Kinematic outcomes following ACL reconstruction

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Abstract Anterior cruciate ligament (ACL) reconstruction aims to restore the translational and rotational motion to the knee joint that is lost after injury. However, despite technical advancements, clinical outcomes are less than ideal, particularly in return to previous activity level. A major issue is the inability to standardize treatment protocols due to variations in materials and approaches used to accomplish ACL reconstruction. These include surgical techniques such as the transtibial and anteromedial portal methods that are currently under use and the wide availability of graft types that will be used to reconstruct the ACL. In addition, concomitant soft tissue injuries to the menisci and capsule are frequently present after ACL injury and, if left unaddressed, can lead to persistent instability even after the ACL has been reconstructed. Advances in the field of biomechanics that help to objectively measure motion of the knee joint may provide more precise data than current subjective clinical measurements. These technologies include extra-articular motion capture systems that measure the movement of the tibia in relation to the femur. With data gathered from these devices, a threshold for satisfactory knee stability may be established in order to correctly identify a successful reconstruction following ACL injury.

Keywords Anterior cruciate ligament (ACL) · Double-bundle ACL reconstruction · Graft type · Concomitant injuries · Ramp lesion · Anterolateral ligament (ALL)

Background

The anterior cruciate ligament (ACL) is the most studied ligament of the knee as it has been believed to play the central role in anterior-posterior as well as rotational knee stability [1]. However, motion in the knee joint occurs across multiple planes of motion [2], and the stability of the knee is maintained by additional primary and secondary stabilizing structures that function to constrain the knee in the three-dimensional context of motion [3]. ACL injuries are frequently accompanied by concomitant injuries to these stabilizing structures, and the resultant multifactorial instability has been shown to increase the risk of developing osteoarthritis (OA) [4–6]. Arthroscopic ACL reconstruction is widely accepted as the treatment of choice to address this problem, particularly for young patients with a high activity level and those who fail to cope with instability [6–9]. Despite a variety of reports that suggest favorable outcomes with reconstruction [10, 11], there are still a number of patients who complain of residual instability [12]. This in turn has led to a high percentage of patients not returning to their previous activity level [13, 14], and for those who do return to their sport, high rates of failure of the reconstructed ACL have been documented [15]. In parallel, the treatment of ACL injuries—in both operative and non-operative treatment paradigms—is accompanied by great costs to the healthcare system [16–18]. In an attempt to counter rising costs, research has focused on optimizing the treatment of ACL injuries in order to provide an intervention with low failure rates and high functional outcomes for patients. However, despite extensive research efforts, there remains

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no accepted gold standard algorithm to address the injured ACL and concomitant soft tissue injuries [19, 20].

Continued advancements in the field of biomechanics in relation to the knee joint allow for a comprehensive analysis of the complex interaction of primary and secondary stabilizers and provide insights into the physical relationship between bone, cartilage, and soft tissue. This information is valuable as an accurate assessment of knee kinematics is essential to estimate the extent to which ACL injuries may affect knee stability and to what extent the stability of the knee is restored after surgery. For this specific purpose, several *in vitro* and *in vivo* methodologies are available and have been described. Utilizing robotic testing, navigation systems, and material testing machines, *in vitro* studies allow for a better understanding of the biomechanical influence of certain injuries and the benefit of different reconstruction techniques. However, the complexity of human motion cannot be captured in its entirety using these experimental approaches. Kinematic data can also be obtained from *in vivo* observations, namely high frequency biplane fluoroscopy, optical motion tracking, or magnetic resonance imaging (MRI). Combining this information with *in vitro* data, the interrelationship between bony morphology, mechanical and structural properties of soft tissue, muscle tension, and the influence of other joints within the kinematic chain can be better understood.

This paper will describe the influence of different injury patterns and subsequent surgical techniques in the context of ACL injuries on *in vitro* and *in vivo* knee kinematics, with attention to relevant aspects that may be applicable for clinical use.

Anatomic ACL reconstruction

Anatomic ACL reconstruction represents the customization of treatment needed to return each patient's knee to the native state, addressing all patient-specific characteristics and preconditions [21–23]. Specifically, the concept can be defined as “the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites” [24]. In order to accomplish this, complete visualization of the insertion sites both on the femur and tibia is crucial to attain precise graft alignment in the orientation of the former ACL and cover a main share of the original insertion site [25], since tunnel position distinctly affects the biomechanical functioning of the ACL reconstruction and poor placement of tunnels can directly lead to failure to restore the stability of the knee.

Transtibial drilling techniques are, in most cases, not amenable for positioning of tunnels within the native ACL insertion sites, since this method causes the tibial tunnel to be positioned medially and the femoral tunnel anterior to the natural footprint [26] (see Fig. 1). A recent meta-analysis

[27] compared the effects of transtibial and independent (e.g., via anteromedial portal or outside-in) tunnel drilling in both cadaveric and *in vivo* environments. Increased anterior tibial subluxation and a persistent pivot shift were noted in transtibial ACL reconstructed knees in cadaveric models [27]. These findings are further substantiated by *in vivo* studies that have reported inferior clinical outcomes in the knees undergoing ACL reconstruction using the transtibial technique. Radiographically, a more horizontal and oblique tunnel direction and less tunnel enlargement on the femoral side were achieved when drilled independently from an anteromedial portal. Using a 10-camera motion tracking system and markers on major joint landmarks of the lower extremity to capture knee kinematics, the anteromedial portal technique was better able to restore the normal anterior-posterior translation of the knee in the swing phase of walking and reduced internal rotation during the stance phase compared to the transtibial technique. However, none of these drilling techniques were able to restore superior-inferior femoral translation during the swing phase to the level observed in an ACL intact knee [28•]. Validated computer models have additionally compared the tibial translation and rotation, graft forces, as well as medial and lateral contact forces of anatomic and transtibial reconstruction. Both techniques could not reproduce consistent restoration of native ACL intact kinematics, although better anterior-posterior stability was obtained with independent tunnel drilling [29]. Comparing the existing literature regarding clinical outcomes, only the Lysholm score revealed slightly better results using anatomic tunnel placement. Other outcome scores considered, no significant differences between International Knee Documentation Committee (IKDC) objective scores, Tegner scores, and failure rates between transtibial and independent reconstruction could be identified [27]. However, the majority of surgeons remain convinced that an anatomic reconstruction better replicates the kinematic environment of the native knee and have consequently adopted this technique.

Double-bundle ACL reconstruction

The bipartite anatomy of the ACL as a construct composed of two functionally independent bundles, the anteromedial and posterolateral bundle, is well documented [30, 31]. In the last decade, a number of biomechanical studies revealed that a double-bundle approach may better restore the mechanical properties of the knee in terms of anterior-posterior and rotatory stability as well as in respect to tibiofemoral contact pressure [32–35].

Multiple studies in recent years have attempted to explore the differences on knee kinematics after single- and double-bundle ACL reconstruction. Using biplane fluoroscopy to capture knee motion during lunges and matching

Fig. 1 View on the lateral femoral condyle from medial perspective after a sagittal cut of the femur. The non-anatomic femoral tunnel is positioned anterior to the natural footprint that constitutes the position for an anatomic tunnel placement

this with 3D models generated with multi-planar MR imaging, sagittal plane orientation of the anatomically reconstructed ACL has been shown to be closer to the native ACL. However, in comparison to a control group, both single- and double-bundle ACL reconstruction decreased the tibial rotation and therefore appeared to partially overconstrain the knee during movement [36]. This finding substantiates other fundamental biomechanical research, showing that ACL reconstruction potentially leads to abnormal motions, which might contribute to long-term degeneration of the joint. For example, Tashman et al. examined downhill running in ACL reconstructed patients using a 250 frame/s stereoradiographic system to gather in vivo kinematics (see Fig. 2) and found that across all subjects, reconstructed knees demonstrated greater external rotation [37]. On a larger scale, all joints of the kinematic chain are affected by the surgical approach to address ACL deficiency. Recently, a study analyzed the gait of patients in the 14th week following surgery after single-bundle and double-bundle reconstruction. A comparison of rotational kinematics in the ankle, knee, hip joints, and the pelvis during ambulation on a flat surface demonstrated that neither technique was able to completely restore the natural motion of these joints; however, double-bundle ACL reconstruction appeared to better replicate kinematics [38, 39].

Just as with the single-bundle approach, the quality of double-bundle ACL reconstruction depends on a multitude of mutually independent factors. A recent cadaveric study investigated the influence of graft fixation angle and tensioning, showing that the best restoration of native ACL

biomechanics was achieved when the anteromedial bundle was fixed in 45° knee flexion using 30 N and the posterolateral bundle was fixed in 15° knee flexion with 10 N tensioning force [40]. Computational modeling further highlighted that the influence of bundle diameters on knee kinematics is rather negligible while the attachment points significantly affected the kinematic outcome and need to be carefully addressed [41]. The variety of influencing factors emphasizes the problems inherent in establishing a standardized treatment protocol that can consistently address these issues.

When accounting for the literature comparing single- and double-bundle ACL reconstruction, improved postoperative laxity and outcome scores for double-bundle ACL reconstruction have been reported in several in vivo studies [11, 42, 43]. However, other studies have shown no significant differences between these techniques [44–46]. A recent meta-analysis attempting to resolve this question suggests that better postoperative knee stability can be attained after double-bundle reconstruction, but that this does not lead to superior clinical outcomes [47]. Therefore, double-bundle surgery still remains a point of controversy, and further research is needed to determine the clinical advantages of this technique. It is worth highlighting that the decision between single- and double-bundle operative reconstruction should be based on careful patient selection and the proper surgical indication. Both of these points constitute key factors for a successful outcome, as the individual morphology and injury pattern of each patient needs to be addressed, as well as the patient's expectations for return to activity after surgery.

Fig. 2 Dynamic stereo X-ray (DSX) images (**b**) are acquired at a rate of approximately 250 frames per second using two gantries to provide two beams parallel to the ground, while the subject is performing specific tasks in the beam focus (**a**). Matching DSX images and subject-specific tibiofemoral bone models (**d**) derived from computed tomography scans (**c**), in vivo knee kinematics can be calculated (**e**)

Graft choice

Since the beginning of ACL surgery, the choice of graft has been a point of controversial discussion when attempting reconstruction. Graft choice depends heavily on factors inherent to the graft itself, such as the biomechanical properties of the tissue, the time to incorporation, and harvest site morbidity. Advantages and disadvantages of different graft types are well known and listed in the table below [48]. The biomechanical properties of each graft have significant implications on the ability to restore kinematic attributes of the native knee (Table 1).

Despite the extensive research throughout the last century and due to the fact that no gold standard algorithm regarding graft choice exists, recent data from studies on graft performance contribute clinically relevant information and continue to lead to modifications in the surgical treatment of ACL injuries.

Bone-patellar-bone autograft has been a staple of ACL reconstruction since the inception of this surgery. This graft has the advantage of bone to bone healing in tunnels that has been shown to incorporate much earlier than tendon to bone healing, thereby allowing for more rapid rehabilitation after surgery [55, 56]. Various other properties of the bone-patellar-bone construct may affect the performance of the graft. The superiority of the central third of the patellar tendon in terms of thickness and mechanical properties compared to the medial and lateral portion of the tendon [57] may potentially play a significant role on the ultimate strength of the graft, particularly when attention is given toward directing graft harvest to this region of the tendon. In addition, the shape of the bone-block and tunnel has an effect on the restoration of ACL kinematics as the reconstruction using a rectangular block and tunnel more closely resembled the mechanical behavior of the

native ACL compared to round grafts and tunnels. Conversely, reconstruction using the round shape appeared to better control anterior translation by means of more superior graft tensioning; however, the positioning of the tibia with respect to the femur was impaired [58]. Therefore, the process of harvesting from the patellar tendon constitutes a very important factor for the subsequent outcome and has recently been given more consideration.

Despite variability in diameter and length [53], which is partially disadvantageous for the subsequent surgical procedure, hamstring autografts have been utilized as an alternative to bone-patella-bone autograft and constitute one of the most commonly used graft types at the present day. Concerns regarding the slower healing involved with tendon to bone incorporation have limited its use as a first line graft in the elite athletic population [59, 60]. In addition, some studies have suggested that the failure rate with hamstring autografts may be somewhat higher than bone-patella-bone autograft [61]. Although the round shape of the hamstring graft may not provide reliable anterior knee stability at low flexion angles as the rectangular shape [62], recent studies have explored ideas to potentially improve outcomes after ACL reconstruction with hamstring autograft. Uniform suturing of the grafts was shown to increase the ability of the graft to withstand tensile loading [63]. By applying both tension and circumferential compression, the average diameter of hamstring ACL grafts can be decreased approximately 1 mm, making smaller tunnels possible when deciding to use this graft. Taking advantage of this viscoelastic effect could potentially be beneficial for graft incorporation as well as in cases with limited space for tunnel drilling, e.g., pediatric ACL surgery or double-bundle ACL reconstruction. However, pre-stretching of the graft by about 10 % of its length may also have a detrimental effect, as subsequent contraction of the graft when

Table 1 Advantages and disadvantages of the most commonly used grafts for ACL reconstruction, including load-to-failure and stiffness [48]

Graft type	Advantage	Disadvantage
Patellar tendon		
- Load-to-failure: 2977 N (10 mm graft)	• Fixation of bone blocks close to aperture of intraosseous tunnel	• Donor-side morbidity and possible complications
- Stiffness: 455 N/mm (10 mm graft) [49]	• Fast bone-to-bone healing	- Pain, tendinitis, stiffness
	• Good preservation of stiffness and load-to-failure	- Early patellofemoral OA [50, 51]
		- Patella tendon rupture
		- Patella fracture
		- N. saphenous injury
Hamstring tendons		
- Load-to-failure: 4590 N (Doubled ST/GR)	• High load-to-failure and stiffness	• Varying tendon size [53]
- Stiffness: 861 N/mm (Doubled ST/GR) [52]	• Greater cross-sectional area	• Slower tendon-to-bone healing
	• Easy graft passage	• Weakness of hamstring muscle
	• Small incision	• Possible complications
	• Little donor-side morbidity	- Tunnel widening
		- N. saphenous injury
Quadriceps tendon		
- Load-to-failure: 2353 N	• Thick tendon	• Bigger incision/scar
- Stiffness: 326 N/mm [54]	• Biomechanical properties closer to values of native ACL	• Bleeding risk
	• Less anterior knee pain	
	• Versatile	
Native ACL		
- Load-to-failure: 2160 N		
- Stiffness: 242 N/mm [43]		

ST semitendinosus tendon, GR Gracilis tendon

in contact with the synovial fluid of the joint may adversely affect overall graft strength [64, 65].

Recently, quadriceps tendons are more frequently being used as grafts for ACL reconstruction. This trend is supported by current literature, revealing the applicability and adequacy of this graft type in single- as well as double-bundle ACL reconstruction [66, 67, 68, 69] (see Fig. 3). However, more high-evidence literature and long-term follow-ups are needed to optimize intricacies related to this technique.

Due to the structural differences inherent in each graft type, individual post-operative rehabilitation protocols are required. High-strain loading of the tendon-bone interface should be avoided in early stages after ACL reconstruction with soft tissue grafts as unfavorable effects on graft incorporation can be observed [70, 71]. Graft motion also contributes to tunnel aperture; so, special care must be taken, especially when using allografts which incorporate at a much slower rate than autograft tissue [72].

In terms of the kinematic outcome, all graft types show similar results by restoring anterior joint stability. However,

when simulating muscle loads, the internal rotation of the tibia was over-constrained regardless of the graft choice [73]. Consequently, the stability of the surgical construct seems to have more influence on hip and knee biomechanics than the graft type [74]. Also, in case of revision surgery, no differences between soft tissue and bone-patellar-bone grafts in terms of rerupture risk and patient-reported outcome seem to exist, whereas the use of autografts potentially provides a better outcome than the use of allografts [75]. Graft choice often depends on preferences of the revising surgeon and patient characteristics (e.g., age) during revision reconstruction, making comparison of outcomes difficult [76].

Associated soft tissue injuries

With the reported prevalence ranging from 47 to 65 % in ACL registries, meniscus tears are frequently observed concomitant injuries during ACL surgery [77–79]. Since the 1970s and 1980s, the menisci have been recognized as critical secondary stabilizers [80–84], with the medial meniscus acting as a

Fig. 3 Tensile testing of a split quadriceps tendon graft during pre-tensioning (a) and during failure in the midsubstance (b). Splitting the quadriceps tendon graft for a double-bundle ACL reconstruction resulted in similar creep, ultimate load, ultimate elongation, stiffness (c), and

tangent modulus regardless of splitting the tendon in the sagittal or in the coronal plane [69]. Graph used with permission from Dr. Robert Matthew Miller

restraint to anteriorly directed forces and the lateral meniscus being a secondary stabilizer to rotational torque, e.g., during a pivoting maneuver [85]. Also, the interrelationship between the ACL and the menisci, mutually increasing each other's in situ forces in case of excision, has been shown in several in vitro robotic studies and is well known [86, 87].

Recent biomechanical in-depth studies have focused on better understanding the dynamic behavior of the menisci with and without ACL injury and have examined how different injury patterns and tears in certain segments of the menisci influence knee kinematics. With the help of minimally invasive implementation of 1.0-mm tantalum beads into the medial and lateral meniscus during dynamic in vitro knee flexion, obtained by dynamic stereo X-rays, the mobility of the menisci in the presence of an intact and deficient ACL can be captured. This novel approach not only demonstrated changes in the cartilage contact location, but also reveals greater translation in the lateral meniscus compared to the medial meniscus once the ACL was cut, potentially providing an explanation for the high incidence of acute lateral meniscus tears and chronic medial meniscus tears [88•]. Furthermore, a recent animal study was able to provide insight into the chronology of the meniscal loads after ACL deficiency. Using 6-degree-of-freedom robotic testing device to reproduce the in vivo joint motions that were captured during a gait analysis on a treadmill before and after arthroscopic ACL transection, the in situ gait loads were recorded with the help of a universal force/moment sensor. A sharp increase of the meniscal loads over time was demonstrated [89]. Comparing isolated ACL injured patients and ACL injuries with concomitant isolated medial, isolated lateral, and bilateral meniscus tears to the contralateral uninjured side during an ascending stair climb activity, captured using a single fluoroscopic image system, significant

effects of meniscal injuries on knee joint kinematics were observed in vivo, influencing rotation as well as translation [90].

Different segments of the menisci may have a strong influence on knee kinematics. Posterior root tears of the lateral meniscus can be found in about 10 % of patients with ACL tear, and the contact pressure in the lateral compartment increases about 50 % following a complete detachment of the posterior horn [91]. However, the biomechanical consequences of posterior root tears of the lateral meniscus significantly depend on the integrity of the meniscofemoral ligaments, which in an intact state sustain the pressure in the lateral knee compartment and preserve the function of the meniscus [92]. Normalization of the contact pressure was achieved by reattaching the posterior root using a tibial ACL tunnel [92]. These observations highlight the complexity of the anatomic relationships and the difficulty in studying their individual and combined effects on knee motion. In the medial compartment, a recent robotic study using porcine knees revealed that the posterior horn of the medial meniscus is more important in controlling internal rotation, while the anterior horn acts as a stronger restraint to external torque [93].

Longitudinal tears in the peripheral attachment of the posterior horn of the medial meniscus, referred to as Ramp lesions by Strobel since the 1980s, have come under scrutiny recently, as these “hidden meniscocapsular lesions” have largely gone unnoticed during ACL reconstruction. With a reported prevalence of about 17 % of the patients undergoing ACL surgery [94], a high number of undetected cases can be assumed as about 40 % of Ramp lesions are only detected after soft tissue debridement via an additional posteromedial portal [95]. A biomechanical study with an optical tracking system and a testing rig showed increased anterior translation as well as

external rotation in the presence of a Ramp lesion in an ACL deficient knee, indicating that failure to address this injury may lead to abnormal meniscal and tibiofemoral laxity [96]. However, further research is needed to understand the interrelationship within the posteromedial corner of the knee.

Recent publications advocating a newly discovered anterolateral ligament [97–100] have led to a re-examination of the anatomy and biomechanical function of the anterolateral complex of the knee (see Fig. 4). Inconsistent findings of the proposed ligament [101–104] and a varying range of reported anatomic insertion sites [105] have led to a controversial discussion about its existence and function. Contradicting results of biomechanical tensile testing of the proposed anterolateral ligament, reporting an ultimate load to failure of 49.9 N (± 14.6 N) [106] and 204.8 N (± 114.9 N) [107], further complicate any conclusions. Without discovering a discrete ligamentous structure, a recent study evaluated the macroscopic, microscopic, and radiologic anatomy of the anterolateral aspect of the knee and discovered a discrete thickening of 2–4 mm in the anterolateral capsule in 30 % of the specimens. Additionally, the histology of this “capsular thickening” was compared to the LCL, displaying a clear, linear alignment of collagen fibers in the LCL, while the thickening of the anterolateral capsule did not show the characteristic organization of a “true ligament” [108]. When performing biomechanical

tensile testing of this region, the iliotibial band had almost 50 % more ultimate load, nearly 3 times higher stiffness, and half of the ultimate elongation in comparison to the anterolateral capsule [109]. Studies attempting to evaluate the biomechanical role of this proposed ligament in knee motion contest that it acts as an important stabilizer of internal rotation especially in high flexion angles and suggest a contribution to a high-grade pivot shift [110–112]. Historical literature has outlined a contribution of anterolateral structures to rotatory stability [113–115], suggesting that the proposed ligamentous structure and structures in anatomic proximity such as the capsulo-osseous layer of the iliotibial band serve a similar biomechanical function. However, determining the contribution of each anterolateral structure to knee stability, a recent biomechanical study revealed that the proposed anterolateral ligament and the anterolateral capsule both had minor influence on restraining internal rotation, while the iliotibial tract acts as main contributor in preventing the anterolateral subluxation of the tibia during the pivot shift and in controlling internal rotation [116•].

Inconsistent findings regarding a newly discovered ligament seem to relativize the biomechanical importance and guard against leaping to conclusions. In fact, the relatively weak biomechanical properties of this ligament suggest that an additional anterolateral restraint might lead to non-physiological kinematics by increasing the external tibial rotation and exposing a non-anatomic constraint upon the knee joint.

Assessment of rotatory laxity

In the context of knee kinematics, differences in the understanding of the terms instability and laxity exist and often cause confusion. Although the definitions of both terms are indistinct, they are not synonymous [117]. While biomechanically, laxity can most likely be defined as “the passive response of a joint to an externally applied force,” instability constitutes a “functional measure,” which is expressed by the patient [118]. However, due to different compensation capabilities by the patients, an increased laxity is not tantamount to knee instability and an inferior outcome [119].

Apart from clinical tests such as the Lachman and the anterior drawer, the pivot shift test “bridges” the appreciation of laxity and instability, since during subluxation of the tibia, indicating increased rotatory laxity, the patient expresses a feeling of instability (“giving way”) [118, 120]. Correlations with clinical outcome, as well as with the development of OA [121–123], further emphasize the importance of this concept. Consequently, a variety of technical tools focus on objectifying the pivot shift. The biomechanical methods can be divided into four general categories, measuring translations, rotations, acceleration/velocity, and calculated indexes [124].

Fig. 4 The anterolateral complex of the knee after reflection of the iliotibial band (ITB) during translumination using arthroscopy. While the lateral collateral ligament (LCL) is well definable, there is no anterolateral ligament in this specimen, although a capsular thickening is noted anterior to the LCL

Fig. 5 Principle of image analysis—the anterior translation of the lateral compartment is calculated based on the motion of the markers relative to each other during the pivot shift

Image analysis

During the pivot shift maneuver, the anterior tibial translation of the lateral compartment exceeds the motion in the medial compartment and correlates with the grading of the pivot shift [125]. Based on this finding, the image analysis principle attempts to gauge anterior tibial translation of the lateral compartment using skin markers attached to the bony landmarks lateral epicondyle, Gerdy's tubercle, and the fibular head (see Fig. 5). A digital camera is used to record the motion of the

markers relative to each other during the pivot shift, and for each frame of the video, anterior translation is determined. This time-dependent anterior-posterior translation of the lateral compartment during the pivot shift illustrates a sudden decrease in ACL-deficient knees, occurring simultaneously to the reduction of the tibia. This sudden decrease is used for the quantification of the pivot shift. An iPad application automatically analyzes the video in the previously mentioned manner. Short analysis times and a user-friendly interface make the principle of image analysis to an easily applicable tool for the daily clinical work (see Fig. 6) [126–128].

Inertial sensors

Another approach to quantify the pivot shift exam aims for measuring the acceleration during the tibial reduction, as acceleration of posteriorly directed translation has been shown to be significantly higher in ACL deficient knees and may correlate with the clinical grading of the pivot shift [129]. For this purpose, commercial inertial sensors, consisting of a 3D accelerometer and three perpendicularly arranged gyroscopes, are attached to the lateral aspect of the proximal tibia, close to Gerdy's tubercle. Acquiring data with 110 Hz frequency, the gathered acceleration is transmitted via Bluetooth to a tablet PC. The developed KiRA software (Orthokey LLC, Lewes, DE, USA) analyzes the data, plots the acceleration in dependence of the time, and saves values in a patient data base. Identifying the corresponding curve generated by the pivot shift, the software automatically calculates the maximum and minimum acceleration of the limb and gauges the slope of the curve for smoothness [130–133].

Rotatory instability is a complex multifactorial problem and is influenced by a variety of soft-tissue and bony factors.

Fig. 6 Objective quantification of the pivot shift in the OR using image analysis and an inertial sensor

However, these technologies provide valuable quantitative information about dynamic rotatory laxity and can obtain data in terms of general and intra-individual imbalances, as tested by the pivot shift test. These insights in different laxity patterns and the chronological assessment of injuries pre-, intra-, and post-operatively might help to optimize treatment algorithms after ACL tear.

Concluding remarks

Advances in the field of biomechanics enable the comprehensive analysis of knee kinematics and draw a picture of sophisticated mutual interrelationships between the different stabilizing structures of the knee. As a consequence, kinematic outcomes following ACL reconstruction are characterized by a complex interaction of multiple influencing factors, heavily dependent on surgical technique, graft type, and concomitant soft tissue injuries. While literature increasingly indicates that non-anatomic approaches via a transtibial tunnel lead to inferior kinematic outcome, there is still controversy if a double-bundle ACL reconstruction better restores the native biomechanical behavior of the knee compared to single-bundle ACL surgery. However, regardless of single- or double-bundle ACL reconstruction, none of these techniques are able to reconstitute the knee kinematics of an intact ACL, as both approaches decrease the tibial rotation and partially overconstrain the knee. Extra-articular reconstructions on the anterolateral aspect of the knee need to be carefully evaluated, as further overconstraining of tibial rotation could result in abnormal knee motion and might lead to premature OA [134–137]. Surgical ACL treatment should rather focus on restoring and preserving the functioning of secondary stabilizers such as the menisci, not only by fixing meniscal tears but also by carefully examining for meniscocapsular separations, e.g., Ramp lesions. In the worst cases, meniscus transplants might be considered. Further options in revision cases are osteotomies to correct coronal plane alignment and alter the posterior tibial slope. Additionally, kinematic evaluation of the patients (e.g., using image analysis or inertial sensor) should also always take place prior to surgical treatment to filter patients, who cope with ACL deficiency and could potentially successfully be treated non-operatively.

However, all biomechanical studies need to be carefully scrutinized and challenged as the organized settings in the laboratories normally do not reflect real-life conditions and the results cannot be conveyed one-on-one to the OR. Additionally, qualitative differences between biomechanical studies exist, and the right assessment of these studies is often difficult to the untrained reader without biomechanical basic knowledge. Unlike the level of evidence system to evaluate clinical research and to provide the reader with information about the type and quality of the research—a classification

system that is widely accepted across peer-reviewed journals—there is no validated classification system or formal set of criteria for grading biomechanical studies. Therefore, every reader needs to carefully evaluate to which degree experimental conditions approximate the real-life environment of the human knee and if the particular study contributes to understanding knee biomechanics and the improvement of the outcome of ACL reconstruction.

Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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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