11-2003

The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs

Stavros Ristanis
University of Ioannina

Giannis Giakas
University of Ioannina

Christos D. Papageorgiou
University of Ioannina

Constantina O. Moraiti
University of Ioannina

Nicholas Stergiou
University of Nebraska at Omaha, nstergiou@unomaha.edu

See next page for additional authors

Authors
Stavros Ristanis, Giannis Giakas, Christos D. Papageorgiou, Constantina O. Moraiti, Nicholas Stergiou, and Anastasios D. Georgoulis

The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs

S. Ristanis, G. Giakas, C. D. Papageorgiou, T. Moraiti, N. Stergiou, A. D. Georgoulis

S. Ristanis, G. Giakas, C. C. Papageorgiou, T. Moraiti, A. D. Georgoulis
Department of Orthopaedic surgery, Orthopaedic Sports Medicine Center of Ioannina, University of Ioannina,
PO BOX 1330, 45110 Ioannina, Greece
Tel.: +30-26510-64980,
Fax: +30-26510-64980,
e-mail: oaki@cc.uoi.gr

N. Stergiou
HPER Biomechanics Laboratory,
University of Nebraska at Omaha,
Omaha, NE 68182, USA

Abstract

Recent in vitro research suggests that ACL reconstruction does not restore tibial rotation. This study investigated rotational knee joint stability in vivo during a combined descending and pivoting movement that applies a high rotational load to the knee joint. We studied 20 ACL reconstructed patients (bone–patellar tendon–bone graft) and 15 matched controls with a six-camera optoelectronic system performing the examined movement. In the control group the results showed no significant differences in the amount of tibial rotation between the two sides. No significant differences were also found between the contralateral intact leg of the ACL group and the healthy control. However, a significant difference was found within the ACL reconstructed group and between the reconstructed and the contralateral intact leg. Therefore ACL reconstruction may not restore tibial rotation even though anterior tibial translation has been reestablished.

Keywords Anterior cruciate ligament reconstruction · Descending-pivoting movement · Knee joint stability · Tibial rotation

Introduction

The current clinical practice in ACL reconstruction is focused on the ability of the ACL grafts to diminish the pathological anterior translation of the tibia [3, 11]. Tibial translation can be evaluated statically using an arthrometer such as the KT-1000 or KT-2000 [8] and dynamically with an adjusted potentiometer [26] or with radiostereometry [4, 15]. However, the main function of the anterior cruciate ligament (ACL) is not only to stabilize the tibia from anterior translation relative to the femur but also to limit excessive rotation of the tibia [21, 23]. Using an optoelectronic system, Andriacchi et al. [5] and Georgoulis et al. [13] found increased tibial rotation in ACL-deficient patients during a low demanding activity such as walking. However, ACL reconstruction partially restored this increased tibial rotation during walking [13].

These results were challenged in vitro [28]. In that study the effectiveness of ACL reconstruction to resist anterior and rotational loads was evaluated using a robotic/universal forcemoment sensor testing system. The robot applied an internal-external tibial torque of 10 Nm, and it was reported that the current reconstruction procedures using single (bone–patellar tendon–bone) or multiple (semitendinosus and gracilis tendon) grafts are successful in limiting the anterior tibial translation, but they fail to restore tibial rotation. Similar results were presented by Brandsson et al. [4] in an in vivo evaluation of tibial rotation during an ascending activity in patients before and after ACL reconstruction.

Therefore it is possible that ACL reconstruction may not completely restore functional dynamic knee stability regarding tibial rotation [5]. To further elucidate this problem we investigated functional dynamic knee stability in vivo during a high demanding activity, a combined descending and pivoting movement. This activity places a high rotational load at the knee joint. Based on the results reported by Woo et al. [28] we hypothesized that tibial rotation during this high stress activity is greater in the ACL reconstructed knee than the contralateral intact knee.

Materials and methods

Subjects

Two groups were included in this study. Were evaluated 20 men with ACL reconstructed knees (mean age 28±5 years, mean weight 76±9 kg, mean height 1.77±0.08 m). Controls consisted of 15 healthy subjects matched for gender, age, height, and weight who had never suffered of any kind of orthopedic or neurological condition (mean age 28±4 years, mean weight 74±5 kg, mean height 1.74±0.04 m). The ACL-reconstructed subjects underwent arthroscopically assisted ACL reconstruction using autologous bone–patellar tendon–bone at an average of 10 months (range 2–24) after injury. These subjects were tested an average of 1 year after ACL reconstruction.

The surgical procedure was performed as follows. The femoral tunnel was drilled arthroscopically through the anteromedial approach, having the knee joint in 120° flexion. The tibial tunnel was performed in the center of the ACL footprint, avoiding the impingement in knee extension. The placement of the graft in the tunnel was with the cortical side of the bone plug, close to the over-the-top position. In the tibia we turned the graft for 90° so as to have the ligament in a more anatomical placement in the tibial tunnel.

In some instances meniscal damage had also been present at the time of injury. In all cases the level of involved meniscus damage was less than 25%. Individuals with more than 25% of meniscus damage, posterior cruciate or collateral ligament injury, symptomatic anterior knee pain, or objective instability at the latest follow-up examination (a positive pivot shift test result, positive Lachman test result and arthrometer side-to-side differences of more than 3 mm) were excluded from the study [18]. All patients underwent a standard rehabilitation protocol including early weight bearing and full range of motion training. Return to sports was permitted 24 weeks after reconstruction, provided that the patients had regained functional strength and stability. At the time of data collection no clinical evidence of knee pain was found in the ACL reconstructed subjects and all of them had resumed their daily living activities. All subjects' physicians were in agreement with the testing protocol and all subjects gave informed consent to participate in the study.

Clinical tests

Prior to any data collection a clinical evaluation was performed in all subjects. This evaluation was conducted for all subjects by the same clinician. Negative Lachman and pivot shift tests indicated that the knee joint stability was regained. During this evaluation, both

Tegner and Lysholm scores were obtained [25]. In addition, anterior tibial translation was evaluated using the KT-1000 knee arthrometer (MEDmetric, San Diego, Calif., USA) for both ACL reconstructed and healthy subjects [8, 24, 29]. The measurements were performed using 134 N posterior-anterior external force at the tibia, as well as maximum posterior-anterior external force until heel clearance. Repeated anterior tractions were performed until a constant reading on the dial was recorded.

Instrumentation-procedure

A six-camera optoelectronic system (Peak Performance Technologies, Englewood, Colo., USA) sampling at 50 Hz was used to capture the movements of 15 reflective markers placed on the selected bony landmarks of the lower limbs and the pelvis using the model described by Davis et al. [9]. All subjects were given enough time (10 min) to warm up and familiarize themselves with walking and ascending-descending on a stairway that included three consecutive steps. The stairway was constructed according to guidelines provided by Andriacchi et al. [2].

The subjects were asked to descent the three steps with their own pace. The descending period was concluded upon initial foot contact with the ground. Following foot contact, the subjects were instructed to pivot (externally rotate) on the landing (ipsilateral) leg at 90° and walk away from the stairway. While pivoting, the contralateral leg was swinging around the body (as it was coming down from the stairway) and the trunk was oriented perpendicularly to the stairway. None of the subjects reported any pain or discomfort during the experiment.

The subjects then continued to walk for at least five consecutive strides. The pivoting period was identified from initial foot contact with the ground of the ipsilateral leg, until touchdown of the contralateral leg. Each subject performed at least three trials for both legs. Data collection was initiated at the top of the stairway and included the descending period, the subsequent pivoting, and the five walking strides. To further validate our procedures and minimize errors reported in the literature [6, 20, 22] regarding video capture of external skin markers, an additional trial was recorded with the subject in the anatomical position, which was used as the reference for the calculation of the anatomical angles. The subjects were instructed to stand in the anatomical position within a purpose-build mold with their feet parallel and 15 cm apart. This calibration procedure allowed for correction of subtle misalignment of the markers that define the local coordinate sys- tem. In addition, it provided with a definition of 0° for all segmental movements in all planes.

Data analysis and reduction

Marker identification and angular displacement calculations were conducted using the Peak Performance software (Motus 5; Peak Performance) and Matlab (Mathworks, Natick, Mass., USA). Spot checking calibration assessment revealed a maximum three-dimensional standard deviation error in marker reconstruction of mm. All data were smoothed using the cross-validated quintic spline [27]. Anthropometric measurements were combined with three-dimensional marker data from the anatomical position trial to provide positions of the joint centers and define anatomical axes of joint rotations [9]. The position of the reflective markers during the movement provided the three-dimensional segmental angles.

Statistical analysis

Based on our hypothesis, the dependent variable examined in the present study was the maximum range of motion of tibial rotation during the pivoting period. A paired *t* test revealed no significant differences between the left and right sides within the control group ($P<0.05$) for this variable, and thus the right side was selected as the representative for the control group. Subsequently an independent *t* test used to examine differences between the control knee (right side) and the intact knee of the ACL reconstructed group. Finally, a paired *t* test used to examine differences between the reconstructed leg and the contralateral intact leg within the ACL group. The level of significance was set at $\alpha=0.05$.

Results

The clinical evaluation of the ACL reconstructed subjects indicated that the anterior-posterior translation of the tibia was restored. All 20 subjects in the ACL-reconstructed group were satisfied with the outcome of surgery. Of the 20 individuals 18 resumed their preinjury level of sports participation, one described mild limitations, and one had not resumed sports for reasons not associated with the knee functional ability.

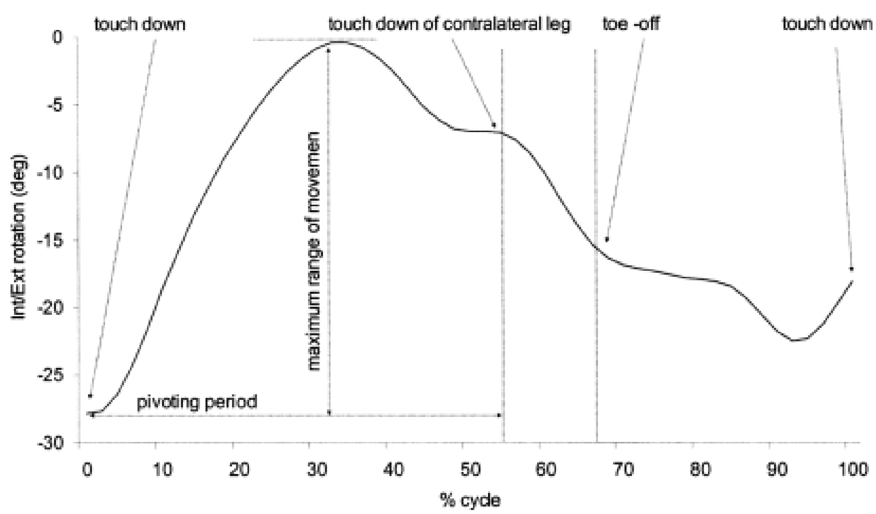

Fig. 1 A typical tibial internal/external rotation curve during the period under study for a full "stride" from one representative subject. Time 0% corresponds to the initial foot contact (*touchdown*) with the ground of the ipsilateral leg and 100% corresponds to the subsequent touchdown of the same leg. The difference between the maximum and the minimum tibial rotation during the pivoting period is indicated. This difference was used as the dependent variable in this study. The pivoting period is also identified

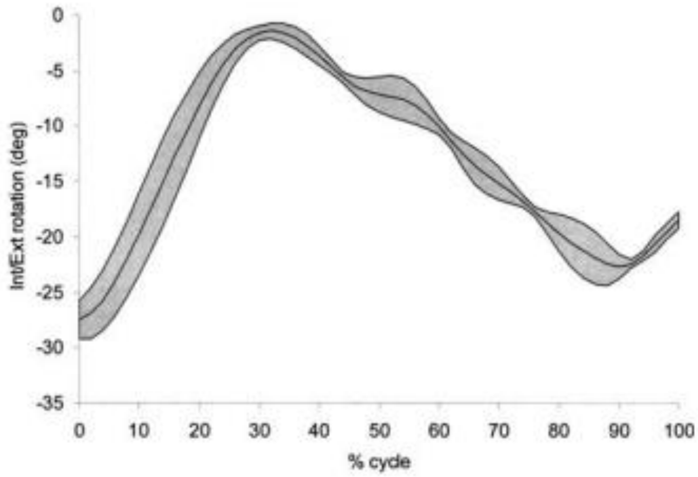

Fig. 2 Typical mean ±1 SD of tibial rotation for one representative subject during the time period under study

Three of the subjects reported occasional activity-related swelling especially after prolonged exercise. In addition, for the ACL reconstructed subjects, the mean Lysholm score was 88 (range 80–97) and the Tegner score was 8 (range 5–9) after surgery. For the healthy controls the mean Lysholm score was 95 (range 92–98) and the Tegner score was 8 (range 7–9). All subjects regained objective stability, with negative Lachman and pivot shift test results. The KT-1000 arthrometer knee testing was performed in both groups and revealed side-to-side differences of 3 mm or less. The mean difference between the anterior tibial translation of the injured and noninjured sides was 1.6 mm (range 1–3) on the 134 N test and 1.5 mm (range 1–2) on the maximum manual test.

Figure 1 demonstrates a typical curve of the tibial internal-external rotation during the pivoting period from one representative subject. The calculated range of movement that was used as the dependent variable is also identified, along with time events for both the ipsilateral and the contralateral legs. The intrasubject variability was in acceptable levels for all subjects with a maximum standard deviation throughout the movement being less than 4° (Fig. 2).

Group means and standard deviations for all legs examined are presented in Table 1. However, there were two ACL reconstructed subjects with approximately 7° of tibial rotation. In comparison with the overall mean, the data from these two subjects were considered as possible outliers. We therefore recalculated our results without these two subjects, and the new means are presented in Table 2. This recalculation did not affect the statistical results, but decreased the standard deviations by several degrees, giving us more representative and cohesive group values. The statistical power of the study was also calculated and was found to be 0.78.

Table 1 Group means and SD values for maximum range of motion of the tibial internal-external rotation during the pivoting period. Asterisks (*) indicate a significant difference within the ACL reconstructed group ($P<0.03$)

	Mean ±SD
ACL-reconstructed group (*n*=20)	
Reconstructed side	21.68±5.7*
Intact side	18.63±5.6*
Control group (*n*=20)	
Left side	19.01±6.7
Right side	19.14±6.8

Table 2 Group means and SD values for maximum range of motion of the tibial internal-external rotation during the pivoting period for 18 subjects (after removing the two outliers). Asterisks (*) indicate a significant difference within the ACL reconstructed group ($P<0.01$)

	Mean ±SD
ACL reconstructed group	
Reconstructed side	22.60±2.85*
Intact side	18.97±4.31*

No significant differences were found between the healthy leg of the control group and the intact leg of the ACL reconstructed group. However, within the ACL reconstructed group, there was a significant difference (*P*=0.01) between the reconstructed leg and the contralateral intact leg.

Discussion

The present study investigated in vivo functional dynamic knee stability in ACL reconstructed patients during a high demanding activity. In this activity a rotational load was applied at the knee joint through a combined descending and pivoting movement. We hypothesized that tibial rotation during this activity would be greater in the ACL reconstructed knee than in the contralateral intact leg.

Our results showed that the group mean value for tibial rotation for the intact knee of the ACL group was similar to those recorded for both legs of the control group (Table 1). This result was expected since these knees did not present any structural alterations. Furthermore, our results indicated greater tibial rotation in the ACL reconstructed leg than in the intact leg (*P*=0.01) of the ACL group. This result supported our hypothesis. Therefore tibial rotation remained a problem 1 year after ACL reconstruction during pivoting activities.

This finding provides support to other studies [4, 5, 13, 19, 28], which have indicated that ACL reconstruction does not fully restore ACL function. Andriacchi et al. [5] dynamically assessed the functional outcome of patients who had undergone ACL reconstruction using an autologous patellar tendon technique. They found that successfully ACL reconstructed patients displayed virtually no abnormality during low demanding activities, but noted that with higher demanding activities such as pivoting or jogging persistent gait adaptations were present. In addition, a previous study from our laboratory [13] also suggested that tibial rotation in ACL reconstructed patients is similar to normative values during walking. This demonstrates that current ACL reconstruction procedures improve tibial rotation in low demanding rotational activities, but fail to stabilize the knee rotationally when higher loads are applied. Another in vivo study by Brandsson et al. [4] using radiostereometry also reported that tibial rotation did not differ significantly before and after ACL reconstruction. However, that study was limited by the very low sampling frequency of the radiostereometric (2–4 Hz) equipment and the movement examined took place in the sagittal plane (ascending stairs) without involving any axial tibial rotation. This conclusion is supported by other studies [19, 28] which show that ACL reconstruction does not fully restore tibial rotation. Specifically, in vitro research [16, 19] indicates that tibial translation is restored after ACL reconstruction, but that tibial rotation is not improved. A possible explanation for these findings is that current practice of ACL reconstruction places the graft in the central part of the tibia and the femur, resulting in inadequate resistive ability to rotational forces [16].

In the present study radiographic assessment of the examined ACL reconstructed knees indicated a femoral tunnel placement between 10 and 11 o'clock position. Recent laboratory studies [16, 19] suggested that a more horizontal graft placement, close to the 10 o'clock position, which is anatomically closer to the femoral insertion of the posterolateral bundle, improves the rotatory stability of the reconstructed knee. Unfortunately, however, this surgical method does not seem to completely restore tibial rotation [19]. The most possible explanation for this is that ACL reconstruction does not reestablish the anatomy of the ACL. Unlike patellar tendon that has a more uniform anatomy, ACL consists of two major bundles that exhibit different patterns during knee motion. The posterolateral bundle seems to play a major role with the knee near extension, while the forces in the anteromedial bundle are relatively constant throughout flexion-extension. Such anatomical complexity of the ACL has not been reproduced by current ACL reconstruction procedures. A two-bundle graft is now been used to simulate better the morphology of the original ACL [14], but this technique has not been investigated extensively.

Currently the success level of an ACL reconstruction is clinically assessed via static measurements of anterior tibial translation [8, 15], and questionnaires of patient functional mobility and satisfaction [5]. Orthopedic surgeons have used these standard static measures of anterior/posterior tibial translation to evaluate knee stability. However, these measures do not necessarily suggest that knee joint function is fully restored [10, 17]. Furthermore, such measures do not provide with information of the level of dynamic rotational control achieved after an ACL reconstruction. In the present study we attempted to objectify the assessment of functional knee rotational stability and subsequently the success level of ACL reconstructions. In addition, we emphasized the need for the development of an objective system to assess tibial rotation after surgery and to improve clinical practice and evaluation.

A limitation of the present study involves the known drawbacks of gait analysis, and especially the movement of skin markers and their ability to predict bone movements. Particularly for transverse plane measurements, small errors derived from skin movement and three-dimensional reconstruction reflect in relatively high deviations on joint angles [6, 22]. However, in the present study we tried to minimize such errors by doing the following. We minimized the interoperator error by having the same clinician placing all the markers and performing all the anthropometric measurements. In addition, the absolute three-dimensional marker reconstruction error of the system was very low (maximum SD 0.303 mm, calibration space approximately 8 m^3). We also incorporated a standing calibration procedure to correct for subtle misalignment of the markers that define the local coordinate system and to provide with a definition of 0° for all segmental movements in all planes. Furthermore, to further validate the differences observed in our study we incorporated a “double” control group since we used as controls both the intact leg of the ACL reconstructed group and a completely healthy group of subjects. Lastly, the tibial rotational values reported in our study (Tables 1, 2) are in close agreement with those of Loh et al. [19]. In that study a rotational load was applied on ACL reconstructed cadaveric knees, and tibial rotation was reported to be 16.7± 9.9° and 22.8±12.6° when the knee was placed at 15° and 30° flexion angles, respectively. With intact cadaveric knees, they found these values to be 16.1±8.3° and 20.6±11.1°. Nevertheless, our results should be viewed in light of the general gait analysis limitations [6, 22]. However, gait analysis is currently considered as a well-established method and it is widely accepted [1, 7, 12].

In conclusion, ACL reconstruction does not fully restore functional dynamic stability of the knee in terms of internal-external rotation of the tibia even if tibial translation is restored. To improve clinical practice it is important to develop an objective measure to assess functional dynamic stability of the knee after surgery, especially in regard to tibial rotation. Moreover, the improvement and the development of new surgical procedures and/or grafts should also contribute in restoring tibial rotation.

Acknowledgements The authors gratefully acknowledge the funding support from the Greek Ministry of Sports.

References

1. Andriacchi T, Birac D (1993) Functional testing in the anterior cruciate ligament-deficient knee. Clin Orthop 228:40–47

2. Andriacchi TP, Andersson GBJ, Fermier RW et al (1980) A study of lower-limb mechanics during stair-climbing. J Bone Joint Surg Am 62: 749–757

3. Bach BRJ, Tradonsky S, Bojchuk J et al (1998) Arthroscopically assisted anterior cruciate ligament reconstruction using patellar tendon autograft. Five- to nine-year follow-up evaluation. Am J Sports Med 26:20–29

4. Brandsson S, Karlsson J, Sward L et al (2002) Kinematics and laxity of the knee joint after anterior cruciate ligament reconstruction. Pre- and postoperative radiostereometric studies. Am J Sports Med 30:361–367

5. Bush-Joseph CA, Hurwitz DE, Patel RR et al (2001) Dynamic function after anterior cruciate ligament reconstruction with autologous patellar tendon. Am J Sports Med 29:36–41

6. Cappozzo A, Catani F, Leardini A et al (1996) Position and orientation in space of bones during movement: experimental artefacts. Clin Biomech 11:90–100

7. Chambers H, Sutherland D (2002) A practical guide to gait analysis. J Am Acad Orthop Surg 10:222–231

8. Daniel DM, Malcom LL, Losse G et al (1985) Instrumented measurement of anterior laxity of the knee. J Bone Joint Surg Am 67:720–726 Davis R, Ounpuu S, Tyburski D et al (1991) A gait analysis data collection and reduction technique. Hum Movement Sci 10:575–587

9. Devita P, Hortobagyi T, Barrier J (1998) Gait biomechanics are not normal after anterior cruciate ligament reconstruction and accelerated rehabilitation. Med Sci Sports Exerc 30:1481–1488

10. Fox JM, Sherman OH, Markolf K (1985) Arthroscopic anterior cruciate ligament repair: preliminary results and instrumented testing for anterior stability. Arthroscopy 1:175–181

11. Gage J (1993) Gait analysis. An essential tool in the treatment of cerebral palsy. Clin Orthop 228:126–134

12. Georgoulis AD, Papadonikolakis A, Papageorgiou CD et al (2003) Three-dimensional tibiofemoral kinematics of the anterior cruciate deficient and reconstructed knee during walking. Am J Sports Med 31:75–79

13. Hara K, Kubo T, Suginoshita T et al (2000) Reconstruction of the anterior cruciate ligament using a double bundle. Arthroscopy 16:860–864

14. Jonsson H, Karrholm J, Elmqvist LG (1993) Laxity after cruciate ligament injury in 94 knees. The KT-1000 arthrometer versus roentgen stereophotogrammetry. Acta Orthop Scand 64: 567–570

15. Kanamori A, Zeminski J, Rudi TW et al (2002) The effect of axial tibial torque on the function of the anterior cruciate ligament: a biomechanical study of a simulated pivot shift test. Arthroscopy 18:394–398

16. Kowalk DL, Duncan JA, McCue FC et al (1997) Anterior cruciate ligament reconstruction and joint dynamics during stair climbing. Med Sci Sports Exerc 29:1406–1413

17. Levy IM, Torzilli PA, Warren RF (1982) The effect of medial meniscectomy on anterior-posterior motion of the knee. J Bone Joint Surg Am 64: 883–888

18. Loh J, Fukuda Y, Tsuda E et al (2003) Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. Arthroscopy 19:297– 304

19. Lucchetti L, Cappozzo A, Cappello A et al (1998) Skin movement artefact assessment and compensation in the estimation of knee-joint kinematics. J Biomech 31:977–984

20. Markolf KL, Bargar WL, Shoemaker SC et al (1981) The role of joint load in knee stability. J Bone Joint Surg Am 63:570–585

21. Reinschmidt C, Bogert Avd, Nigg B et al (1997) Effect of skin movement on the analysis of skeletal knee joint motion during running. J Biomech 30: 729–732

22. Sakane M, Fox RJ, Woo SL et al (1997) In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 15: 285–293

23. Steiner M, Brown C, Zarins B et al (1990) Measurement of anterior-posterior displacement of the knee. A comparison of the results with instrumented devices and with clinical examination. J Bone Joint Surg Am 72: 1307–1315

24. Tegner Y, Lysholm J (1985) Rating systems in the evaluation of knee ligament injuries. Clin Orthop 198:43–49

25. Vergis A, Gillquist J (1998) Sagittal plane translation of the knee during stair walking. Comparison of healthy and anterior cruciate ligament-deficient subjects. Am J Sports Med 26:841–846

26. Woltring HJ (1986) A Fortran package for generalised, cross-validatory spline smoothing and differentiation. Adv Eng Software 8:104–107

27. Woo SL, Kanamori A, Zeminski J et al (2002) The effectiveness of anterior cruciate ligament reconstruction by hamstrings and patellar tendon: a cadaveric study comparing anterior tibial load vs rotational loads. J Bone Joint Surg Am 84:907–914

28. Wroble R, Ginkel LV, Grood E et al (1990) Repeatability of the KT-1000 arthrometer in a normal population. Am J Sports Med 18:396–399