The relation between static and dynamic knee stability after acl reconstruction

Hiroshi HIGUCHI, Masanori TERAUCHI, Masashi KIMURA, Atsushi KOBAYASHI, Mitsuhiro TAKEDA, Hideomi WATANABE, Kenji TAKAGISHI

The purpose of this prospective study was to quantify and compare the amount of anterior tibial translation (ATT) occurring in ACL-reconstructed knees during both a static passive Lachman test and an isokinetic knee extension exercise, pre- and postoperatively. Stress-radiography combined with an electrogoniometer system was applied to 49 knees before and after ACL reconstruction. The Lysholm score was calculated and subjective evaluation assessed before operation and at follow-up. Both measurement methods confirmed a significant decrease of ATT after surgery. Side-to-side differences in ATT were seen in the passive Lachman test postoperatively, and were not found during isokinetic extension from 90° to 0°. There was no significant correlation between static passive stability and the functional knee score at follow-up. In addition, the patients with a more than 3 mm side-to-side difference in the passive Lachman test after surgery, showed less than a 1 mm side-to-side difference during isokinetic exercise at a flexion angle of 20°. These results suggest that ACL reconstruction improves ATT in both tests, but the side-to-side difference is greater with the static Lachman test.

INTRODUCTION

It is generally accepted by orthopaedic surgeons that the purpose of anterior cruciate ligament (ACL) reconstruction is re-stabilisation of the knee (2, 3, 29). The joint laxity in ACL-deficient knees is commonly measured, using the static Lachman test with a knee arthrometer or stress radiography (5, 6, 8, 25, 26, 28). However, it remains unclear whether knee laxity, demonstrated by knee arthrometer or stress radiography, accurately reflects anterior tibial translation (ATT) during dynamic knee motion. Several reports have recently studied the characteristics of ATT under dynamic conditions in ACL-deficient knees (9, 15, 18, 21, 32, 34). However, to our knowledge there is little information on the effect of ACL reconstruction on ATT. Moreover nobody has compared joint laxity after ACL reconstruction, using the static Lachman test with the laxity during dynamic knee motion.

Because an *in vivo* strain gauge study of the ACL (12, 35) demonstrated that tension is significantly

From the Department of Orthopaedic Surgery of Gunma University Faculty of Medicine, Gunma, Japan and the Gunma Sports Medicine Research Center, Gunma, Japan

[1] Department of Orthopaedic Surgery, Gunma University Faculty of Medicine, 3-39-22 Showa-machi, Maebashi-shi, Gunma-ken 371-8511 Japan

Hiroshi Higuchi, Assistant Professor

Masanori Terauchi, Consultant Orthopaedic Surgeon

Atsushi Kobayashi, Clinical Fellow

Mitsuhiro Takeda, MD, Research Fellow

Hideomi Watanabe, Associate Professor

Kenji Takagishi, Professor and Chairman

[2] Gunma Sports Medicine Research Center, Zenshukai Hospital, 1381 Ninomiya-machi, Maebashi-shi, Gunma-ken, 379-2117 Japan

Masashi Kimura, Director.

Correspondence and reprints : Hiroshi Higuchi, Department of Orthopaedic Surgery, Gunma University Faculty of Medicine, 3-39-22 Showa-machi, Maebashi-shi, Gunma-ken 371-8511 Japan. E-mail : higuchih@med.gunma-u.ac.jp.

greater with open kinetic chain than with closed chain exercises, rehabilitation should proceed with care to avoid overstressing the reconstructed ACL during open kinetic knee motion (18, 21, 32, 34). A quantitative study of ATT with open kinetic knee motion, would be helpful to better understand the characteristics of joint laxity in both ACL-deficient and ACL-reconstructed knees.

The purpose of this prospective study was to quantify and analyse the amount of ATT occurring during both a static passive Lachman test and an isokinetic knee extension exercise, before and after ACL reconstruction. It also aimed at determining the relation between static and isokinetic anterior tibial displacement, and between anterior knee laxity in the passive Lachman test and subjective knee function after surgery.

MATERIALS AND METHODS

Subjects

Forty-nine patients (21 men and 28 women) with unilateral isolated ACL-deficient knees were assigned and enrolled for this prospective study. The average age at the time of the surgery was 24.2 years, ranging from 16 to 42 years. The time from injury to operation ranged between 1 and 40 months. No patients had previously undergone ligament surgery or suffered any trouble in either limb except the ACL tear. The same surgeon performed all operations, during the years 1998 and 1999, using a one- incision arthroscopic technique. The ACL was reconstructed with a 10-mm wide, autologous central bone-ligament-bone patellar tendon strip following previously described techniques for tunnel placement and isometry (1, 2, 11). After intercondylar notch plasty, the strip was fixed at both ends with canulated interference screws (Linvatec, Florida, USA). Thirteen patients required meniscal surgery (11 partial meniscectomies ; 2 meniscal sutures). After surgery, progressive weight bearing was allowed as tolerated, if meniscal repair was not performed. Full range of motion was permitted at 4 weeks, but a protective routine knee brace was used until 8 weeks after surgery. Further rehabilitation consisted of isokinetic strength training, bicycling and balance training. The patients were gradually allowed full activities after 6 months postoperatively, if the knees met these conditions : 1) no swelling of the operated knee ; 2) acceptable knee function acquired ; 3) 80% of their normal knee strength. After return to sports, follow-up examinations were performed between 20 and 28 months (mean 24 months) after surgery.

Subjective knee function

Subjective assessment was quantified using the Lysholm score (19) before operation and at follow-up. The patients were asked to respond with a simple "yes" or "no" if they would have the procedure done on the opposite knee, in a similar circumstance.

Measurement of static passive stability

Before surgery and at follow-up, stress radiographs of both knees were taken using a Telos device (Telos, Medizinisch-Technische GmbH, D-6103 Griesheim, Germany) (8, 25, 28), equipped with a screw-threaded shaft that permits stress to be applied gradually. The pressure was monitored on a light-emitting-diode with digital read-out. With the patients lying on the side to be tested and the knee flexed to 20°, an anterior displacing force of 15kg (147 N) was gradually applied to the tibia, and standard radiographs were taken after that force had been applied for one minute. The patients were instructed to relax the leg muscles. Fluoroscopy was used to check the exact lateral position of the knee. For comparison, the same measurements were taken on the unaffected knee of each patient. ATT was calculated by measuring the displacement of the midpoint between the tangents to the posterior contours of the tibial condyles, drawn perpendicular to the tibial plateau and relative to the position of the corresponding midpoint between the posterior aspects of the femoral condyles (25). The measurements were made by an independent radiologist, the mean value being used for statistical assessment.

Execution of the isokinetic concentric contraction exercise

The Biodex exercise dynamometer system (Biodex Medical System Inc., Shirley, NY, USA) was employed for isokinetic concentric contraction exercises. The patients were instructed on the use of the isokinetic machine and allowed to become fully acquainted with the device before testing. First they performed a 5-minutes warm-up on a stationary bicycle. Each patient was seated in the Biodex dynamometer and positioned to align the flexion-extension axis of the knee with the rotational axis of the leg attachment. The patient was then strapped in the seat and the resistance pad on the

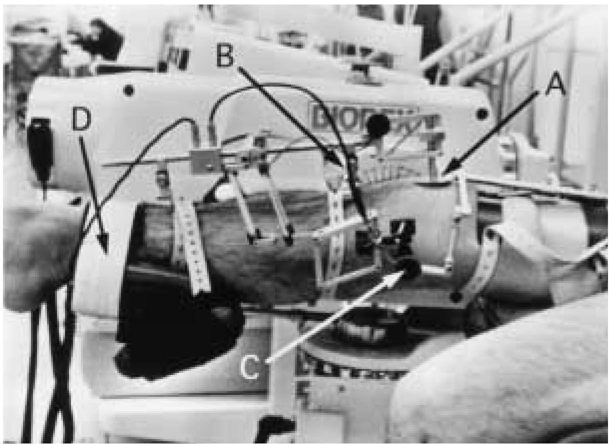

Fig 1. — The electrogoniometer system (CA-4000) fitted to a lower limb of a patient sitting on a Biodex seat. The removal arm is padded on the patella (A) and the tibial tuberosity (B). Potentiometer C is used to measure the knee joint angle and is aligned with the knee joint center. The resistance pad (D) of the Biodex is placed on the tibia just above the ankle joint.

lower leg was fixed just above the ankle joint. This distal pad position was selected because the applied loads provoke higher joint forces and displacement, than with a more proximal application at similar muscle torques (21, 22). Patients were tested at a velocity of 30°/sec along a 90° motion range, knowing that the largest tibial sagittal translation in isokinetic exercises was noted at a speed of 30°/sec with various velocities (21). After several submaximal cycles, the subjects were asked to perform three times at maximum thigh action.

Measurement of the anterior tibial translation with exercise

To measure ATT before surgery and at follow-up, a computerised goniometer linkage (CA-4000, OSI, CA, USA) was fixed to the knee with broad elastic bands (fig 1). The reproducibility of this system has been reported earlier (20, 24, 31) and it has been employed by many authors to investigate the characteristics of knee motion (9, 13, 15-17, 18, 21, 32). It is composed of femoral and tibial frames and three goniometers in a rotation module to measure the relative rotation between the femur and the tibia. The potentiometer for sagittal motion mounted in the tibial frame registers the difference in position between a spring-loaded patellar pad and the fixation point of the tibial tuberosity during knee motion. The sagittal plane direction is perpendicular to the tibial frame. The linear accuracy of the sagittal parallelogram linkage was 0.1 mm and the angular accuracy for the potentiometers was 0.125°. The application of the CA-4000 followed the manufacturer's instructions. The system was zeroed with the subject lying relaxed at full knee extension and neutral knee rotation. Following previous reports (9, 20, 21, 32), the alignment of the potentiometers was checked repeatedly and carefully in the zeroing screen of the computer during exercise. The protocol was repeated with fresh zeroing if values were different from the original. In this study, only the sagittal plane translation (mm) and the change in flexion angles (degrees) were studied during the two different measurements (isokinetic and passive motion) assisted by the Biodex machine. For comparison the same procedure was repeated on the unaffected side.

Analysis of electrogoniometric data

The CA-4000 system recorded two vertically oriented curves throughout the range of motion in each exercise. A graphical display of sagittal plane translation during a test cycle of the two different exercises was used. During a passive knee motion cycle, the curve representing tibial sagittal translation from 90° to 0° demonstrated a gradually increasing posterior translation with increasing extension, both during the extension as the flexion phase. During isokinetic motion, in contrast, an obvious difference in tibial sagittal translation was apparent between the extension and the flexion phase from 90° to 0°. It is generally considered that the slope of this line in exercise represents the relative motion between the measuring arm and the patella during the range of motion (9, 18, 20, 21, 34). In the present study, ATT was measured in terms of the difference with isokinetic exercise compared to the value for passive extension motion, as previously described (fig 2) (15, 18). From 90° to 0° of knee flexion in the extension phase, differences in anterior sagittal displacement between passive and isokinetic motion were measured at every 10 degrees position with the help of a computer (IBM PC/AT compatible EVEREX computer, California, USA) equipped for the CA-4000. Data from the second cycle of each test were used for calculation, as in previous reports (18, 20, 21, 34).

Statistics

Commercially available software (Statistica, Stat Soft, Tulsa OK, USA) was used. To compare the same test in the same patient between the normal and the injured knee, the Student's t- test was employed with the

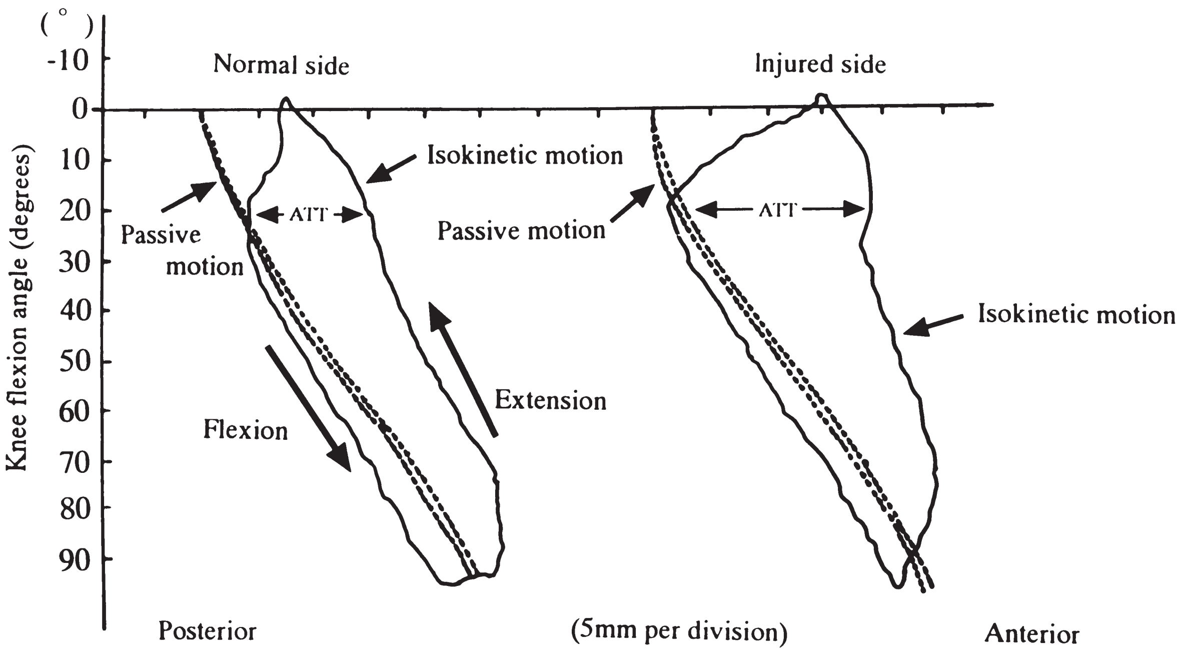

Fig 2. — Typical graphical display (CA-4000 system) of sagittal plane knee translation during passive and isokinetic test cycles. ATT, in terms of the difference with isokinetic extension exercise compared to the value for passive extension motion with the Biodex system, was measured at every 10 degrees position with the help of a computer. ATT, anterior tibial translation. *X*-axis, sagittal plane translation ; *Y*-axis, knee flexion angle.

significance level set at $p < 0.05$. The coefficients of variation were calculated from the actual tests, and correlation analysis was also performed, with significance level of 1%.

RESULTS

Subjective knee functional score

The subjective knee functional score improved from 59 ± 12 before surgery to 89 ± 9 points ($p < 0.001$). No difference in functional score was apparent for gender or age.

Static passive laxity

The mean ATT of the control knees was 2.1 ± 1.5 mm with the static passive Lachman test. In operated knees it improved from 11.9 ± 3.3 mm preoperatively to 4.9 ± 2.4 mm at follow-up ($p < 0.001$), the mean ATT difference dropping from +9.4 ± 2.7 mm to +2.8 ± 1.8 mm ($p < 0.001$). Seven patients (14%) had side-to-side differences of 0 mm or less, 20 patients (41%) had differences between 0,1 mm and 3 mm, 21 patients (43%) had differences between 3,1 mm and 6 mm, and one patient had a difference of more than 6 mm at follow-up.

Postoperative relation between subjective knee score and static laxity

There was no significant correlation between static passive laxity and functional knee score at follow-up (fig 3). In the 27 patients who had 3 mm or less ATT difference apparent on stress-radiography postoperatively, the mean Lysholm score was 89 ± 10 at follow-up. In the other 22 patients, who had more than 3 mm ATT difference postoperatively, the mean functional score was 90 ± 9. However, the one patient who demonstrated a greater than 6 mm ATT difference postoperatively, had a poor knee score (75 points) because of instability and pain on exercise.

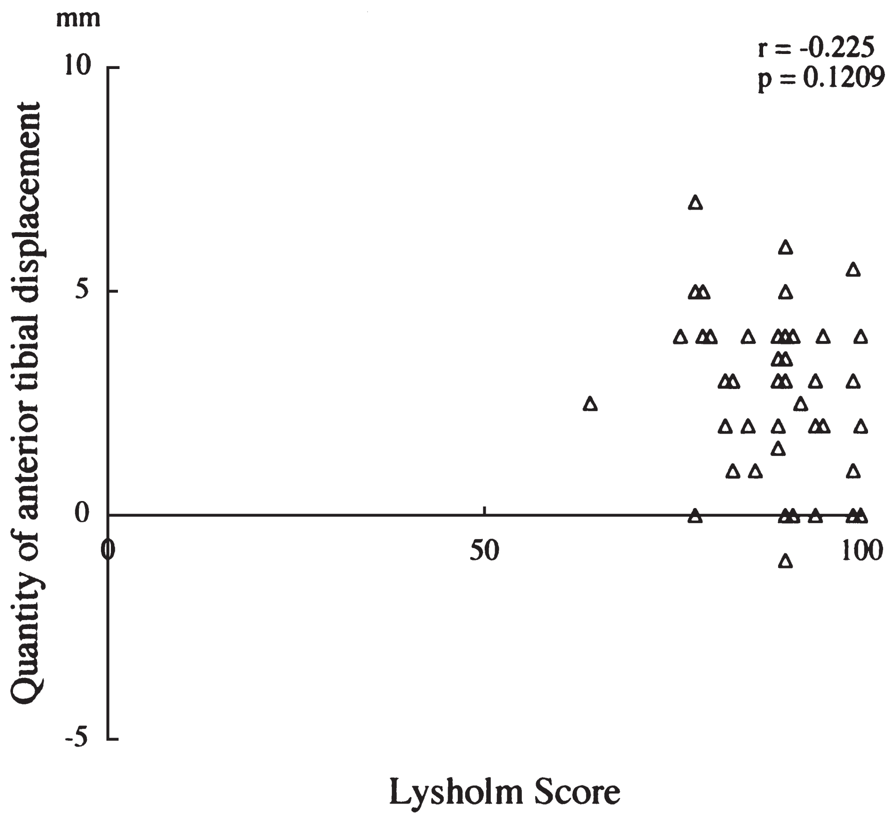

Fig 3. — Postoperative correlation (r = -0.225, p = 0.1209) between the passive Lachman test value and the Lysholm score for all patients.

Laxity in isokinetic exercise

For both normal and ACL-deficient knees before surgery, the ATT reached a maximum at a flexion angle of 20° for isokinetic extension exercise. The mean maximum ATT for normal and ACL-deficient knees were 12.7 ± 2.8 mm and 15.8 ± 3.1 mm, respectively. Within a range of flexion between 0° and 60°, the mean preoperative ATT of ACL-deficient knees was considerably greater than on the normal side ($p < 0.05$). At a flexion angle of 20°, the mean maximum preoperative ATT difference was 3.1 ± 2.3 mm (fig 4). In contrast, the mean maximum ATT for operated knees was 13.1 ± 2.5 mm at a flexion angle of 20° during isokinetic exercise and no ATT difference was seen during concentric extension from 90° to 0° in the isokinetic exercise. The curve for ATT of operated knees displayed almost the same pattern as control knees (fig 5).

Postoperative relation between static laxity and the anterior tibial translation in isokinetic exercise

Static and dynamic laxity correlated during the extension phase from 40° to 0° postoperatively, but not with flexion angles of 40° (table I).

Patients were grouped according to the results of the static passive Lachman test at follow-up : Group A, 27 patients, with 3 mm or less ATT difference at stress-radiography ; Group B, 22 patients, with more than 3 mm difference. In Group A, the mean ATT of operated knees was constantly less than in normal knees during isokinetic exercise from 90° to 0°, and the maximum side-to-side difference was -1.1 ± 2.3 mm at a flexion angle of 10°. On the other hand, the isokinetic ATT of operated knees was greater than for the normal knees within a range of flexion between 0° and 30° in Group B. The mean maximum side-to-side difference was

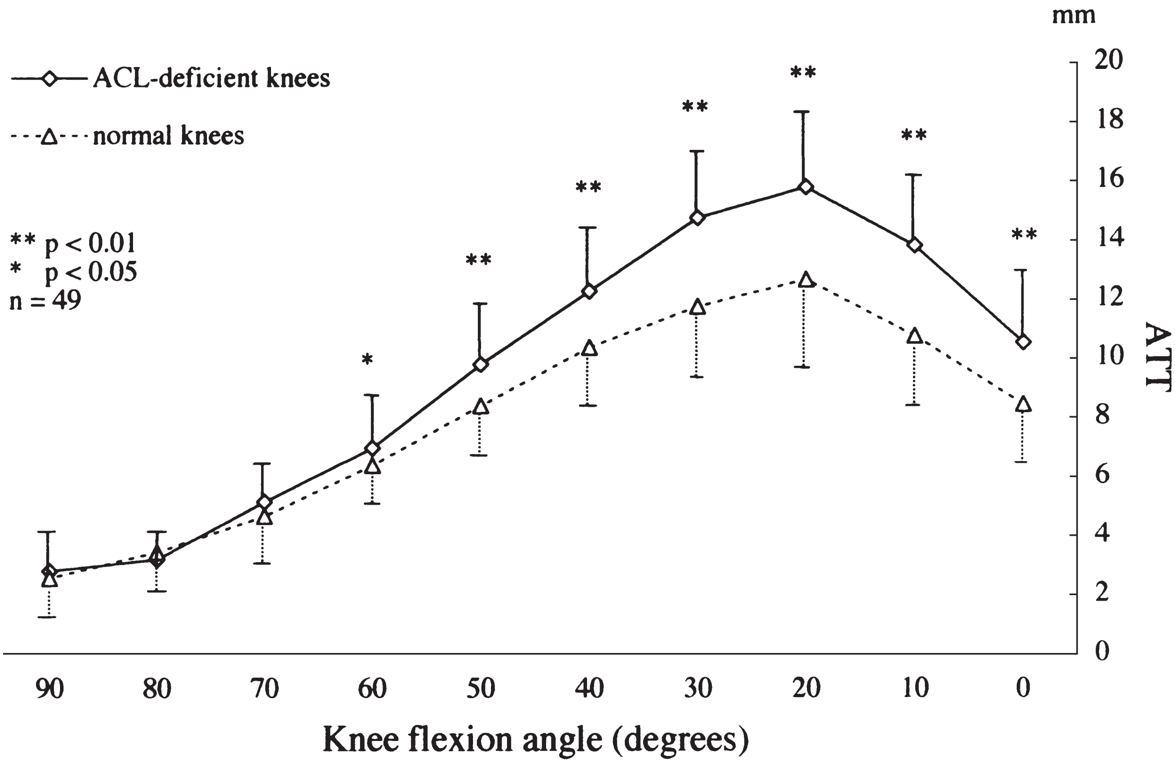

Fig 4. — Comparison of the anterior tibial translation between the ACL-deficient and the normal knees for isokinetic extension exercise. A significant difference was seen within a range of flexion between 0° and 60° preoperatively, with a maximum of 3.1 ± 2.3 mm at a flexion angle of 20°. ATT, anterior tibial translation, measured as described in fig 2.

+0.9 ± 2.1 mm at a flexion angle of 20°. At a flexion angle of 40° as a turning point, the isokinetic ATT of operated knees was constantly less than for the normal side within a range of flexion 50° or more, as the side-to-side difference in Group A (fig 6).

DISCUSSION

Stress-radiography is more sensitive than clinical examination for diagnosing ACL deficiency (8, 25, 28). Sensitivity and specificity of stress radiography using a Telos device for diagnosis of anterior laxity of the knee have been reported (8, 25, 28) : in one study the sensitivity was less than 67% and specificity was 100% (8). Side-to-side ATT difference of up to 3 mm has been considered normal in the literature. We found a side-to-side difference of more than 3 mm in 22 of 49 patients. However, the Lysholm score of these patients was similar as in cases with 3 mm or less ATT. Thus, anterior tibial displacement measured in a standard static passive position, does not explain the differences between ACL-deficient and ACL-reconstructed knees.

Several studies evaluated ATT of ACL-deficient knees during open kinetic motion (9, 13, 15, 18, 20, 21, 34). Preoperative anterior laxity in open kinetic exercise was found between 0° and 60° of flexion, and diminished after ACL reconstruction (9, 15, 18) as in this study. One explanation for the phenomenon that postoperative side-to-side anterior tibial displacement differences were only observed during a static passive Lachman, is that the anterior shear force of the tibia differs from that during isokinetic exercise. One earlier study, however, indicated that this might not be the case (18). Moreover, isokinetic exercises with maximal quadriceps exertion have been found to produce high shear forces up to one-third of body weight (16). Even if postoperatively a certain extent of anterior

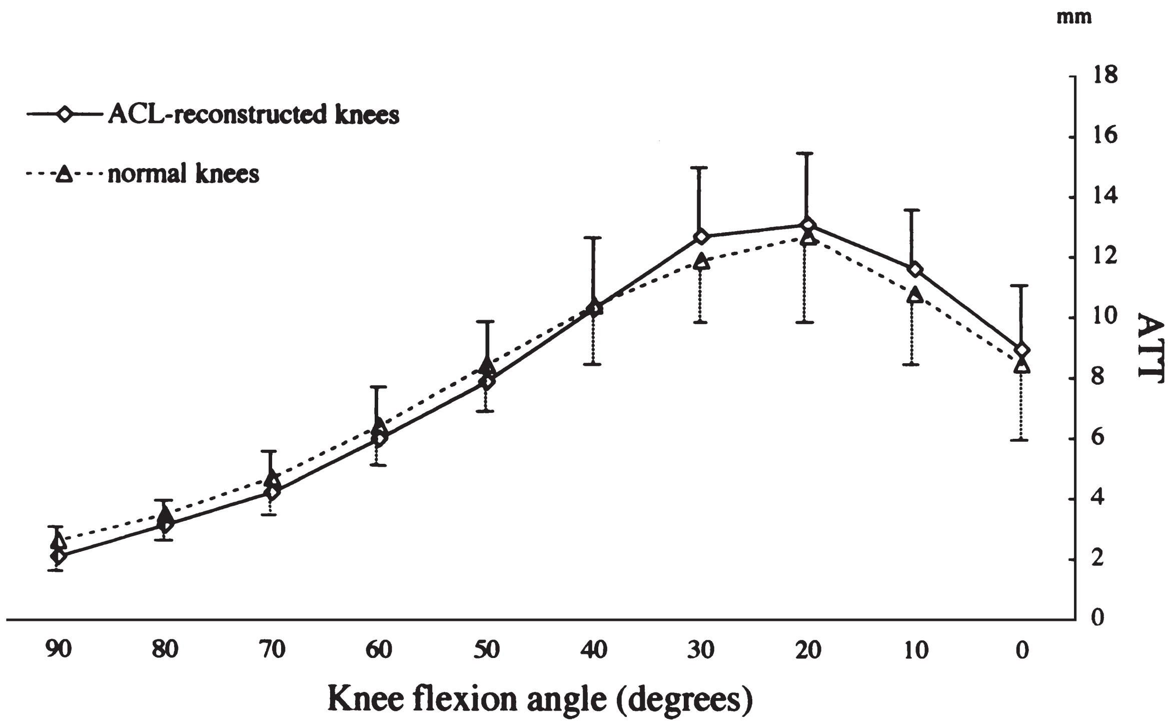

Fig 5. — Comparison of the anterior tibial translation between the ACL-reconstructed and the normal knees for isokinetic extension exercise at follow-up. No significant difference was seen with any testing flexion angles. ATT, anterior tibial translation, quantified as described in fig 2.

Table I. — Correlation concerning anterior tibial translation between stress radiography and isokinetic exercise

	Correlation coefficient	
Angle (degrees)	Before surgery	At follow-up
0	0.129	0.604*
10	0.075	0.616*
20	0.187	0.630*
30	0.218	0.661*
40	0.185	0.389*
50	0.041	0.311
60	-0.222	0.070
70	-0.318	-0.026
80	-0.282	-0.022
90	-0.251	-0.018

Angle means knee flexion angle with isokinetic exercise.
* $p < 0.01$.

laxity remained with the static passive Lachman test under conditions of low muscle activity, one would expect ATT to decrease in active knee motion due to the action of dynamic stabilisers as the hamstrings (13, 17). Indeed, even in our cases that showed more than 3 mm side-to-side difference in anterior tibial displacement in stress tests at follow-up, that difference was reduced to less than 1mm in an isokinetic exercise. This might explain why postoperative clinical knee function was good, in spite of anterior laxity on stress radiography.

The main purpose of ACL reconstruction is undoubtedly to restore restraints to anterior tibial displacement (2, 3, 29). Some reports have suggested that the recovery of some of the proprioceptive function of the normal ACL is as important as the mechanical reconstruction with surgery (4, 7, 10, 27). Noyes *et al* popularised the "rule of thirds" : one third of patients with untreated ACL tears would continue to participate in their desired sports at pre-injury level, possibly thanks to secondary static stabilisers and muscular compensatory mechanisms (22). The protective action of the hamstring musculature in the rehabilitation of the ACL injuries has been known and understood by

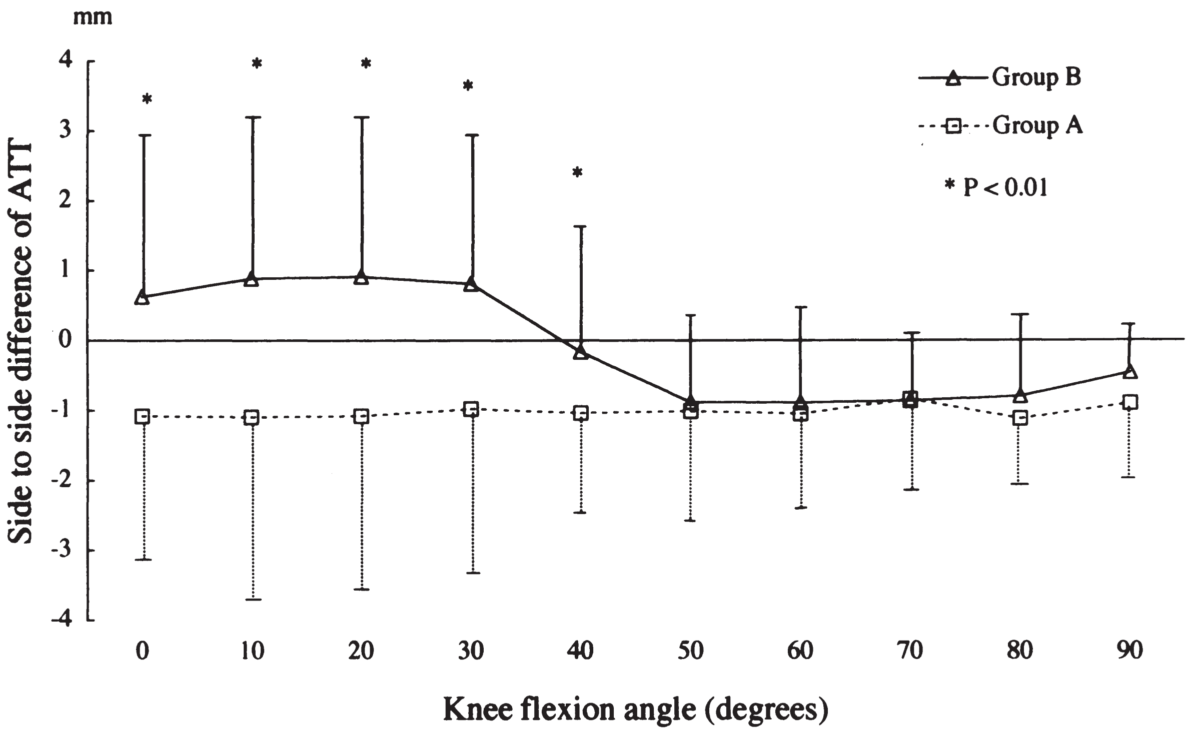

Fig 6. — Postoperative side-to-side difference of ATT according to the postoperative value on stress radiography. Groups A and B consisted of patients who had 3 mm or less and more than 3mm anterior tibial displacement difference, respectively. Postoperative side-to-side difference in ATT differed between the two groups within a range of flexion from 0° to 30°. ATT, anterior tibial translation, quantified as described in fig 2.

sports orthopaedists for many years (23, 30). With regard to the synergetic action between ACL and hamstrings, the existence of an ACL-hamstring reflex has been studied and it is generally thought to disappear in ACL-deficient knees (4, 10, 27). If the proprioceptive mechanoreceptors and the biomechanical stabilisers are restored by ACL reconstruction, the anterior knee laxity in dynamic motion would decrease in cooperation with hamstring forces even if some knee laxity were recognised in the static position. Solomonow *et al* (27) applied surface electrodes to the quadriceps and hamstrings of 12 patients who had ACL-deficient knees and recorded their muscle activity while performing isokinetic concentric exercise (15°/sec). The protective efforts of hamstrings against abnormal translation of the tibia, detected at approximately 42° from full extension, were recorded. They were thought to be a reflective attempt to counteract the dynamic anterior tibial subluxation occurring during explosive knee extension. The results of this study for 30°/second isokinetic concentric knee motion also showed that even in the patients who had more than 3 mm of anterior tibial displacement difference in passive Lachman tests postoperatively, the mean isokinetic anterior tibial displacement of the operated side was consistently less than for the normal side over flexion angles of 40°. Since electromyographic assessment of hamstrings was not performed, it was impossible to determine whether this phenomenon was caused by simultaneous hamstring activation. However, it is very interesting that the side-to-side differences in anterior tibial displacement with isokinetic exercise decreased at a certain flexion angle. Further studies are wanted to determine the role of biomechanical reconstruction and proprioceptive recovery in the restoration of function after ACL surgery.

CONCLUSION

The amount of ATT after ACL reconstruction was significantly improved as assessed by both a static passive Lachman test and an isokinetic knee extension exercise. Mean side-to-side differences in ATT were only seen in the passive Lachman test postoperatively, and were not found during isokinetic extension from 90° to 0°. There was no significant correlation between static passive stability and functional knee score at follow-up. These results suggest that the ACL reconstruction procedure improves ATT during the passive Lachman test and isokinetic knee motion, mean side-to-side differences being greater with the Lachman test. This could explain why clinical knee function was good postoperatively, even if some degree of anterior knee laxity persisted on stress radiography.

Acknowledgements

We thank the physical therapists of Social Insurance Gunma Chuo General Hospital for their technical assistance : Masafumi Miura, Noriko Kimura, Ena Sato, Tomoko Takai, and Atsuko Yamada. We also thank Atsushi Hasegawa, M.D., Department of Orthopaedic Surgery, Social Insurance Gunma Chuo General Hospital for his help in data correction. Dr. Malcolm Moore kindly reviewed this manuscript for the scientific English.

REFERENCES

1. **Bach BR Jr.** Arthroscopy-assisted patellar tendon substitution for anterior cruciate ligament insufficiency. *Am J Knee Surg* 1989 ; 2 : 3-20
2. **Bach BR Jr, Jones GT, Sweet FA, Hager CA.** Arthroscopy-assisted anterior cruciate ligament reconstruction using patellar tendon substitution. Two- to four-year follow-up results. *Am J Sports Med* 1994 ; 22 : 758-767
3. **Barber-Westin SD, Noyes FR.** The effect of rehabilitation and return to activity on anterior-posterior knee displacements after anterior cruciate ligament reconstruction. *Am J Sports Med* 1993 ; 21 : 264-270
4. **Biedert RM, Zwick EB.** Ligament-muscle reflex arc after anterior cruciate ligament reconstruction. Electromyographic evaluation. *Arch Orthop Trauma Surg* 1998 ; 118 : 81-84
5. **Daniel DM, Stone ML, Sachs R, Malcom L.** Instrumented measurement of anterior knee laxity in patients with acute anterior cruciate ligament disruption. *Am J Sports Med* 1985 ; 13 : 401-407
6. **Forster IW, Warren-Smith CD, Tew M.** Is the KT 1000 knee ligament arthrometer reliable ? *J Bone Joint Surg* 1989 ; 71-B : 843-847
7. **Friden T, Roberts D, Movin T, Wredmark T.** Function after anterior cruciate ligament injuries. Influence of visual control and proprioception. *Acta Orthop Scand* 1998 ; 69 : 590-594
8. **Garces GL, Perdomo E, Guerra A, Cabrera-Bonilla R.** Stress radiography in the diagnosis of anterior cruciate ligament deficiency. *Int Orthop* 1995 ; 19 : 86-88
9. **Gillquist J, Messner K.** Instrumented analysis of the pivot shift phenomenon after reconstruction of the anterior cruciate ligament. *Int J Sports Med* 1995 ; 16 : 484-488
10. **Gomez-Barrena E, Nunez A, Ballesteros R, Martinez-Moreno E, Munuera L.** Anterior cruciate ligament reconstruction affects proprioception in the cat's knee. *Acta Orthop Scand* 1999 ; 70 : 185-193
11. **Hardin GT, Bach BR Jr, Bush-Joseph CA, Farr J.** Endoscopic single-incision anterior cruciate ligament reconstruction using patellar tendon autograft. Surgical technique. *Am J Knee Surg* 1992 ; 5 : 144-155
12. **Henning CE, Lynch MA, Glick KR.** An in vivo strain gage study of elongation of the anterior cruciate ligament. *Am J Sports Med* 1985 ; 13 : 22-26
13. **Jenkins WL, Munns SW, Jayaraman G, Wertzberger KL, Neely K.** A measurement of anterior tibial displacement in the closed and open kinetic chain. *J Orthop Sports Phys Ther* 1997 ; 25 : 49-56
14. **Jurist KA, Otis JC.** Anteroposterior tibiofemoral displacements during isometric extension efforts. The roles of external load and knee flexion angle. *Am J Sports Med* 1985 ; 13 : 254-258
15. **Kanai H.** Dynamic analysis in the knees with chronic anterior cruciate ligament insufficiency. An evaluation of antero-posterior instability, leg rotation and ground reaction force. *J Jpn Orthop Assoc* 1993 ; 67 : 617-630
16. **Kaufman KR, An KN, Litchy WJ, Morrey BF, Chao EY.** Dynamic joint forces during knee isokinetic exercise. *Am J Sports Med* 1991 ; 19 : 305-316
17. **Kellis E, Baltzopoulos V.** The effects of the antagonist muscle force on intersegmental loading during isokinetic efforts of the knee extensors. *J Biomech* 1999 ; 32 : 19-25
18. **Kizuki S, Shirakura K, Kimura M, Fukasawa N, Udagawa E.** Dynamic analysis of anterior tibial translation during isokinetic quadriceps femoris muscle concentric contraction exercise. *Knee* 1995 ; 2 : 151-155
19. **Lysholm J, Gillquist J.** Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *Am J Sports Med* 1982 ; 10 : 150-154
20. **Lysholm M, Goertzen D, Messner K.** Reproducibility of sagittal plane knee translation during isokinetic exercises. *Isokinet Exerc Sci* 1994 ; 4 : 16-21
21. **Lysholm M, Messner K.** Sagittal plane translation of the tibia in anterior cruciate ligament-deficient knees during

commonly used rehabilitation exercises. *Scand J Med Sci Sports* 1995 ; 5 : 49-56
22. **Noyes FR, Mooar PA, Matthews DS, Butler DL.** The symptomatic anterior cruciate-deficient knee. Part I : the long-term functional disability in athletically active individuals. *J Bone Joint Surg* 1983 ; 71-A : 154-162
23. **Osternig LR, Caster BL, James CR.** Contralateral hamstring (biceps femoris) coactivation patterns and anterior cruciate ligament dysfunction. *Med Sci Sports Exerc* 1995 ; 27 : 805-808
24. **Riederman R, Wroble RR, Grood ES, VanGinkel L, Shaffer BL.** Reproducibility of the knee signature system. *Am J Sports Med* 1991 ; 19 : 660-664
25. **Rijke AM, Tegtmeyer CJ, Weiland DJ, McCue FC III.** Stress examination of the cruciate ligaments. A radiologic Lachman test. *Radiology* 1987 ; 165 : 867-869
26. **Shino K, Inoue M, Horibe S, Nakamura H, Ono K.** Measurement of anterior instability of the knee. *J Bone Joint Surg* 1987 ; 69-B : 608-613
27. **Solomonow M, Baratta R, Zhou BH, Shoji H, Bose W, Beck C, D'Ambrosia R.** The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med* 1987 ; 15 : 207-213
28. **Staubli HU.** Stress radiography. Measurements of knee motion limits. In : Daniel DM, Akeson WH, O'Connor JJ (eds) : *Knee Ligaments. Structure, Function, Injury, and Repair.* New York, Raven Press Ltd, 1990, pp 449-459
29. **Tibone JE, Antich TJ.** A biomechanical analysis of anterior cruciate ligament reconstruction with the patellar tendon. A two year follow-up. *Am J Sports Med* 1988 ; 16 : 332-335
30. **Tibone JE, Antich TJ.** Electromyographic analysis of the anterior cruciate ligament-deficient knee. *Clin Orthop* 1993 ; 288 : 35-39
31. **Vergis A, Hammarby S, Gillquist J.** Fluoroscopic validation of electrogoniometrically measured femorotibial translation in healthy and ACL deficient subjects. *Scand J Med Sci Sports* 2002 ; 12 : 223-229
32. **Vergis A, Hindriks M, Gillquist J.** Sagittal plane translation of the knee in anterior cruciate deficient subjects and controls. *Med Sci Sports Exerc* 1997 ; 29 : 1561-1566
33. **Wilk KE, Andrew JR.** The effects of pad placement and angular velocity on tibial displacement during isokinetic exercise. *J Orthop Sports Phys Ther* 1993 ; 17 : 24-30
34. **Yack HJ, Collins CE, Whieldon TJ.** Comparison of closed and open kinetic chain exercise in the anterior cruciate ligament-deficient knee. *Am J Sports Med* 1993 ; 21 : 49-54
35. **Zheng N, Fleisig GS, Escamilla RF, Barrentine SW.** An analytical model of the knee for estimation of internal forces during exercise. *J Biomech* 1998 ; 31 : 963-967