non-English articles (21 articles) and articles not

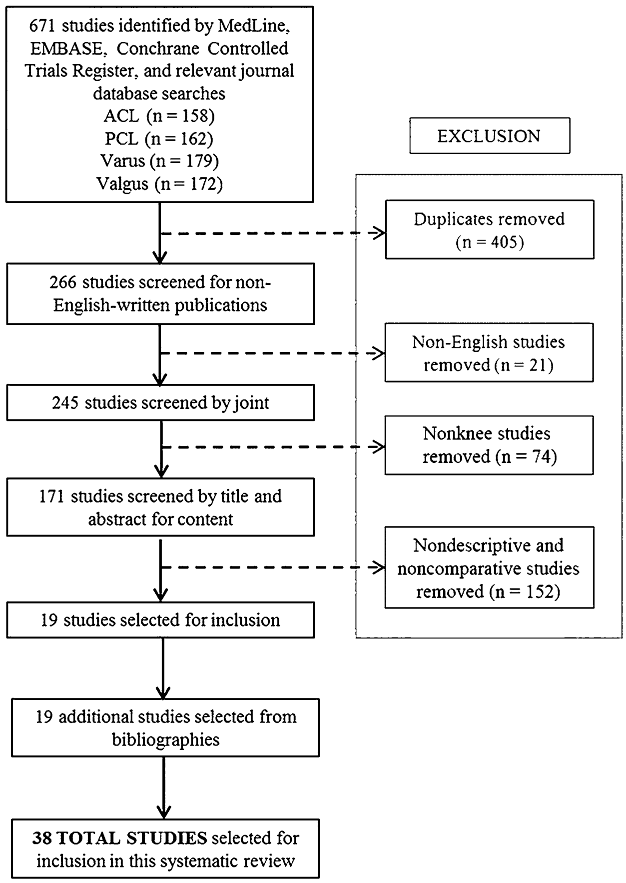

Fig. 1 The flowchart illustrates study selection criteria and the results of the systematic literature search.

pertaining to the knee (74 articles) were excluded. The remaining 171 articles were manually screened by title, abstract, and, if necessary, full text to identify studies that specifically (1) described a stress technique for the diagnosis of knee ligament injury; (2) described or compared the accuracy and/or reliability of one or several stress radiography techniques; or (3) compared stress radiography with other diagnostic techniques. All Level V evidence studies (expert opinion, case reports), editorials, and letters to the editor were also excluded. Articles considered relevant or of questionable relevance were extracted in full text and reviewed. A total of 19 studies were identified for inclusion from the electronic literature search. Reference lists were systematically reviewed to include studies consistent with the inclusion criteria that did not appear in the initial database queries. An additional 19 studies were identified by reviewer consensus to arrive at a total of 38 studies included in the final review.

After the final selection of articles was agreed on, the same two reviewers independently examined study quality using the QUADAS-2 tool [50–52] (Table 1). Differences between reviewers were settled by consensus. The QUADAS-2 tool provides an objective and transparent rating of bias and applicability for diagnostic accuracy studies. Four domains are used to assess for bias: patient selection, index text, reference standard, and flow and timing. Risk of bias was classified as low, high, or unclear for each of the four domains (Fig. 2). An overall designation of low, moderate, or high risk of bias was then assigned to each study. Overall high risk of bias was defined as a score of high or unclear risk of bias in three or four of a total of four categories, overall moderate risk of bias was defined as a score of high or unclear risk of bias in two of four categories, and an overall low risk of bias was defined as a score of high or unclear risk of bias in zero or one of four categories.

Data extraction identified the following key elements: (1) ligament(s) investigated; (2) stress technique; (3) magnitude of force; (4) measures of accuracy and reliability including sensitivity, specificity, positive predictive value (PPV), negative predictive value (NPV), and intrarater and interrater intraclass correlation coefficients (ICCs); (5) comparative diagnostic techniques; and (6) results and conclusions regarding comparative diagnostic techniques.

There has been a recent increase in the frequency of stress radiography publications for the diagnosis of knee injuries with nearly half of all studies (18 of 38 studies) included in this review published in the last 10 years (Fig. 3). Fifteen studies (39%) focused solely on the diagnosis of anterior cruciate ligament (ACL) instability, nine (24%) on the posterior cruciate ligament (PCL), two (5%) on varus, two (5%) on valgus, and 10 (26%) on multiligament assessment. Of the multiligament studies, four studies described anterior, posterior, varus, and valgus stress radiography [13, 17, 19, 32]; one described anterior, posterior, and varus stress [18]; four described anterior and posterior stress only [28, 46–48]; and one described posterior and varus stress only [43]. A total of 23 studies were purely descriptive studies of a stress radiography technique, whereas 15 studies were comparative either among stress radiograph techniques or between stress radiography and other diagnostic techniques.

Results

Stress Techniques

The stress radiography techniques and devices described in the literature varied by the plane of stress and therefore the ligament(s) isolated (Table 2). Several techniques were used for the assessment of more than one plane of stability, including the Telos device (Metax, Hungen-Obbornhofen, Germany) [1, 2, 5, 8–10, 13, 21, 28, 31, 34, 37, 38, 41–43,

Table 1. Risk of bias assessment for stress radiography diagnostic studies using the QUADAS-2 tool

First author	Risk of bias by domain				Overall risk of bias§
	Patient selection	Index test	Reference standard	Flow and timing	
ACL					
Hooper [15]	High	Unclear	Unclear	Unclear	High
Rijke [38]	Low	Low	High	High	Moderate
Granberry* [11]	–	–	–	–	–
Franklin [7]	Low	High	Low	Unclear	Moderate
Rijke [37]	High	Low	High	Low	Moderate
Stäubli [45]	High	High	Low	Low	Moderate
Lerat [29]	Low	Low	High	Unclear	Moderate
Dejour [6]	Unclear	Low	Unclear	Unclear	High
Garcés [9]	Low	Low	Low	Low	Low
Lerat [30]	High	Low	Unclear	High	High
Wirz* [54]	–	–	–	–	–
Beldame [1]	Low	Low	Low	Unclear	Low
Beldame [2]	Low	Low	High	Low	Low
Panisset [34]	Low	Low	High	Low	Low
Dejour [5]	Low	Low	High	Low	Low
PCL					
Stäubli [44]	High	Low	High	Low	Moderate
Hewett [14]	High	High	High	High	High
Margheritini [31]	Low	High	High	High	High
Schulz‡ [41]	–	–	–	–	–
Jung [21]	Low	Low	High	Unclear	Moderate
Garavaglia* [8]	–	–	–	–	–
Schulz [42]	Low	High	Low	Low	Low
Jackman‡ [16]	–	–	–	–	–
Garofalo [10]	Low	High	Low	Low	Low
Valgus					
Sawant [40]	Low	High	Low	Low	Low
LaPrade* [25]	–	–	–	–	–
Varus					
LaPrade* [26]	–	–	–	–	–
Gwathmey [12]	Low	Unclear	Unclear	Unclear	High
Multiligament					
Jacobsen† [17]	–	–	–	–	–
Jacobsen [18]	Low	High	Low	Low	Low
Jacobsen [19]	Unclear	Low	High	Unclear	High
McPhee [32]	Unclear	Low	High	Low	Moderate
Tozilli [48]	High	Low	High	High	High
Stäubli [46]	Unclear	Low	High	Low	Moderate
Harilainen [13]	Low	Unclear	Unclear	High	High
Stäubli [47]	High	Low	High	Low	Moderate
Sekiya* [43]	–	–	–	–	–
Lee‡ [28]	–	–	–	–	–

Studies unable to be assessed using the QUADAS-2 tool [50–52]: * cadaveric study; †descriptive of a technique using healthy controls only; ‡characterize the reliability and repeatability of a technique only; §overall risk of bias: high = score of high or unclear risk of bias in 3 or 4 of a total of 4 categories; moderate = score of high or unclear in 2 of a total of 4 categories; low = score of high or unclear in 0 or 1 of a total of 4 categories; ACL = anterior cruciate ligament; PCL = posterior cruciate ligament.

47], manual force [6, 12, 13, 32, 40, 44, 46], hydraulic force [17–19], S-type load cell [25, 26], a constant-tension spring [48], and the dynamic stress test using active muscle contraction [1, 7, 21]. A total of 16 unique stress techniques were described across all studies included in this review (Table 3). Including the multiligament studies, 12 stress radiography techniques were reported for applying stress to the ACL, eight techniques for applying stress to the PCL, three techniques for valgus stress, and four techniques for varus stress. The method for applying force and the magnitude of the force also varied across studies and stress techniques. Among ACL and PCL studies, the Telos stress device was the most commonly used stress device [1, 2, 5, 8–10, 13, 21, 28, 31, 34, 37, 38, 41–43, 47].

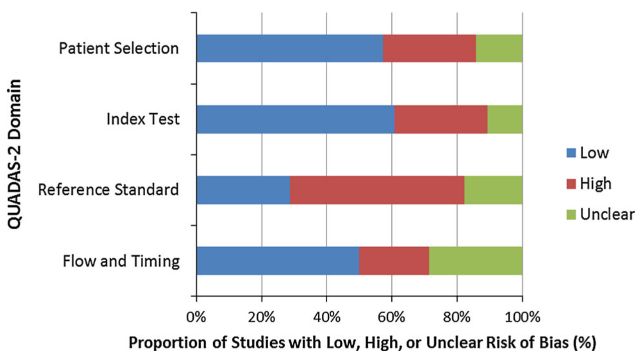

Fig. 2 A graphical risk of bias assessment is presented using the QUADAS-2 tool to indicate the percentage of studies with low, high, or unclear risk of bias for the patient selection, index test, reference standard, and flow and timing domains [50–52].

Stress Radiography Diagnostic Accuracy and Reliability

There was no consensus in the literature as to the most accurate and reliable stress radiography technique for the diagnosis of ACL, posterior cruciate ligament (PCL), medial collateral ligament (valgus), and posterolateral corner (PLC) (varus) injuries. Diagnostic accuracy and/or precision were reported in 55% of studies (21 of 38 studies) (Table 4). Sensitivity, specificity, PPV, and NPV were consistently high for the diagnosis of ACL, PCL, and combined cruciate ligament and valgus knee injuries but varied considerably among studies. No diagnostic accuracy data were reported for diagnosis of isolated varus knee injuries on stress radiography. Overall, excellent intrarater and interrater ICCs were reported for the diagnosis of ACL [28, 30], PCL [28, 42], varus [12, 26], and valgus [25] injuries on stress radiography. However, only six studies included analysis of intrarater and interrater reliability [12, 25, 26, 28, 30, 42].

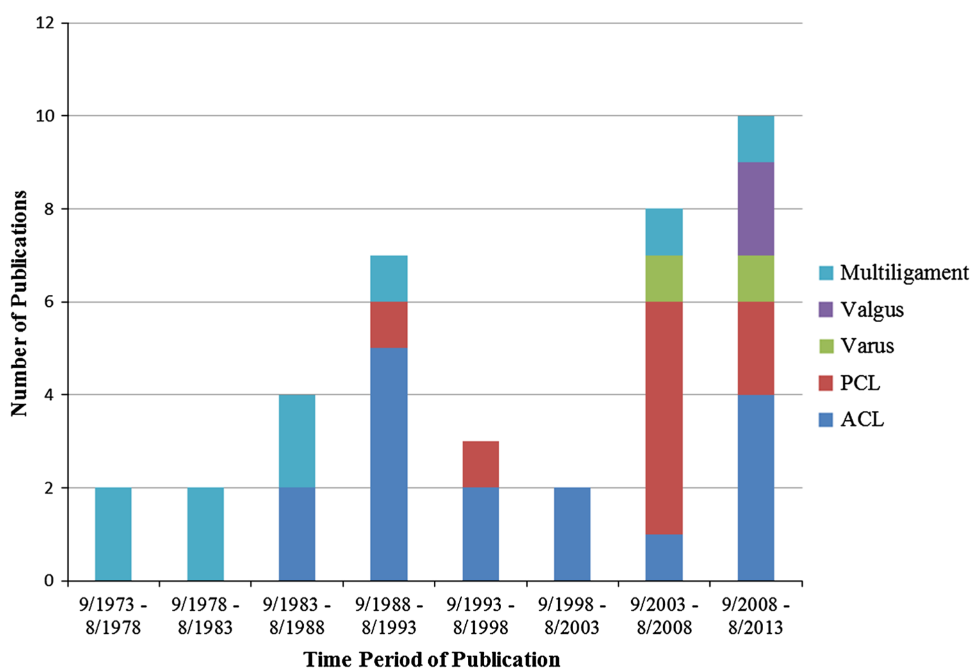

Fig. 3 The number of publications assessing stress radiographs for diagnosis of knee ligament injuries has increased over the last 10 years.

Table 2. Stress radiography techniques‡

First author	Stress technique	Force applied
ACL		
Hooper [15]	Sandbag	3 kg
Rijke [38]	Telos	15 kPa
Granberry [11]	Genucom device	140 N
Franklin [7]	Quadriceps contraction	133–178 N
Rijke [37]	Telos	0, 7, 14, 21 kPa
Stäubli [45]	KT-1000	89 N
Lerat [29]	Free weight	9 kg
Dejour [6]	Manual	–
	Monopodal stance test	Body weight
Garces [9]	Telos	147 N
Lerat [30]	Free weight	9 kg
Wirz [54]	Custom steel apparatus	50 N
Beldame [1]	Telos/quadriceps contraction	250 N/–
Beldame [2]	Telos/free weight	250 N/9 kg
Panisset [34]	Telos	15 kg
Dejour [5]	Telos	15 kg
PCL		
Stäubli [44]	Manual	25–30 kg
Hewett [14]	X-stress device	89 N
Margheritini [31]	Telos	89 N
Schulz [41]	Telos	15 kPa
Jung [21]	Telos/hamstring contraction/kneeling	150 N/–/–
Garavaglia [8]	Telos/PCL Press	150 N/150 N
Schulz [42]	Telos	150 N
Jackman [16]	Kneeling	–
Garofalo [10]	Telos/kneeling	15 kg/–
Valgus		
Sawant [40]	Manual	–
LaPrade [25]	S-type load cell	10 N-m
Varus		
LaPrade [26]	S-type load cell/manual	12 N-m/–
Gwathmey [12]	Manual	–
Multiligament		
Jacobsen [17]	Hydraulic force*/†	9 kg/20–30 kg
Jacobsen [18]	Hydraulic force*/†	9 kg/30 kg
Jacobsen [19]	Hydraulic force	196–294 N
McPhee [32]	Manual	–
Tozilli [48]	Constant-tension spring	50 N
Stäubli [46]	Manual	200–300 N
Harilainen [13]	Manual*/Telos†	147 N/–
Stäubli [47]	Telos	178 N
Sekiya [43]	Telos	200 N
Lee [28]	Telos	150 N

* Varus/valgus; †AP; ‡refer to Table 3 for a more detailed description of each study and stress technique; ACL = anterior cruciate ligament; PCL = posterior cruciate ligament.

Stress Radiography Compared With Other Diagnostic Techniques

Stress radiography techniques were compared with alternate diagnostic techniques including instrumented arthrometry, MRI, and physical examination in 12 studies (Table 5). Three of five studies comparing stress radiography with the KT-1000 or KT-2000 (MEDmetric Corporation, San Diego, CA, USA) for the diagnosis of AP instability concluded that stress radiography is superior, whereas the other two studies showed excellent but equivalent diagnostic ability [7, 14, 29, 31, 45]. For diagnosis of ACL injury, stress radiography correlated with results of the pivot shift test but not the Lachman's test [15], was equivalent to the GNRB computerized arthrometer [2], and offered greater sensitivity but similar specificity to the Rolimeter [34]. For the assessment of multiligament injury, stress radiography was more accurate than examination under anesthesia and clinical examination [18]. Stress radiographs with > 10 mm of posterior tibial displacement and a Grade 3 posterior drawer test were equally indicative of a combined PCL and PLC injury [43]. Varus stress radiographs correlated well with the severity of injury on MRI [12] but was not compared with physical examination or any other diagnostic tests in any study. Valgus stress radiography was not compared with other diagnostic tests in any study.

Discussion

Stress radiography offers an objective, quantifiable, noninvasive, and retrievable record that can be used to augment the diagnosis of knee ligament injuries. Over the last 10 years, interest in stress radiography has grown as was evident from the recent increase in publications on this topic. However, although stress radiography is now widely used in the clinical setting, there is a current lack of consensus as to which technique is best for assessing anterior, posterior, varus, and valgus knee stability. This review was undertaken to identify the various stress techniques that have been described in the literature for the diagnosis of acute or chronic knee ligament injuries, to compare the accuracy and reliability of these techniques, and to describe the use of stress radiography compared with other diagnostic tests.

We acknowledge several limitations in this review. First, this review excluded non-English-language articles, which may have led to the omission of additional descriptive studies of stress techniques, accuracy and reliability data, and comparative studies not available in the English language literature. Second, this review did not

Table 3. Summary of the stress techniques described for diagnosis of knee ligament injuries

Stress technique	Studies using the technique (first author)	Number	Stress plane	Summary of technique	Radiographic view
Constant tension spring	LaPrade [26]	10	Varus	A jig was used to secure the cadaveric knees at 20° of flexion and a 12-N-m stress was applied using a model SM S-type Load Cell with an attached handle (Interface, Scottsdale, AZ, USA)	AP
	LaPrade [25]	18	Valgus	A jig was used to secure the cadaveric knees at 0° and 20° of flexion; a 10-N-m stress applied using an S-type load cell	AP
Custom steel apparatus	Wirz [54]	3	Anterior	Apparatus holds a cadaveric knee in precise flexion and rotation while a drawer forces are applied; a pulley system applies force to the tibia and the xray cassette is placed in a standard location	L
Free weight	Lerat [29]	100	AP	Anterior drawer: the patient is supine on a table with the lower extremity supported in a special leg holder and the thigh free; the foot and ankle are fixed with a strap; the opposite limb is positioned on a stool at a lower level; a free hanging 9-kg weight is hung from the distal femur	L
				Posterior drawer: the leg support is turned 180° and moved closer to support the patient and a 9-kg weight is hung from a strap at the proximal tibia	
	Lerat [30]	1050	Anterior	See Lerat [29]	L
	Beldame [2]	157	Anterior	See Lerat [29]	L
Genucom device	Granberry [11]	8	Anterior	A cadaveric knee is fixed and an electrogoniometer with 6 degrees of freedom is used to measure displacement; force is applied with a strap	L
Hamstring contraction	Jung [21]	30	Posterior	Patient seated and relaxed with the knee in 90° of flexion and the leg fixed to a rigid stand; the patient sustains a hamstring contraction for 10 seconds while a radiograph is taken	L
Hydraulic force	Jacobsen [17]		Multi	A hydraulically operated machine with 9-kg forces for varus/valgus stability at 20° flexion and 5° external rotation	L
	Jacobsen [18]		Multi	See Jacobsen [17]	L
	Jacobsen [19]		Multi	See Jacobsen [17]	L
Kneeling	Jung [21]	30	Posterior	The patient kneels on a padded bench with the knee in 90° of flexion; a grip is available in front of the bench for patients to steady themselves	L
	Garofalo [10]	20	Posterior	The patient kneels on a padded bench with the knee in 90° of flexion supporting the tibial tubercle; the xray cassette was placed between the knees of the patient	L
KT-1000	Stäubli [45]	16	Anterior	KT-1000 arthrometer used to apply an 89-N anterior drawer force for stress radiography; knee in 20° of flexion, distal femoral support, foot support to control for tibial rotation	L

Table 3. continued

Stress technique	Studies using the technique (first author)	Number	Stress plane	Summary of technique	Radiographic view
Manual force	Dejour [6]	281	Anterior	Lachman test performed with simultaneous radiograph	L
	Stäubli [44]	24	Anterior	25–30 kg applied downward force on the tibia with 10°–15° knee flexion using 15-cm thigh support; 2 preloading cycles	L
	Sawant [40]	23	Valgus	Supine anesthetized patients with knees firmly bound together; feet are held in slight external rotation with valgus applied force to separate feet	AP
	LaPrade [26]	10	Varus	One hand placed at medial femoral condyle and the other placed just proximal to the lateral malleolus to apply the varus moment in 20° knee flexion	AP
	Gwathmey [12]	27	Varus	Physician applied varus stress in 20° knee flexion	AP
	McPhee [32]	60	Multi	Valgus/varus taken in both extension and 20°–30° knee flexion; using lateral stress, views were taken with the patient in the lateral position with the knee adjacent to the table; knee flexed at 90° for anterior and posterior drawer	AP/L
	Stäubli [46]	138	AP	Supine anesthetized patient; 10° knee flexion held by thigh support; 2 preloading cycles followed by 200–300 N posterior directed force; support moved to proximal tibia for anterior stress radiographs	L
	Harilainen [13]	85	Varus/valgus	Varus and valgus loads applied in 20° and 90° knee flexion, respectively	AP
Monopodal stance	Dejour [6]	281	Anterior	Patient stands on one leg in 20° knee flexion	L
PCL press	Garavaglia [8]	15	Posterior	180-N posterior load with the knee flexed at 100°	Ax.
Quadriceps contraction	Franklin [7]	70	Anterior	6.8-kg ankle-suspended weight while the knee is supported by a 30 wedge; the patient straightens the knee by contracting the quadriceps	L
	Beldame [1]	112	Anterior	7-kg ankle weight is placed on the patient while contracting the quadriceps in 20° knee flexion	L
Sandbag	Hooper [15]	70	Anterior	3-kg sandbag placed on thigh proximal to the patella; patient lie supine in 20° knee flexion	L
S-type load cell	LaPrade [26]	10	Varus	12-N-m load applied to the cadaveric specimen 25 cm distal to the joint line in 20° knee flexion	AP
	LaPrade [25]	18	Valgus	10-N-m load applied at the medial malleolus of the cadaveric specimen at 20° knee flexion and full extension (0°)	AP

Table 3. continued

Stress technique	Studies using the technique (first author)	Number	Stress plane	Summary of technique	Radiographic view
Telos	Rijke [37]	82	Anterior	15-kPa force while patient lies in lateral decubitus position in 15° knee flexion	L
	Rijke [38]	55	Anterior	See Rijke [37]	L
	Garcés [9]	116	Anterior	137-N anterior displacing force for 1 minute while the patient lies on the side being tested in 20° knee flexion	L
	Beldame [1]	112	Anterior	250-N force while the patient lies on the side being tested in 20° knee flexion	L
	Beldame [2]	157	Anterior	See Beldame [1]	L
	Panisset [34]	177	Anterior	15-kg force while the patient lies on the side being tested in 20° knee flexion	L
	Dejour [5]	300	Anterior	15-kg force while the patient lies on the side being tested in 20° knee flexion	L
	Margheritini [31]	60	Posterior	89-N posterior load while the patient lies on the side being tested in 90° and 25° knee flexion	L
	Schulz [41]	787	Posterior	19 kPa applied force while the patient lies on the side being test in 90° knee flexion	L
	Jung [21]	30	Posterior	150-N force while the patient lies on the side being tested in 90° knee flexion	L
	Garavaglia [8]	15	Posterior	180-N posterior load on cadaveric specimen in 30° and 80° knee flexion	L
	Schulz [42]	1041	Posterior	150-N posterior load while the patient lies on the side being tested in 90° knee flexion	L
	Garofalo [10]	20	Posterior	15-kg force while the patient lies on the side being tested in neutral rotation and 90° knee flexion	L
	Harilainen [13]	85	AP	15 kp in 90° knee flexion	L
	Stäubli [46]	138	AP	A/P preloading cycles (x 2) to 223-N; lateral radiographs taken under 178-N force	L
	Sekiya [43]	10	Posterior	200-N force posterior drawer on cadaveric specimen in 90° knee flexion	L
	Lee [28]	80	AP	150-N load while the patient lies in decubitus position in 25° (anterior stress radiograph) and 90° (posterior stress radiograph) knee flexion; 3 preloading cycles	L
X-stress device	Hewett [14]	21	Posterior	89-N posterior load is applied to the proximal tibia at approximately 70° of knee flexion	L

L = lateral; Ax. = axial; Multi = multiligament; AP = anteroposterior.

Table 4. Diagnostic accuracy and precision of stress radiography

First author	Threshold (SSD)	Sensitivity	Specificity	PPV	NPV	Reliability (ICC)	
						Intrarater	Interrater
ACL							
Rijke [37]	–	0.88	1.00	1.00	0.93	–	–
Rijke [37]	–	0.67* 0.50† 1.00‡	0.98* 1.00† 1.00‡	–	–	–	–
Stäubli [45]	3 mm	0.81	–	–	–	–	–
Lerat [29]	5 mm	0.84	0.90	0.89	0.85		
Dejour [6]	2 mm	0.92	–	–	–	–	–
Garcés [9]	–	0.575 0.66	1.00 1.00	–	–	–	–
Lerat [30]	6 mm	0.87‡,§	0.90‡,§	0.89‡,§	0.85‡,§	0.91*,§ 0.95‡,§ 0.92*,‖ 0.92‡,‖	0.97*,§ 0.98‡,§ 0.93*,‖ 0.95‡,‖
Beldame [1]	–	0.594§	0.906§	–	–	–	–
Beldame [2]							
Telos	–	0.648	0.758	–	–	–	–
Lerat	–	0.432	0.827	–	–	–	–
Panisset [34]	5 mm	0.809	0.818	–	–	–	–
PCL							
Hewett [14]	8 mm	1.00	1.00				
Schulz [41]	–	–	–	–	–	0.95	0.91
Garavaglia [8]							
Telos 30							
Isolated	3 mm	0.933	0.867	0.955	0.813	–	–
Combination	9 mm	0.880	0.771	0.733	0.900	–	–
Telos 80							
Isolated	6 mm	0.976	0.778	0.911	0.933	–	–
Combination	12 mm	0.885	0.794	0.767	0.900	–	–
Valgus							
Sawant [40]	–	0.9375	0.857	0.937	0.857	–	–
LaPrade [25]	–	–	–	–	–	0.99	0.98
Varus							
LaPrade [26]	–	–	–	–	–	0.99	0.97
Gwathmey [12]	–	–	–	–	–	–	0.963
Multiligament							
Jacobsen [18]							
Varus	2 mm	–	–	1.00	0.92	–	–
AP	3 mm	–	–	0.98	0.96	–	–
Jacobsen [19]	–	–	–	1.00	0.81	–	–
Harilainen [13]	–	–	0.86	–	0.99	–	–
Varus	–	0.55	0.89	0.71	0.80	–	–
Valgus	–	0.28	0.93	0.85	0.49	–	–
A (J)	–	0.16	1.00	1.00	0.50	–	–
A (L)	–	1.00	0.88	0.33	1.00	–	–
P (J)	–	1.00	0.90	0.40	1.00	–	–
P (L)							

Table 4. continued

First author	Threshold (SSD)	Sensitivity	Specificity	PPV	NPV	Reliability (ICC)			
						Intrarater		Interrater	
Lee [28]	–	–	–	–	–	A	P	A	P
MM	–	–	–	–	–	0.713	0.859	0.853	0.884
LL	–	–	–	–	–	0.624	0.814	0.794	0.773
Mid-Mid	–	–	–	–	–	0.834	0.914	0.887	0.859
PC	–	–	–	–	–	0.722	0.852	0.851	0.914
BAT						0.891	0.893	0.923	0.934

* Healthy knees; †partial tear; ‡complete tear; §medial compartment displacement; ||lateral compartment displacement; ¶combined MCL and ACL or PCL tear; SSD = side-to-side difference between knees in displacement on stress radiography; PPV = positive predictive value; NPV = negative predictive value; ICC, intraclass correlation coefficient; ACL = anterior cruciate ligament; Combined = combined PCL and peripheral ligament injury; PCL = posterior cruciate ligament; MCL = medial collateral ligament. Radiographic measurements: BAT = Blumensaat line–anterior tibia; LL = lateral-lateral; Mid-Mid = middle-middle; MM = medial-medial; PC = peripheral-central; A = anterior; P = posterior. Jacobsen's (J) and Leven's (L) measuring methods. If not otherwise specified, values are for diagnosis of complete tears only. For Lee et al., lower limit reproducibility reported only.

compare landmarks and reference points for measuring displacement or gapping on stress radiographs. Only two studies in this review reported results for comparison of measurement techniques using different landmarks and reference points on stress radiographs [28, 30]. Although we recognize that the choice of landmarks may influence the accuracy and reliability of measurements in stress radiography, this was beyond the scope of the present review. Future studies should define the optimal reference points for measuring displacement and/or gapping in knee stress radiography.

In addition, this review's conclusions rest on the quality of the studies that have been included. Overall risk of bias was high in eight studies and moderate in 10 studies (Table 1). Risk of bias was especially high in the reference standard domain attributable in large part to interpretation of reference standard results with prior knowledge of the corresponding results of stress radiography. Conversely, when physical examination was used as the reference standard, these studies introduced bias in the index test domain by interpreting the results of stress radiography with knowledge of the results of physical examination. Other notable sources of bias included the use of multiple or inconsistent reference standards. Reported reference standards included arthroscopy, physical examination, arthrometry, and MRI. Remarkably, some comparative studies did not explicitly name a reference standard. Additional bias was potentially introduced in studies that enrolled nonconsecutive or nonrandom patients or observed an inappropriately long, highly variable, or unreported time interval between stress radiography and record of the reference standard test. To address these sources of bias, future studies should include appropriate blinding at all phases of the study to ensure independence of stress radiography protocols, reference standard evaluation of ligament stability, and measurements of displacement or gapping. Moreover, a single reference standard must be used in future studies to allow for improved comparison across studies. Based on the reference standards used in the current literature, we would recommend a consistently applied surgical reference standard because it allows for direct visualization and assessment of ligament integrity and minimizes the inaccuracies inherent in other reference standards such as MRI and physical examination.

A total of 16 unique stress radiography techniques for the diagnosis of knee ligament injuries were identified in this review, indicating a high degree of heterogeneity in methodology across studies. Although no clear consensus emerged in the literature, the Telos device was the most widely used for ACL and PCL injury studies, especially in those performed within the past 10 years. The Telos device produces an adjustable, quantifiable, and reproducible anterior or posterior force on the injured knee. Currently, no analogous device has been described in the literature for standardization of varus- or valgus-directed forces used to diagnose medial or PLC knee injuries.

Measures of the diagnostic accuracy and reliability of stress radiography varied considerably from study to study and were likely influenced by stress technique, use of anesthesia, cadaveric laboratory study design, sample size, choice of reference standard, and the threshold set for the maximum acceptable side-to-side difference for normal knees. Stress radiography performed in a clinic setting may yield varying results resulting from patient guarding or muscle contraction secondary to pain, whereas testing performed under anesthesia or in a cadaveric model would eliminate this effect. In addition, the calculated diagnostic accuracy of stress radiography techniques changes depending on the side-to-side difference limit that defines a nonfunctional ligament. For the ACL, the threshold varied from 2 mm [6] to 6 mm [30] and from 3 mm [8] to 12 mm [8] for the PCL. The inconsistent threshold for side-to-side

Table 5. Stress radiography compared with alternate diagnostic tests

First author	Comparative test	Results and conclusions
ACL		
Hooper [15]	Pivot shift test and Lachman test	Significant correlation between the mean sagittal displacement on stress radiographs and clinical pivot shift test for a mean lateral displacement of 13.5 mm; there was no correlation with the Lachman test
Franklin [7]	KT-1000	No significant difference between KT-1000 and stress radiography
Stäubli [45]	KT-1000	Both KT-1000 and stress radiography are diagnostic for chronic ACL-deficient knees
Lerat [30]	KT-1000	Both KT-1000 and stress radiography provide excellent diagnostic value of ACL integrity with predictive values of 90%; stress radiographs provide superior precision and independent evaluation of medial and lateral compartments
Beldame [2]	GNRB device	No significant difference between diagnostic performance of computerized GNRB arthrometer and stress radiography; however, stress radiography was more easily implemented in a clinical setting
Panisset [34]	Rolimeter and pivot shift test	Telos stress radiography provides greater sensitivity relative to Rolimeter with similar specificity; however, Telos specificity was superior when used in combination with the pivot shift test
PCL		
Hewett [14]	KT-1000 and posterior drawer	Stress radiography is superior to both the KT-1000 and the posterior drawer in assessing for presence or absence of a complete PCL tear
Margheritini [31]	KT-2000	Stress radiography is superior to the KT-2000 for quantifying posterior tibial translation; the KT-2000 underestimates the degree of posterior laxity compared with stress radiography
Valgus		
–	–	–
Varus		
Gwathmey [12]	MRI	Stress radiography correlates with the severity of injury diagnosed on MRI and provides information regarding degree of laxity that MRI does not
Multiligament		
Jacobsen [18]	Clinical examination and EUA	Stress radiography was more accurate than EUA, which in turn was more accurate than clinical examiantion
Sekiya [43]	Grade III posterior drawer	Stress radiographs with > 10 mm of posterior tibial displacement and a Grade 3 posterior drawer test are equally indicative of a combined posterolateral corner injury

EUA = examination under anesthesia; GNRB (GeNouRoB, Laval, France); KT-1000 (MEDmetric Corporation, San Diego, CA, USA); KT-2000 (MEDmetric Corporation); Rolimeter (Aircast Incorporated, Summit, NJ, USA); Telos (Austin & Associates, Inc, METAX, Hungen, Germany); ACL = anterior cruciate ligament; PCL = posterior cruciate ligament.

difference for ACL and PCL injuries clouds any comparison of the diagnostic accuracy among studies and techniques.

In general, diagnostic varus and valgus stress radiography has been under underinvestigated in the literature. Future studies must validate diagnostic gapping benchmarks that have been previously described in cadaveric models. For simulated posterolateral corner injuries in a cadaveric model, LaPrade et al. [26] described an average increase in side-to-side varus gapping of 2.7 mm for isolated fibular collateral ligament tears compared with 4.0 mm for combined Grade III posterolateral corner injuries. This demonstrates the potential of stress radiography to distinguish between varying degrees of instability and injuries to multiple structures. In the case of PLC injuries, it is possible to detect injuries to multiple structures with a single stress radiography technique. However, in cases of multiligament injuries, it is necessary to perform stress radiography techniques in the appropriate planes to sufficiently assess stability.

For simulated medial knee injuries in a cadaveric model, LaPrade et al. [25] described a threshold of 3.2 mm of medial compartment gapping compared with the contralateral knee for the diagnosis of Grade III medial collateral ligament tears. However, the distribution of varus and valgus gapping across a large cohort of patients with suspected medial or lateral knee injuries and its correlation with surgically verified tears has not been investigated. Once standard cutoff points are validated in vivo, these thresholds can then be used to calculate and compare the diagnostic accuracy and reliability for varus and valgus stress radiography between studies with greater confidence.

Finally, results of the comparative diagnostic studies included in this review yield no clear consensus on the use of stress radiography compared with other diagnostic tests for knee ligament injuries. The ability to draw conclusions is limited even among studies that compared stress radiography with the same alternative diagnostic technique. One reason for this is the varying stress techniques and forces used between studies. For example, although Franklin et al. [7], Stäubli and Jakob [45], and Lerat et al. [30] all compared stress radiography for the diagnosis of ACL injury to the KT-1000, stress techniques varied. Franklin et al. use the quadriceps contraction technique at 133 N to 178 N, Stäubli et al. used the KT-1000 at 89 N, and Lerat et al. used a 9-kg free weight. A greater emphasis on consistent methodology across studies will be required in the future.

In summary, this review highlights the wide array of techniques, varying degrees of diagnostic accuracy and reproducibility, and at times contradictory conclusions regarding the use of stress radiography compared with alterative techniques for diagnosing knee ligament injury. Based on the multitude of stress techniques reported, varying levels of diagnostic accuracy, and inconsistencies regarding comparative efficacy of stress radiography to other diagnostic modalities, we are not able to make specific recommendations with regard to the best stress radiography technique for the diagnosis of knee ligament injury. To date, no gold standard for a specific stress radiographic technique or the magnitude of force applied during testing has been established for assessing anterior, posterior, varus, and valgus knee stability. Additional comparative studies are needed to further define the use of stress radiography compared with other diagnostic techniques and to establish evidence-based recommendations for the most accurate, reliable, easy-to-use, and cost-effective stress radiography technique. Specifically, further studies should be designed to eliminate common sources of bias identified in this review by using consecutive patients, a consistent and reliable reference standard, and sufficient blinding between stress radiography and reference standards. Additionally, future in vivo studies are required to validate cadaveric models as in the case of varus and valgus stress radiography.

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References

1. Beldame J, Bertiaux S, Roussignol X, Lefebvre B, Adam JM, Mouilhade F, Dujardin F. Laxity measurements using stress radiography to assess anterior cruciate ligament tears. *Orthop Traumatol Surg Res.* 2011;97:34–43.
2. Beldame J, Mouchel S, Bertiaux S, Adam JM, Mouilhade F, Roussignol X, Dujardin F. Anterior knee laxity measurement: comparison of passive stress radiographs Telos and 'Lerat,' and GNRB arthrometer. *Orthop Traumatol Surg Res.* 2012;98:744–750.
3. Benvenuti JF, Vallotton JA, Meystre JL, Leyvraz PF. Objective assessment of the anterior tibial translation in Lachman test position. Comparison between three types of measurement. *Knee Surg Sports Traumatol Arthrosc.* 1998;6:215–219.
4. Daniel DM, Stone ML, Barnett P, Sachs R. Use of the quadriceps active test to diagnose posterior cruciate-ligament disruption and measure posterior laxity of the knee. *J Bone Joint Surg Am.* 1988;70:386–391.
5. Dejour D, Ntagiopoulos PG, Saggin PR, Panisset JC. The diagnostic value of clinical tests, magnetic resonance imaging, and instrumented laxity in the differentiation of complete versus partial anterior cruciate ligament tears. *Arthroscopy.* 2013;29:491–499.
6. Dejour H, Bonnin M. Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. *J Bone Joint Surg Br.* 1994;76:745–749.
7. Franklin JL, Rosenberg TD, Paulos LE, France EP. Radiographic assessment of instability of the knee due to rupture of the anterior cruciate ligament. A quadriceps-contraction technique. *J Bone Joint Surg Am.* 1991;73:365–372.
8. Garavaglia G, Lubbeke A, Dubois-Ferrière V, Suva D, Fritschy D, Menetrey J. Accuracy of stress radiography techniques in grading isolated and combined posterior knee injuries: a cadaveric study. *Am J Sports Med.* 2007;35:2051–2056.
9. Garcés GL, Perdomo E, Guerra A, Cabrera-Bonilla R. Stress radiography in the diagnosis of anterior cruciate ligament deficiency. *Int Orthop.* 1995;19:86–88.
10. Garofalo R, Fanelli GC, Cikes A, N'Dele D, Kombot C, Mariani PP, Mouhsine E. Stress radiography and posterior pathological laxity of knee: comparison between two different techniques. *Knee.* 2009;16:251–255.
11. Granberry WM, Noble PC, Woods GW. Evaluation of an electrogoniometric instrument for measurement of laxity of the knee. *J Bone Joint Surg Am.* 1990;72:1316–1322.
12. Gwathmey FW Jr, Tompkins MA, Gaskin CM, Miller MD. Can stress radiography of the knee help characterize posterolateral corner injury? *Clin Orthop Relat Res.* 2012;470:768–773.
13. Harilainen A, Myllynen P, Rauste J, Silvennoinen E. Diagnosis of acute knee ligament injuries: the value of stress radiography compared with clinical examination, stability under anesthesia and arthroscopic or operative findings. *Ann Chir Gynaecol.* 1986;75:37–43.
14. Hewett TE, Noyes FR, Lee MD. Diagnosis of complete and partial posterior cruciate ligament ruptures. Stress radiography compared with KT-1000 arthrometer and posterior drawer testing. *Am J Sports Med.* 1997;25:648–655.
15. Hooper GJ. Radiological assessment of anterior cruciate ligament deficiency. A new technique. *J Bone Joint Surg Br.* 1986;68:292–296.
16. Jackman T, LaPrade RF, Pontinen T, Lender PA. Intraobserver and interobserver reliability of the kneeling technique of stress radiography for the evaluation of posterior knee laxity. *Am J Sports Med.* 2008;36:1571–1576.
17. Jacobsen K. Stress radiographical measurement of the anteroposterior, medial and lateral stability of the knee joint. *Acta Orthop Scand.* 1976;47:335–334.
18. Jacobsen K. Stress radiographical measurements of post-traumatic knee instability. A clinical study. *Acta Orthop Scand.* 1977;48:301–310.
19. Jacobsen K. Gonylaxometry. Stress radiographic measurement of passive stability in the knee joints of normal subjects and patients with ligament injuries. Accuracy and range of application. *Acta Orthop Scand Suppl.* 1981;194:1–263.

20. Jacobsen K, Rosenkilde P. A clinical and stress radiographical follow-up investigation after Jones' operation for replacing the anterior cruciate ligament. *Injury.* 1977;8:221–226.
21. Jung TM, Reinhardt C, Scheffler SU, Weiler A. Stress radiography to measure posterior cruciate ligament insufficiency: a comparison of five different techniques. *Knee Surg Sports Traumatol Arthrosc*. 2006;14:1116–1121.
22. Kastelein M, Wagemakers HP, Luijsterburg PA, Verhaar JA, Koes BW, Bierma-Zeinstra SM. Assessing medial collateral ligament knee lesions in general practice. *Am J Med.* 2008;121: 982–988.
23. Katz JW, Fingeroth RJ. The diagnostic accuracy of ruptures of the anterior cruciate ligament comparing the Lachman test, the anterior drawer sign, and the pivot shift test in acute and chronic knee injuries. *Am J Sports Med.* 1986;14:88–91.
24. Kim SJ, Kim SH, Kim SG, Kung YP. Comparison of the clinical results of three posterior cruciate ligament reconstruction techniques: surgical technique. *J Bone Joint Surg Am.* 2010;92(Suppl 1):145–157.
25. LaPrade RF, Bernhardson AS, Griffith CJ, Macalena JA, Wijdicks CA. Correlation of valgus stress radiographs with medial knee ligament injuries: an in vitro biomechanical study. *Am J Sports Med.* 2010;38:330–338.
26. LaPrade RF, Heikes C, Bakker AJ, Jakobsen RB. The reproducibility and repeatability of varus stress radiographs in the assessment of isolated fibular collateral ligament and grade-III posterolateral knee injuries. An in vitro biomechanical study. *J Bone Joint Surg Am.* 2008;90:2069–2076.
27. LaPrade RF, Terry GC. Injuries to the posterolateral aspect of the knee. Association of anatomic injury patterns with clinical instability. *Am J Sports Med.* 1997;25:433–438.
28. Lee YS, Han SH, Jo J, Kwak KS, Nha KW, Kim JH. Comparison of 5 different methods for measuring stress radiographs to improve reproducibility during the evaluation of knee instability. *Am J Sports Med.* 2011;39:1275–1281.
29. Lerat JL, Moyen B, Jenny JY, Perrier JP. A comparison of preoperative evaluation of anterior knee laxity by dynamic X-rays and by the arthrometer KT 1000. *Knee Surg Sports Traumatol Arthrosc.* 1993;1:54–59.
30. Lerat JL, Moyen BL, Cladière F, Besse JL, Abidi H. Knee instability after injury to the anterior cruciate ligament. Quantification of the Lachman test. *J Bone Joint Surg Br.* 2000;82:42–47.
31. Margheritini F, Mancini L, Mauro CS, Mariani PP. Stress radiography for quantifying posterior cruciate ligament deficiency. *Arthroscopy.* 2003;19:706–711.
32. McPhee IB, Fraser JG. Stress radiography in acute ligamentous injuries of the knee. *Injury.* 1981;12:383–388.
33. Oberlander MA, Shalvoy RM, Hughston JC. The accuracy of the clinical knee examination documented by arthroscopy: a prospective study. *Am J Sports Med.* 1993;21:773–778.
34. Panisset JC, Ntagiopoulos PG, Saggin PR, Dejour D. A comparison of Telos™ stress radiography versus Rolimeter™ in the diagnosis of different patterns of anterior cruciate ligament tears. *Orthop Traumatol Surg Res.* 2012;98:751–758.
35. Peeler J, Leiter J, MacDonald P. Accuracy and reliability of anterior cruciate ligament clinical examination in a multidisciplinary sports medicine setting. *Clin J Sports Med.* 2010;20:80–85.
36. Prins M. The Lachman test is the most sensitive and the pivot shift the most specific test for the diagnosis of ACL rupture. *Aust J Physiother.* 2006;52:66.
37. Rijke AM, Goitz HT, McCue FC 3rd, Delp JL, Lam D, Port Southall E. Graded stress radiography of injured anterior cruciate ligaments. *Invest Radiol.* 1991;26:926–933.
38. Rijke AM, Tegtmeyer CJ, Weiland DJ, McCue FC 3rd. Stress examination of the cruciate ligaments: a radiologic Lachman test. *Radiology.* 1987;165:867–869.
39. Rios CG, Leger RR, Cote MP, Yang C, Arciero RA. Posterolateral corner reconstruction of the knee: evaluation of a technique with clinical outcomes and stress radiography. *Am J Sports Med.* 2010;38:1564–1574.
40. Sawant M, Narasimha Murty A, Ireland J. Valgus knee injuries: evaluation and documentation using a simple technique of stress radiography. *Knee.* 2004;11:25–28.
41. Schulz MS, Russe K, Lampakis G, Strobel MJ. Reliability of stress radiography for evaluation of posterior knee laxity. *Am J Sports Med.* 2005;33:502–506.
42. Schulz MS, Steenlage ES, Russe K, Strobel MJ. Distribution of posterior tibial displacement in knees with posterior cruciate ligament tears. *J Bone Joint Surg Am.* 2007;89:332–338.
43. Sekiya JK, Whiddon DR, Zehms CT, Miller MD. A clinically relevant assessment of posterior cruciate ligament and posterolateral corner injuries. Evaluation of isolated and combined deficiency. *J Bone Joint Surg Am.* 2008;90:1621–1627.
44. Stäubli HU, Jakob RP. Posterior instability of the knee near extension. A clinical and stress radiographic analysis of acute injuries of the posterior cruciate ligament. *J Bone Joint Surg Br.* 1990;72:225–230.
45. Stäubli HU, Jakob RP. Anterior knee motion analysis. Measurement and simultaneous radiography. *Am J Sports Med.* 1991;19:172–177.
46. Stäubli HU, Jakob RP, Noesberger B. Anterior-posterior knee instability and stress radiography a prospective biomechanical analysis with the knee in extension. *Biomechanics: Current Interdisciplinary Research Developments in Biomechanics.* 1985;2:397–402.
47. Stäubli HU, Noesberger B, Jakob RP. Stress radiography of the knee. Cruciate ligament function studied in 138 patients. *Acta Orthop Scand Suppl.* 1992;249:1–27.
48. Torzilli PA, Greenberg RL, Hood RW, Pavlov H, Insall JN. Measurement of anterior-posterior motion of the knee in injured patients using a biomechanical stress technique. *J Bone Joint Surg Am.* 1984;66:1438–1442.
49. Wagemakers HP, Luijsterburg PA, Boks SS, Heintjes EM, Berger MY, Verhaar JA, Koes BW, Bierma-Zeinstra SM. Diagnostic accuracy of history taking and physical examination for assessing anterior cruciate ligament lesions of the knee in primary care. *Arch Phys Med Rehabil.* 2010;91:1452–1459.
50. Whiting P, Rutjes AW, Dinnes J, Reitsma J, Bossuyt PM, Kleijnen J. Development and validation of methods for assessing the quality of diagnostic accuracy studies. *Health Technol Assess.* 2004;8:iii,1–234.
51. Whiting PF, Rutjes AW, Westwood ME, Mallett S, Deeks JJ, Reitsma JB, Leeflang MM, Sterne JA, Bossuyt PM; QUADAS-2 Group. QUADAS-2: a revised tool for the quality assessment of diagnostic accuracy studies. *Ann Intern Med.* 2011;155:529–536.
52. Whiting PF, Weswood ME, Rutjes AW, Reitsma JB, Bossuyt PN, Kleijnen J. Evaluation of QUADAS, a tool for the quality assessment of diagnostic accuracy studies. *BMC Med Res Methodol.* 2006;6:9.
53. Wiertsema SH, van Hooff HJ, Migchelsen LA, Steultjens MP. Reliability of the KT1000 arthrometer and the Lachman test in patients with an ACL rupture. *Knee.* 2008;15:107–110.
54. Wirz P, von Stokar P, Jakob RP. The effect of knee position on the reproducibility of measurements taken from stress films: a comparison of four measurement methods. *Knee Surg Sports Traumatol Arthrosc.* 2000;8:143–148.
55. Zaffagnini S, Bonanzinga T, Marcheggiani Muccioli GM, Giordano G, Bruni D, Bignozzi S, Lopomo N, Marcacci M. Does chronic medial collateral ligament laxity influence the outcome of anterior cruciate ligament reconstruction? A prospective evaluation with a minimum three-year follow-up. *J Bone Joint Surg Br.* 2011;93:1060–1064.