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Comparison of three non-invasive quantitative measurement systems for the pivot shift test

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Abstract
Purpose The purpose of this study was to evaluate three different non-invasive measuring devices for the pivot shift phenomenon with reference to direct bony movement measured by an electromagnetic device rigidly attached to the tibia and femur.
Methods A lower body cadaveric specimen was prepared to create a positive pivot shift in both knees. Twelve expert knee surgeons from worldwide performed their preferred pivot shift technique three times in each knee. After watching an instructional video, the examiners used a standardized technique to perform three additional pivot shift maneuvers in each knee. An electromagnetic tracking system, rigidly attached to femur and tibia, was used to provide reference measurements during the pivot shift test. Three different devices were correlated to the reference method and evaluated in this study: (1) Electromagnetic tracking system with skin sensors; (2) Triaxial accelerometer system; (3) Simple image analysis.
Results When results from both pivot shift techniques (preferred and standardized) were combined, the electromagnetic tracking system with skin sensors showed positive correlation with the reference measurement for acceleration and translation parameters ($r = 0.88$ and $r = 0.67$, respectively; both $P < 0.01$); The triaxial accelerometer system demonstrated good correlation with the reference measurement for acceleration ($r = 0.75$; $P < 0.001$). The image analysis system was poorly correlated to the translation of the reference measurement ($r = 0.24$; $P < 0.01$).
Conclusion The electromagnetic tracking system with skin sensors provided the best correlation with the reference method. The triaxial accelerometer showed also a good correlation and the image analysis system showed a positive, but poor correlation with the reference method. More research is needed in order to validate simple and non-invasive devices for clinical application.

Keywords ACL · Pivot shift · Quantitative analysis · Acceleration · Anterior tibial translation

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Introduction

The pivot shift test is a manually performed exam to clinically address knee rotational laxity in anterior cruciate ligament (ACL) deficient patients [1, 2]. Quantitative assessment of the pivot shift test is flawed by numerous different techniques and subjective clinical grading [3, 4].

In an attempt to address these inconsistencies, many studies have been conducted to decompose the pivot shift movement into quantifiable parameters [5–13]. As a consequence, anterior tibial translation and acceleration of tibial reduction have emerged as more stable criteria to evaluate the pivot shift [14], while others such as rotational measurements were shown not to be consistent, even if the test is performed by the same examiner [8, 14]. Several devices have been developed to quantitatively assess these components of the pivot shift phenomenon [9–13, 15], including non-invasive devices that can be used in the clinical setting [7, 11]. Appropriate validation of those systems has yet to be determined, particularly compared to the actual bony movement.

The purpose of this study was to evaluate the capacity of three different non-invasive devices, i.e., electromagnetic device, triaxial accelerometer, and simple image analysis, to quantitatively evaluate the pivot shift phenomenon with reference to direct bony movement measured by an electromagnetic device attached to the tibia and femur. It was hypothesized that the non-invasive application of the electromagnetic device would demonstrate greater correlation with the reference method compared to a triaxial accelerometer and the simple image analysis system.

Materials and methods

A whole lower body cadaveric specimen (male; age 70 years) was used in this study. A fluoroscopic exam was conducted prior to the test to confirm the absence of fracture or other bony pathology. The knees were examined arthroscopically to confirm the absence of previous injury or osteoarthritis. The ACL was transected in both knees to create a positive pivot shift. The anterior horn of the lateral meniscus was additionally severed in the right knee to increase the pivot shift grading in this side.

An electromagnetic tracking system (LIBERTY™, Polhemus, VT), capable of providing 6° of motion kinematics, was used for direct measurements of the knee motion and it was considered in this study as the reference method to obtain measurements for the pivot shift test. The electromagnetic sensors were rigidly fixed to the femur and tibia using two 4.0-mm K-wires and a platform, allowing the rotation and orientation of the sensors to be accurately tracked. The knee kinematics coordinate system defined by Grood and Suntay [16] was digitally configured after digitizing the three-dimensional (3-D) position of the anatomical landmarks using another sensor as previously described [16, 17]. From the knee kinematics data, the anterior tibial translation and tibial acceleration for the pivot shift test could be calculated [3, 7, 18–22]. This electromagnetic system had a root mean square accuracy of 0.76 mm for position and 0.15° for orientation [23].

Three non-invasive measurement devices were concomitantly used in the specimen to provide quantitative information on the pivot shift test for correlation with the reference method (Fig. 1):

1. *Electromagnetic tracking system* Used with sensors attached to the skin to provide tibial acceleration and anterior tibial translation measurements non-invasively. The electromagnetic sensors were applied to the skin on the thigh and calf by means of a plastic brace fixed by circumferential Velcro® straps 10 cm above the superior pole of the patella and 7 cm below the tibial

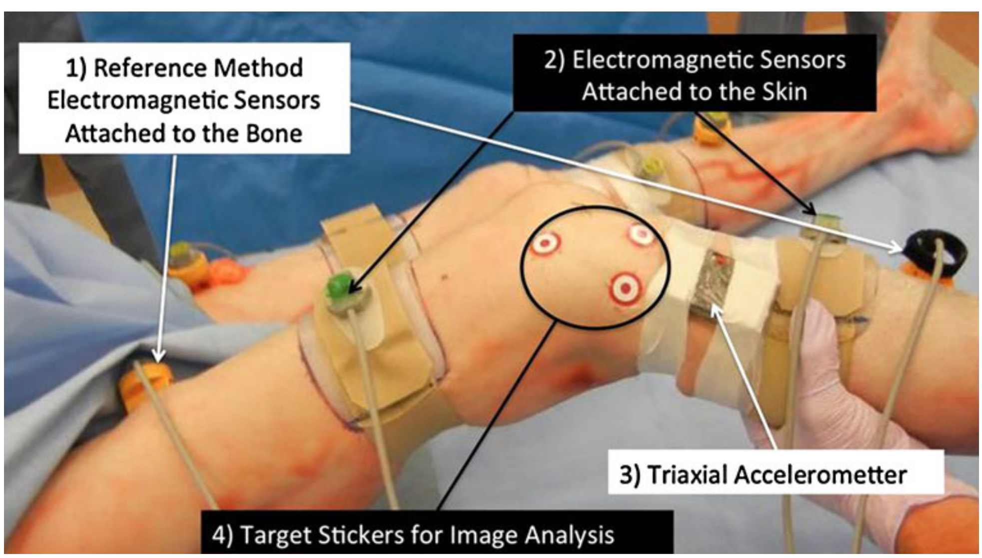

Fig. 1 The electromagnetic tracking system for direct measurement (*1*) and the three devices tested in this study: electromagnetic tracking system attached to the skin (*2*), triaxial accelerometer (*3*), and image analysis system (*4*)

tubercle, respectively. The results were calculated as described in previous studies [3, 7, 18–22].

2. *Triaxial accelerometer system* KiRA, Orthokey LLC, Lewes, DE, USA: This device was attached to the lateral aspect of the shank between the tibial tuberosity and Gerdy's tubercle by a tape surrounding the proximal aspect of the leg. This system was wirelessly connected to a laptop computer with Bluetooth (Bluetooth SIG, Inc., Kirkland, WA, USA) where the knee movement analysis was conducted as described in a previous study by Lopomo et al. [11]. Previous on-site testing demonstrated that the accelerometer employed in this experiment did not interfere with the electromagnetic field created by the electromagnetic tracking motion systems, which was simultaneously utilized in this experiment.
3. *Simple image analysis* This system was utilized to measure the anterior tibial translation of the lateral aspect of the knee. For this method, small target stickers (Staples, Framingham, MA, USA) were placed on bony landmarks of the lateral aspect of the knee, i.e., the lateral femoral epicondyle, Gerdy's tubercle, and fibula head. Movement of the stickers was captured using a digital camera (Nikon COOLPIX S8100, Nikon Corp., Tokyo, Japan) and the movies were analyzed frame by frame to calculate anterior tibial translation of the lateral compartment using Image J Software (NIH, Bethesda, MD, USA).

Twelve expert knee surgeons from worldwide performed the pivot shift test three consecutive times on each knee using their preferred technique. A standardized pivot shift technique was then presented to each surgeon by use of an instructional video. Subsequently, the surgeons performed additional three pivot shift tests in each knee using the instructed technique. Data from the three measuring devices were collected simultaneously during each test. The relationship between each of the three non-invasive measurements and the reference measurement was analyzed for each technique individually and for the technique's results combined. Surgeons were blinded to each other's tests.

Statistical analysis

Pearson correlation coefficient was used to address the relationship between each of the non-invasive measuring devices and the reference method.

Statistical significance was set at $P < 0.05$. All statistical calculations were performed using PASW Statistics 18 (formerly SPSS Statistics, IBM Corp., Armonk, NY, USA).

Results

The electromagnetic tracking system with skin sensors showed the best correlation with the reference measurement for both translation ($r = 0.67$; $P < 0.01$) and acceleration ($r = 0.88$; $P < 0.01$) parameters.

The triaxial accelerometer system demonstrated moderate correlation with the reference measurement for the acceleration parameter when the standardized technique was applied ($r = 0.51$; $P < 0.01$). However, when the preferred technique was utilized or when the results of both techniques were analyzed together the correlation was good ($r = 0.78$ and $r = 0.75$, respectively; $P < 0.01$).

The simple image analysis system was poorly correlated to the translation of the reference measurement when the standardized technique was used for the pivot shift test ($r = 0.32$; $P < 0.05$) or when the results of both techniques were combined ($r = 0.24$; $P < 0.01$). When the preferred technique was applied, the results showed no statistical significance correlation with the reference method.

The results for each system are reported in Table 1.

Anterior tibial translation and tibial acceleration during a single test as recorded by each of the three measurement systems are shown in Figs. 2 and 3, respectively.

Table 1 Correlation for each device and the reference method for surgeons' preferred pivot shift technique, standardized technique, and both techniques' results combined

Measurement	Method	Preferred technique	Standardized technique	Techniques combined
Anterior tibial translation	Electromagnetic system	0.63**	0.70**	0.67**
	Image analysis	NS	0.32*	0.24**
Acceleration of tibial reduction	Electromagnetic system	0.90**	0.66**	0.88**
	Triaxial accelerometer	0.78**	0.51**	0.75**

Pearson correlation coefficient of the non-invasive measurements compared to the direct bony measurement

NS no statistically significant relationship

* Statistically significant relationship, $P < 0.05$

** Statistically significant relationship $P < 0.01$

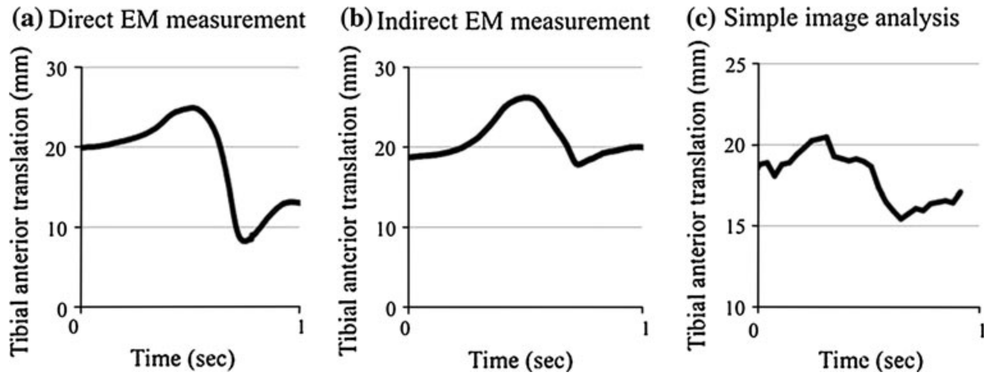

Fig. 2 A sample of tibial anterior translation measurement results from the same testing session. **a** Direct electromagnetic (EM) measurement (sensors fixed to bones). **b** Indirect EM measurement (sensors attached on the skin). **c** Simple image analysis

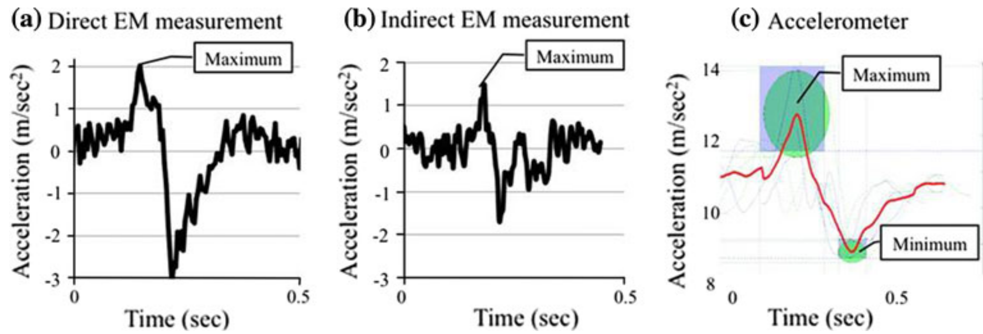

Fig. 3 A sample of tibial acceleration measurement results from the same testing session. **a** Direct EM measurement (sensors fixed to bones). **b** Indirect EM measurement (sensors attached on the skin). **c** Triaxial accelerometer

Discussion

The most important finding of this study was that all three non-invasive tested devices were capable of quantitatively assessing kinematic components of the pivot shift phenomenon, however, providing variable measurements.

The hypothesis under study was proven as the results demonstrate that the electromagnetic tracking system attached to skin is the most valid among the three tested devices. The electromagnetic tracking system can calculate objective measurements for both components of the pivot shift test: Anterior tibial translation and tibial acceleration in the reduction phase of the pivot shift. Moreover, the measurements collected by this device showed the best correlation with the reference method for both anterior tibial translation and tibial acceleration.

The pivot shift test has been used as the gold standard test to diagnose ACL deficiency with specificity as high as 98% [24]. However, its subjective nature and numerous different techniques applied by different examiners increase the variability of the pivot shift test. The sensitivity of the pivot shift test is reported in the literature ranging from 18 to 48% [15, 25–28]. In this study, a standardized pivot shift maneuver was introduced to the 12 expert surgeons. Although a limited time to acquire the new technique (2-min video instruction), the surgeons could adequately perform the test providing good correlation between non-invasive and direct measurements. Additionally, the translation measurement by simple image analysis was correlated to the bony movement only when the standardized technique was used. Therefore, the use of a standardized pivot shift test maneuver may ultimately decrease the test variability and therefore increase the test sensitivity.

In an attempt to objectify the pivot shift test, some authors also reported measurements from invasive devices such as navigation systems [13, 29]. Despite reliable parameters obtained with this method, its clinical use remains debatable and not affordable for most of surgeons due to the higher costs implied, extra time in the operating room, and invasiveness. The different devices tested in the present study, on the other hand, are characterized by their non-invasiveness, potentially making them more applicable in a clinical setting.

The electromagnetic tracking system has the advantage of comprehensive evaluation of the pivot shift test by including both translation and acceleration.

In addition to a previously demonstrated high inter examiner repeatability of measurements [7] and more consistent results between examiners obtained by using the standardized technique, a good correlation to bony motion was demonstrated in the present study. This system's disadvantages are the cost ($20,000 plus software which is currently available only for research), possible interference with wireless networks and the electromagnetic field, and possible skin motion artifacts.

The triaxial accelerometer showed a moderate correlation with the acceleration measured by the electromagnetic system attached to the bone when the standardized technique was applied. On the other hand, a good correlation was shown when the preferred technique or when the results of both techniques were combined. These results may reflect the more consistent pattern of acceleration provided by the technique surgeons are already familiar with and the lack of practice of the standardized technique before the testing. The triaxial accelerometer has the advantage of being a wireless system that is easy-to-use in the office setting. The costs are around $3,000 plus originally developed software whose availability is also limited. However, the acceleration component of the pivot shift phenomenon is not an intuitive concept and still not completely understood. Therefore, further validation is warranted to explore the clinical and biomechanical meaning of the pivot shift tibial acceleration component.

Conversely, anterior tibial translation is a very intuitive concept. While the Lachman test determines anterior tibial translation of the central joint, the pivot shift test determines anterior tibial translation of the lateral compartment [5]. The image system analysis takes advantage of this characteristic and proposes to describe the pivot shift test by means of a quantitative measurement of anterior tibial translation of the lateral compartment during the dynamic testing motion. This system is cheap ($100 for a digital camera; the software download is free on the Internet), simple, and easily understandable. However, in the present study the image analysis system showed poor correlation to the actual bony movement ($r = 0.32$; $P < 0.01$). Future analyses are necessary to improve the technology and its repeatability.

The technology used for measuring the complex phenomenon of the pivot shift has been improved over the past few years. Further research to simplify the complexity of the devices will improve their applicability. Ideally, the pivot shift test would be performed using a standardized technique and utilizing a highly repeatable, non-invasive, and quantitative measurement system that can be used in a clinical setting at affordable cost. This study provides the initial steps toward the development of simple and inexpensive devices to quantify the pivot shift phenomenon.

Limitations of the study include the use of only specimens with obvious instability. There was no comparison to the intact knee. There were also no comparisons to other clinical tests or outcome scores.

Conclusion

Among the three devices tested, the electromagnetic tracking system provided the best correlation (good) with the reference method. The triaxial accelerometer showed also a good correlation and the image system analysis showed a positive, but poor correlation with the electromagnetic tracking motion system directly attached to the femur and tibia. Future research is planned to further standardize both the pivot shift test maneuver as well as quantitative measurement devices. Ultimately, the goal is to have a universally available and affordable device that can be used in the office to assess clinical outcome of ACL reconstruction surgery.

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References

1. Galway HR, MacIntosh DL (1980) The lateral pivot shift: a symptom and sign of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 147:45–50
2. Slocum DB, James SL, Larson RL, Singer KM (1976) Clinical test for anterolateral rotary instability of the knee. Clin Orthop Relat Res 118:63–69
3. Kuroda R, Hoshino Y, Kubo S, Araki D, Oka S, Nagamune K, Kurosaka M (2011) Similarities and differences of diagnostic manual tests for anterior cruciate ligament insufficiency: a global survey and kinematics assessment. Am J Sports Med 14(5): 236–255. doi:10.1177/0363546511423634
4. Noyes FR, Grood ES, Cummings JF, Wroble RR (1991) An analysis of the pivot shift phenomenon: the knee motions and subluxations induced by different examiners. Am J Sports Med 19(2):148–155
5. Bedi A, Musahl V, Lane C, Citak M, Warren RF, Pearle AD (2010) Lateral compartment translation predicts the grade of pivot shift: a cadaveric and clinical analysis. Knee Surg Sports Traumatol Arthrosc 18(9):1269–1276
6. Bignozzi S, Zaffagnini S, Lopomo N, Fu FH, Irrgang JJ, Marcacci M (2010) Clinical relevance of static and dynamic tests after anatomical double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 18(1):37–42
7. Hoshino Y, Kuroda R, Nagamune K, Yagi M, Mizuno K, Yamaguchi M, Muratsu H, Yoshiya S, Kurosaka M (2007) In vivo measurement of the pivot-shift test in the anterior cruciate ligament-deficient knee using an electromagnetic device. Am J Sports Med 35(7):1098–1104
8. Katchburian M, Hassan A, Amis A (2002) Intraoperative measurement of knee kinematics in reconstruction of the anterior cruciate ligament. J Bone Jt Surg Br 84(7):1075–1081
9. Labbe DR, de Guise JA, Mezghani N, Godbout V, Grimard G, Baillargeon D, Lavigne P, Fernandes J, Ranger P, Hagemeister N (2010) Feature selection using a principal component analysis of the kinematics of the pivot shift phenomenon. J Biomech 43(16):3080–3084
10. Lane CG, Warren RF, Stanford FC, Kendoff D, Pearle AD (2008) In vivo analysis of the pivot shift phenomenon during computer navigated ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 16(5):487–492

11. Lopomo N, Zaffagnini S, Bignozzi S, Visani A, Marcacci M (2010) Pivot-shift test: analysis and quantification of knee laxity parameters using a navigation system. J Orthop Res 28(2):164–169
12. Maeyama A, Hoshino Y, Debandi A, Kato Y, Saeki K, Asai S, Goto B, Smolinski P, Fu FH (2011) Evaluation of rotational instability in the anterior cruciate ligament deficient knee using triaxial accelerometer: a biomechanical model in porcine knees. Knee Surg Sports Traumatol Arthrosc 19(8):1233–1238
13. Pearle AD, Kendoff D, Musahl V, Warren RF (2009) The pivot-shift phenomenon during computer-assisted anterior cruciate ligament reconstruction. J Bone Jt Surg Am 91(Suppl 1):115–118
14. Hoshino Y, Kuroda R, Nagamune K, Nishimoto K, Yagi M, Mizuno K, Yoshiya S, Kurosaka M (2007) The effect of graft tensioning in anatomic 2-bundle ACL reconstruction on knee joint kinematics. Knee Surg Sports Traumatol Arthrosc 15(5):508–514
15. Hardaker WT, Garrett WE, Bassett FH (1990) Evaluation of acute traumatic hemarthrosis of the knee joint. South Med J 83(6):640–644
16. Grood ES, Suntay WJ (1983) A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng 105(2):136–144
17. Nishimoto K, Kuroda R, Mizuno K, Hoshino Y, Nagamune K, Kubo S, Yagi M, Yamaguchi M, Yoshiya S, Kurosaka M (2008) Analysis of the graft bending angle at the femoral tunnel aperture in anatomic double bundle anterior cruciate ligament reconstruction: a comparison of the transtibial and the far anteromedial portal technique. Knee Surg Sports Traumatol Arthrosc 17(3): 270–276
18. Araki D, Kuroda R, Kubo S, Fujita N, Tei K, Nishimoto K, Hoshino Y, Matsushita T, Matsumoto T, Nagamune K, Kurosaka M (2010) A prospective randomised study of anatomical single-bundle versus double-bundle anterior cruciate ligament reconstruction: quantitative evaluation using an electromagnetic measurement system. Int Orthop 35(3):439–446
19. Fujita N, Kuroda R, Matsumoto T, Yamaguchi M, Yagi M, Matsumoto A, Kubo S, Matsushita T, Hoshino Y, Nishimoto K, Araki D, Kurosaka M (2011) Comparison of the clinical outcome of double-bundle, anteromedial single-bundle, and posterolateral single-bundle anterior cruciate ligament reconstruction using hamstring tendon graft with minimum 2-year follow-up. Arthroscopy 27(7):906–913
20. Hoshino Y, Kuroda R, Nagamune K, Araki D, Kubo S, Yamaguchi M, Kurosaka M (2011) Optimal measurement of clinical rotational test for evaluating anterior cruciate ligament insufficiency. Knee Surg Sports Traumatol Arthrosc 36(34):125–136. doi:10.1007/s00167-011-1643-5
21. Kubo S, Muratsu H, Yoshiya S, Mizuno K, Kurosaka M (2007) Reliability and usefulness of a new in vivo measurement system of the pivot shift. Clin Orthop Relat Res 454:54–58
22. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M (2007) Double-bundle ACL reconstruction can improve rotational stability. Clin Orthop Relat Res 454:100–107
23. Nafis C, Jensen V, Beauregard L, Anderson P (2006) Method for estimating dynamic EM tracking accuracy of surgical navigation tools. Progr Biomed Opt Imaging—Proc SPIE 6141:152–167
24. Benjaminse A, Gokeler A, van der Schans CP (2006) Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. J Orthop Phys Ther 36(5):267–288
25. Boeree NR, Ackroyd CE (1991) Assessment of the menisci and cruciate ligaments: an audit of clinical practice. Injury 22(4): 291–294
26. Richter J, Dàvid A, Pape HG, Ostermann PA, Muhr G (1996) Diagnosis of acute rupture of the anterior cruciate ligament: value of ultrasonic in addition to clinical examination. Der Unfallchirurg 99(2):124–129
27. Rubinstein RA, Shelbourne KD, McCarroll JR, VanMeter CD, Rettig AC (1994) The accuracy of the clinical examination in the setting of posterior cruciate ligament injuries. Am J Sports Med 22(4):550–557
28. Steinbrück K, Wiehmann JC (1988) Examination of the knee joint: the value of clinical findings in arthroscopic control. Zeitschrift für Orthopädie und ihre Grenzgebiete 126(3):289–295
29. Lopomo N, Zaffagnini S, Signorelli C, Bignozzi S, Giordano G, Marcheggiani Muccioli GM, Visani A (2011) An original clinical methodology for non-invasive assessment of pivot-shift test. Comput Methods Biomech Biomed Eng 12(23):125–136. doi:10.1080/10255842.2011.591788