8 Laxity Objective Measurement Within MRI of ACL Lesions

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8.1 Laxity Versus Instability

Joint laxity is an objective and measurable parameter. Within human joints, we may have physiological laxity (normal laxity) or pathological laxity (abnormal laxity). Common language and definitions are crucial to enable a clear and constructive communication and scientific discussion. Back in 2006, during the works of the Anterior Cruciate Ligament (ACL) Study Group, John Feagin addressed the audience making a simplified but pretty clear distinction between instability and joint laxity, often used in an interchangeable manner. He stated that "instability is a symptom described by a patient, whereas laxity is an objective finding" [1]. Instability is present when the individual describes the joint as unstable when moving, walking, running, jumping, or twisting. Frequently, patients will refer that the joint "gives way". Biomechanically joint laxity is the passive response of a joint to an externally applied force or torque [2]. The presence of abnormal laxity may or may not exist along with instability. The joint laxity profile varies among individuals. Differences in joint laxity have been reported related to sex [3–5], bone morphology

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and morphometrics [6–9], in presence of ligament or menisci injury [10–14], and outcomes of surgery [15–18], among others.

8.2 Measurement of Joint Laxity

When measuring any parameter, or you do it or you do not within an acceptable range. Resolution, precision, and accuracy of the measuring device are critical to enable the development of a screening system with clinical usefulness supported by its sensitivity and specificity. It should not be uncritically accepted the existence of important disparities in measurements outcomes (both under arthrokinematics and clinical views) that are obtained by different professionals, techniques, or devices [19] since they may mislead inappropriate interventions or absence of it. Both arthrokinematic and clinical outcomes may hinder the safety and efficacy that should support, by default, the clinical interventions. Precision and accuracy of joint laxity measurements should fit within physics conformity frames and not in general practices frames. Once it is considered a specific parameter, testing significance and setting, for the same person within a determined anatomofunctional status and period of human development, the outcomes expected must be reproducible and accurate. Methodological rigor is indispensable for research validity, usefulness of joint laxity measurements, and especially safety and effectiveness. We acknowledge though that majority of tests and testing principles yield value. Even facing different outcomes when assessing a same parameter (e.g., knee sagittal joint laxity as a quantity under observation) with different techniques or instruments, they may yield clinical useful information if the resolution and precision are suitable, and the accuracy is sufficiently close to its actual value. This may however be deceptive if the outcomes do not comprehend magnitudes indexed to normal and abnormal ranges. Take as an example that we acquired a thermometer which maximum scaling is 37 degrees Celsius (98.6 degrees Fahrenheit), it may yield an outstanding reliability, but there is no room for validity.

Knee joint laxity assessment has several angles that are worthy of research. We may allocate factors that interfere with knee joint multiplanar laxity envelope, to the individual intrinsic factors and the interplay of these with the choices and actions taken in case of need (e.g., treatment option in case of ACL ligament tear). Existing knee joint laxity may differ between uninjured and injured knees [20–22], either among different people in the same clinical condition [23], ontogenetic status of development [3, 24], biological circumstances [24, 25], sex [3–5], and different patterns of ACL tears [19].

There is great clinical and preventive potential to characterize and quantify the multiplanar knee joint laxity envelope. We are in need of studies that accurately assess joint laxity within different biological, pathological, or clinical conditions. This should be accomplished using laximetry—i.e., objective measurement of joint laxity—and, eventually, combining tests and/or equipment either for screening and to improve diagnosis [26]. The two main categories of laximetry are stress imaging and arthrometry. These two techniques classically aim to describe and quantify the displacement of the tibia in relation to the femur within the sagittal and transversal planes. These techniques often use cut-off values as dichotomic screening tools to elicit one of two diagnostic results: ruptured or not ruptured. The joint laxity data derive from an applied external force that aims to quantify bony displacement, either in unilateral or by side-to-side difference (SSD). Beyond the dichotomous application, laximetry can become an important diagnosis and profiling tool of different patterns of ACL tears (partial or total rupture) [19] and their interference in knee arthrokinematics, treatment decision, and surgical planning, prognostic purposes, or to quantify post-operative joint laxity.

8.3 Clinical Examination Combined with Laximetry and Imaging

While manual clinical examination is paramount for diagnosis, it is subjective both in the technique and interpretation [27]. The sensitivity and specificity of instrumented joint laxity measurements seem to increase with the combination of standard clinical examination in a two-step assessment process. Increased accuracy is found when combining clinical examination with Telos™ stress radiography [28]. The exposure to radiation and lack of ability to provide imaging evidence of soft tissue injury of stress radiography make the combined use of magnetic imaging resonance (MRI) and instrumented joint laxity testing the obvious next step to accurately measure knee joint laxity [22, 29].

The MRI alone does not provide for biomechanical competence data and joint laxity underestimation associated with some laximeters can mislead algorithm of treatment. Accurate laximetry combined with MRI will overcome barriers in anatomical and biomechanical competence assessment of apparent remaining intact ACL fibers or bundles or inserted grafts. When combining MRI with instrumented joint laxity, we sum up the visualization of anatomical structural evidence of injury and the ligament functional competence. The devices that are compatible with MRI use intrinsic anatomical landmarks [30] as references to measure the bony displacement and calculate the knee joint laxity.

Attempts also have been made, within a single-step assessment process, coupling measuring devices with manual elicited testing maneuvers, as the pivot shift, to confer objectivity and quantification [27]. Yet, the subjective variability in the testing technique persists due to disparities among professionals when eliciting the motion and determining which parameters use. These disparities are predominantly dependent on the assessor skills, training and experience, being present even in the often-used clinical tests as the pivot-shift [31].

The quest for accuracy and clinical usefulness should be the main goal of researchers and health care providers. The type of information is not so important—whereas from static or dynamic sagittal and/or rotatory testing, instrumented or not, separately or coupled with imaging assessment, under anesthesia or unanesthetized—but the validity, reliability, and accuracy should remain our focus. There are however premises learned from decades of research that pinpoint that settings and parameters are critical in joint laxity objective assessment and quantification.

8.4 Joint Laxity After Single ACL or Combined with Other Anterolateral Structures Injury

The diagnosis of different patterns of ACL tear is important for precision health care. New knowledge and evidence gathered in different domains as anatomy, biomechanics, pathomechanics, reinjury rates, and surgical techniques related to ACL injury and treatment should support customized risk management interventions and surgical planning.

Observed anterior translation and internal rotation of the tibia varies due to different ACL injury patterns. Partial or total tears, partial tears involving either the anteromedial or the posterolateral bundles and, it is also believed, that part of the abnormal rotatory joint laxity originates from additional injury to the anterolateral soft tissue structures. This is well documented in studies of biomechanical testing of cadaveric specimens. Lagae et al. [32] have recently reported different patterns of knee joint laxity after sectioning different anterolateral soft tissue structures which potentially mimic injuries subsequent to knee trauma, as the anterolateral ligament (ALL) and the deep fibers of the iliotibial band (ITB). Cutting the ACL did not significantly increase tibial internal rotation laxity significantly compared to the intact knee at any flexion angle. In the ACL-deficient knee, sectioning the ALL significantly increased the anterior laxity only at 20° to 30° of knee flexion, and only significantly increased internal rotation at 50° of knee flexion. A large increase in internal rotatory laxity is found however between 20° and 100° of flexion after sectioning the deep fibers of the ITB (including the Kaplan fibers), specifically the proximal and distal bundles [33] and the condylar strap [34]. This goes in line with the findings of Godin et al. [33] that support the role of the proximal and distal Kaplan fibrous bundles in rotational knee stability. The proximal and distal (Kaplan) bundles are 22.5 mm apart at the distal femur and revealed a mean maximum load during pull-to-failure testing of 71.3 N and 170.2 N, respectively. Later, Landreau et al. [34] identified a third and more distal bundle of deep ITB fibers attaching to the femur between the distal Kaplan fibers and the epicondyle, which they named as "condylar strap". Even lacking biomechanical analysis, the qualitative evaluation of behavior in internal rotation revealed a tenodesis effect of the ITB which may add to anterolateral knee stability.

Several legit questions and concerns of translation to the clinical practice arise when interpreting these valuable anatomic and biomechanical studies. While biomechanical evidence suggests an important role of ITB in anterolateral instability control, injury frequency of deep ITB fibers in the setting of acute ACL tear [35, 36] is low compared to that of the ALL [37]. Yet, in presence of Segond fractures [38], where the ITB seems to be attached approximately in half of the cases and even in the absence of a Segond fracture [39], an ITB injury is a good marker for ACL injury. In fact, Lagae et al. [32] have shown that an isolated ACL anatomic reconstruction restored anterior tibial translation, but the remaining and significant internal rotatory laxity was only normalized after adding an extra-articular lateral tenodesis. Inderhaug et al. [40] also showed us that isolated ACL reconstruction does not restore normal kinematics, ACL combined with ALL reconstruction resulted in abnormal rotational joint laxity and that adding a lateral extra-articular tenodesis (MacIntosh or Lemaire) restored the knee internal rotation laxity to its native values. Other studies have also highlighted the importance of deep fibers of the ITB in controlling rotational joint laxity, but with a minimal influence of the ALL [41–43]. This makes us think of a potential overlooking behavior in MRI patterns in the setting of ACL injury and of the utility to combine the assessment of the ligament structural integrity and its functional competence within the same examination.

Correlational studies involving MRI and surgical exploration of the anterolateral complex (ALC) have shown high incidence in the setting of acute ACL-injured knees. However, MRI alone has low sensitivity, specificity, and accuracy for the diagnosis of ITB injury. The ITB was considered abnormal in approximately 31% of the cases [36]. Giving the number of cases, low diagnostic values of MRI alone, and relevance of ITB injury on rotatory joint laxity [32], the PKTD can play a role in functional diagnosis workflow of these additional injuries through joint laxity profiling. Rotatory joint laxity assessment within MRI may also be of particular importance in presence of Segond fractures since different structures of the ALC can be detached along with the bone avulsed fragment. The ITB often detaches along with the fragment with frequency depending on the dimensions and volume of the fragment as distance sparing it from the center of Gerdy's tubercle [38, 44]. It is important to identify the patients with injury of the anterolateral structures, that if combined with increased rotatory joint laxity, are candidates to concomitant procedures such as lateral extra-articular tenodesis to better control the tibial internal rotation [45] and decrease the risk of graft failure [46].

8.5 Partial ACL Tears: MRI Diagnosis, Instrumented Joint Laxity Discrimination and Assessment of Biomechanical Competence

The MRI has high diagnostic accuracy for complete ACL tears [47]. Even the novel fully automated deep learning MRI techniques show high accuracy in identifying ACL tears [48]. However, when used to diagnose partial tears, the MRI is not capable to reliably detect partial tears [49] showing a high rate of false positives [47], even when using 3-Tesla MRI machines [50, 51]. Indeed, the MRI has low correlation with arthroscopic findings in cases of partial ACL tears [28, 52] and does not assess the functional competence of the intact ACL bundle. The instrumented joint laxity assessment is able to discriminate and document significant differences in mean SSD anterior tibial displacement in partial ACL tears [28]. Near one-third of patients treated arthroscopically for ACL injuries display a partial tear, being 14.1% classified as intact posterolateral bundle, 4.0% as intact anteromedial bundle, and 12.4% as posterior cruciate ligament healing. The SSD tibial displacement between ACL complete tear and all types of partial tears was significantly greater with Telos (mean 7.4 mm in total vs. 4.0 mm in partial ACL tears) than with the Rolimiter (mean 5.3 mm in total vs. 2.6 mm in partial ACL tears) [19]. The underestimation of joint laxity using the Rolimiter can hamper the desired accuracy for treatment decision and follow-up. The GeNouRoB, also comparing to Telos device, has showed a reasonably high diagnostic accuracy for ACL partial tears using a 2.5 mm cut-off (sensitivity of 84% and specificity of 81%) [53].

The ability to discriminate total from partial tears can be decisive for the surgical planning because the preservation of the ACL remnants enables anatomical landmarks for tunnel positioning [54] and provides vascular and mechanical benefits to the graft [55–57]. A selected group of patients with partial ACL tears may also respond well to conservative treatment [58–61] and in these cases it is crucial to assess the intact bundle competence. In cases of suspected partial tears, we use MRI instrumented-assessment to evaluate if there is any associated abnormal joint laxity [62].

8.6 Post-operative Knee Joint Laxity

Residual sagittal [63] and rotatory joint laxity [30, 64] as well as abnormal rotational motion [65–68] often persist after ACLR and are a common cause of poor long-term outcomes [69–71]. Residual knee joint laxity may disclose differences after ACL reconstruction procedures that might be related to the surgical technique [72–74], graft choice [75], concomitant procedures [16], graft tension or fixation angle [76, 77], and healing [78]. Residual anterior knee joint laxity 6 months following primary ACL reconstruction is associated with younger age (<30 years old), preoperative anterior laxity (SSD >5 mm), hamstring tendon graft, and resection of the medial meniscus [79]. Residual rotatory joint laxity measured by the pivot shift at 1 year after ACL reconstruction is associated with knee hyperextension and greater preoperative pivot shift under anesthesia. Age, gender, Lachman test, KT-1000 measurement, single-bundle vs. double-bundle, meniscus injury sites, and meniscus surgery were not predictors of residual rotational joint laxity [80].

Despite the evolution of surgical techniques, residual joint laxity should be a concern because it increases the ACL peak strain and has a fourfold increased risk for ACL injury for every 1.3 mm increase in SSD in anterior-posterior tibial displacement [81]. When athletes display residual joint laxity that is combined with neuromuscular deficits common in patients who tear the ACL [82]—such as weakness of hip external rotators—they will be exposed to a higher risk of reinjury during sport-specific tasks that involve pivoting or landing where the strain applied to graft is increased.

The use of accurate multiplanar laximetry techniques is important to monitor the post-operative outcomes. Restoration of knee stability is the main goal of surgical reconstruction and post-operative joint laxity evaluation should therefore always take part of a complete follow-up assessment. Despite the current literature on the importance of knee joint laxity on the treatment outcomes [83], but only 6% of studies use laxity-based assessment as a criterion for the return to sport decision [84]. In our experience, we use the MRI instrumented-assessment [85] that, in addition to the other often reported clinical and physical impairment-based objective criteria, supports our decision on when the athlete is ready to return to unrestricted sports.

8.7 MRI Instrumented-Assessment of Knee Joint Laxity

The Porto Knee Testing Device (PKTD) is an MRI-safe knee joint laxity testing device, made of polyurethane-based mixed resins, for the measurement of sagittal and rotatory knee joint laxity

(Fig. 8.1). The PKTD operates through two movable platforms that are activated by plunger mechanisms. One platform induces an antero-posterior translation and the other internal or external rotation of the leg. These two movable platforms can operate isolated or in combination, allowing to measure isolated sagittal and rotatory joint laxity, or the two simultaneously combined. The operator can control the magnitude of load transmission and adjust for different degrees of knee flexion.

We combine the PKTD assessment with MRI visualization to objectively assess the knee joint laxity. After applying postero-anterior and/or rotatory stress, we measure the tibial displacement in the medial and lateral plateaus relative to the resting baseline position (Fig. 8.2). The tibial displacement is used as an isolated measure—i.e., the total amount of displacement—and is also compared with the contralateral knee.

Fig. 8.1 Photograph of the Porto-Knee Testing Device (PKTD)

The PKTD is a valid tool to assess ACL complete tears. The sagittal joint laxity is correlated with the KT-1000 and the rotational joint laxity is correlated with the pivot shift results [29]. While combining the anterior tibial displacement in both the medial and lateral plateaus, we obtain the most specific measure (94%); when combining the tibial internal and external rotation in the lateral plateau, we obtain the most sensitive measure (93%) [22].

The ability to visualize soft tissues concomitantly with accurate objective joint laxity measurement [30] allows to correlate the structural integrity of the ligament with its functional competence. Eventually, we can establish multiplanar knee joint laxity cluster profiles that may be associated with specific injury patterns [37, 86–88], time between injury and surgery [89], different ACL reconstruction surgical

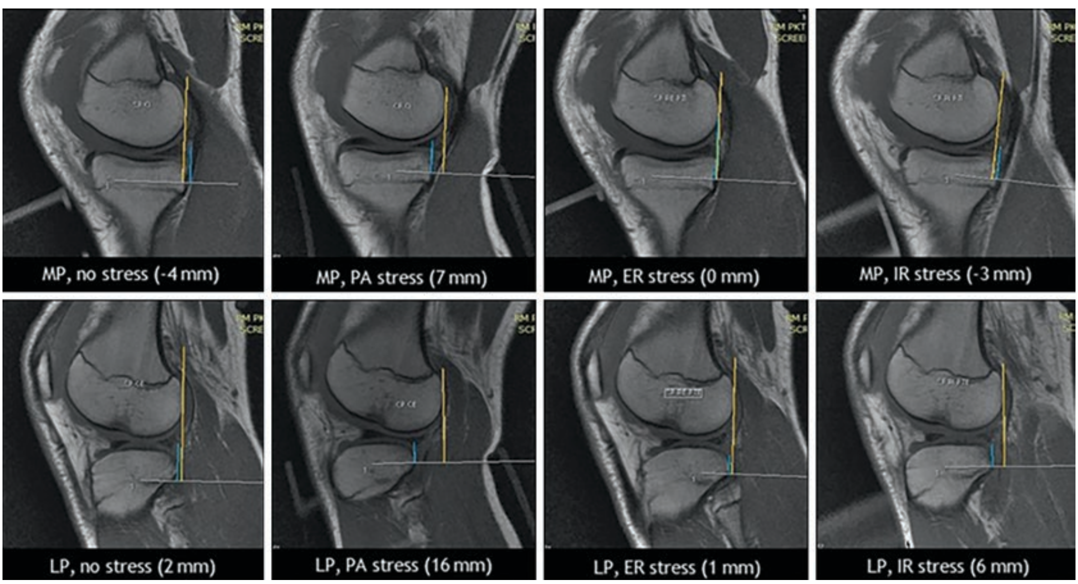

Fig. 8.2 PKTD exam of an ACL total rupture. *MP* medial plateau, *LP* lateral plateau, *PA* posteroanterior translation, *ER* external tibial rotation, *IR* internal tibial rotation. Blue line indicates tangent line to the posterior tibial plateau and orange line indicates tangent line to the posterior femoral condyle

techniques outcomes [68, 90], or anatomic features such as bone morphology or morphometrics [91–95]. The PKTD can have an important role in establishing these multiplanar knee joint laxity cluster profiles as it combines the assessment of both "anatomy" and "function" [96]. For instance, the MRI visualization might identify a partial ACL tear with an intact bundle, that after the PKTD assessment can reveal incompetent to provide stability to the knee (Fig. 8.3) [62]. We may find also injury of the anterolateral structures of the knee that, if combined with abnormal rotational joint laxity, may require the addition of a lateral extra-articular tenodesis. When examining external tibial rotation laxity at 30 degrees of flexion, it may identify cases with posterolateral corner injury that may have been undetected during the dial test (Fig. 8.4) [97]. Using the PKTD, we can identify these subclinical groups that may require differentiated or additional surgical intervention and thus refine our surgical indications and

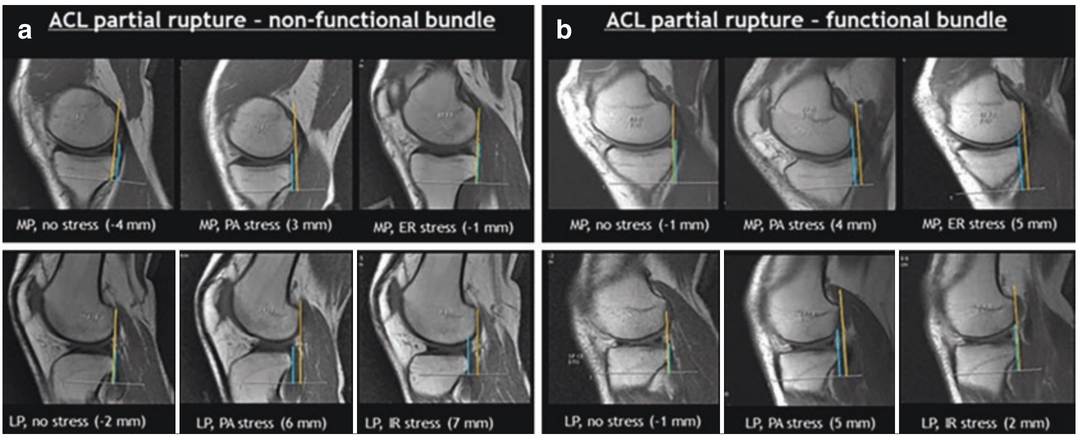

Fig. 8.3 PKTD exam of two cases of ACL partial rupture. (**a**) Partial ACL rupture with an intact, but non-functional bundle; (**b**) partial ACL rupture with an intact and functional bundle. *MP* medial plateau, *LP* lateral plateau, *PA* posteroanterior translation, *ER* external tibial rotation, *IR* internal tibial rotation. Blue line indicates tangent line to the posterior tibial plateau and orange line indicates tangent line to the posterior femoral condyle

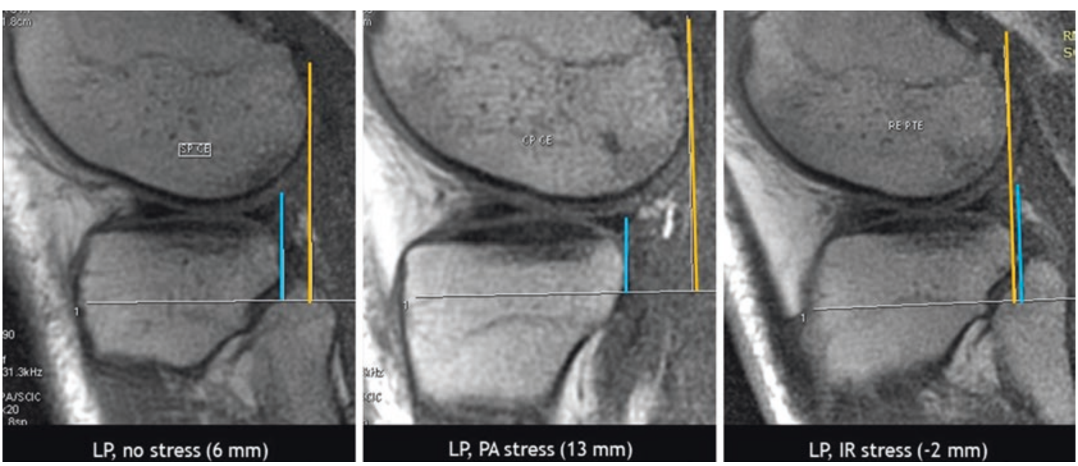

Fig. 8.4 PKTD exam showing increased external rotation that was undetected under the dial test. *LP* lateral plateau, *PA* posteroanterior translation, *ER* external tibial rotation. Blue line indicates tangent line to the posterior tibial plateau and orange line indicates tangent line to the posterior femoral condyle

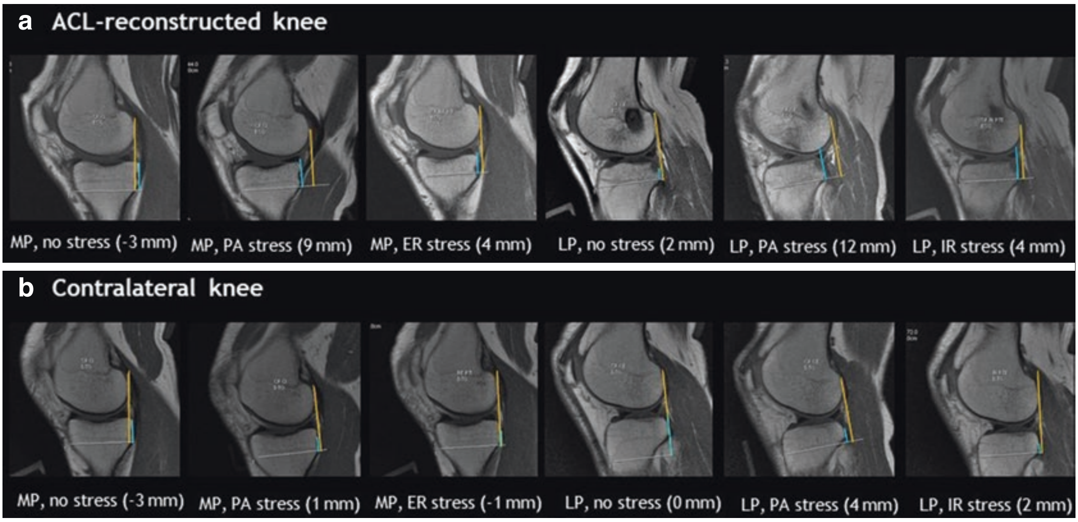

Fig. 8.5 PKTD exam comparing an ACL-reconstructed knee (**a**) with its contralateral healthy knee (**b**). From the PKTD examination, we can observe that there is still residual laxity that requires reintervention. *MP* medial plateau, *LP* lateral plateau, *PA* posteroanterior translation, *ER* external tibial rotation, *IR* internal tibial rotation. Blue line indicates tangent line to the posterior tibial plateau and orange line indicates tangent line to the posterior femoral condyle

individualize the treatment. In the follow-up of conservative or surgical approaches, the PKTD also plays an important role in the prospective monitoring of knee joint laxity and identify those with residual joint laxity (Fig. 8.5) [98]. It will provide useful information for the decision to clear the athletes to unrestricted sporting activities or those that may require further rehabilitation or surgical reintervention [85].

8.8 Conclusions

The PKTD is an MRI-safe knee joint laxity testing device which enables assessment of isolated or combined anteroposterior and rotatory joint laxity. Accurate assessment of multiplanar tibial displacement with imaging visualization can establish joint laxity cluster profiles that may correlate with specific injury patterns. Joint laxity can vary in quantity and in quality if there is an isolated ACL injury or there is additionally injury to peripheral structures, such as the ALC (especially the ALL and deep fibers of the ITB) or the menisci. Combining the MRI visual inspection of anatomical injury with the mechanical capability using the PKTD, we are able to accurately assess and characterize the knee joint multiplanar laxity and thus support treatment decisions and customized interventions while aiming for superior outcomes. The restoration of passive sagittal and transversal knee stability is the main purpose of surgical interventions addressing ACL reconstruction and pre- and post-operative measurements should therefore be systematically performed to support orthopedic precision medicine.

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