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Gait analysis after total knee arthroplasty. Comparison of posterior cruciate retention and substitution

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Abstract: The objective of this study was to measure three-dimensional knee motion during gait in patients with total knee replacements which either retained the posterior cruciate ligament (n = 11), or required sacrifice of the posterior cruciate ligament and replacement of its function with a posterior stabilizing articular surface (n = 9). Clinically meaningful translations (anterior and posterior, medial and lateral, proximal and distal) and rotations (flexion and extension, internal and external rotation, abduction and adduction) were measured using an instrumented spatial linkage. Although patients from both groups were able to achieve passive full extension and a minimum of 95° flexion, some of their translations and rotations during free speed walking were consistently less than those in a group of healthy controls. Motion during the swing phase of gait was similar for both knee replacement groups. However, abduction and adduction and proximal and distal translation were larger (but neither difference was significant) for the patients with implants with a posterior stabilizing surface, which suggests that the stabilizing surface may not reliably provide as much stability in these directions as does retention of the posterior cruciate ligament.

Key words: total knee arthroplasty, gait analysis, posterior cruciate ligament retention, posterior cruciate ligament substitution

Introduction

Retention of the posterior cruciate ligament in total knee arthroplasty remains a controversial issue. It has been shown that the posterior cruciate ligament is important in guiding femoral rollback in flexion, and in limiting posterior translation of the tibia. This rollback serves to increase the moment arm of the extensor mechanism, thereby decreasing quadriceps force and patellofemoral contact loads.[24] Two types of total knee arthroplasty design are in current use; one provides for retention of the posterior cruciate ligament, while the other requires excision of the posterior cruciate ligament and replaces its function with a posterior stabilizing articular surface. Although clinical studies have reported that both designs yield satisfactory results,[2,4,7,8,12–16,18,19,25,30] the particular significance of posterior cruciate ligament retention has not been identified, and the specific advantages of one design over the other have yet to be documented.

The goal of this study was to address this issue in an objective manner by using an instrumented spatial linkage (ISL) to measure three-dimensional knee motion during gait in patients with retention of the posterior cruciate ligament and in those with a posterior stabilizing articular surface total knee replacement design (Genesis I Total Knee System, Smith & Nephew Richards Memphis, TN, USA). The hypotheses to be tested were: (1) there are no significant differences in knee motion during free speed walking in patients with retention of the posterior cruciate ligament and those with posterior stabilizing articular surface total knee replacements; and (2) knee motion during free speed walking in patients with retention of the posterior cruciate ligament or posterior stabilizing articular surface knee replacements would be significantly different from this motion in healthy control individuals.

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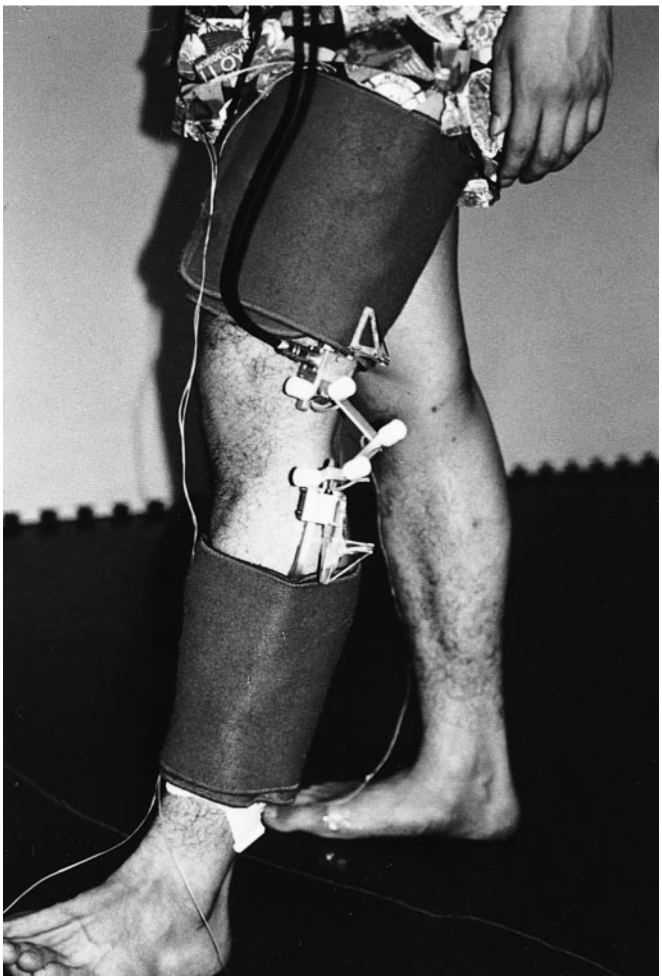
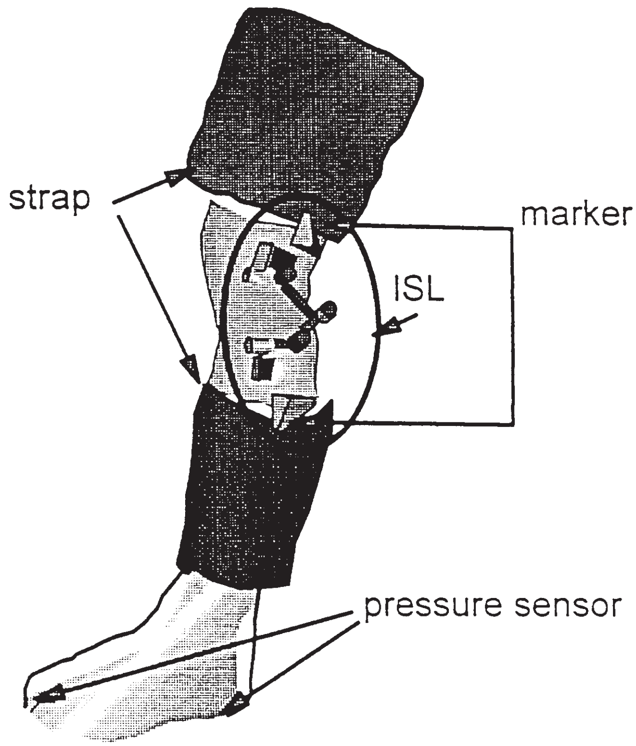
Patients and methods

Knee motion was measured in 11 patients (11 knees) who had had a posterior cruciate-retaining total knee arthroplasty. Their average age was 67.6 years (range, 65–73), and three were 6 men and 5 women. Motion also was recorded during gait in 9 patients (9 knees) who had had a posterior cruciate-stabilizing total knee arthroplasty. Their average age was 68.5 years (range, 65–75 years), and there were 4 men and 5 women. All patients had osteoarthritis, and all had undergone a total knee arthroplasty in which the Genesis I (Smith & Nephew Richards, Memphis, TN, USA) prosthesis was used. In patients with retention of the posterior cruciate ligament, appropriate tension was confirmed intraoperatively. The average time to follow-up was 42.6 months (range, 18–64 months) for patients with retention of the posterior cruciate ligament, and 25.9 months (range, 18–37 months) for patients with the posterior stabilizing articular surface. At follow-up none of the patients had clinical complaints. All walked without support, and all had achieved passive full extension and at least 95° of flexion. There were no significant differences in sagittal or coronal plane alignment between the group with retention of the posterior cruciate ligament and the group with the posterior stabilizing articular surface. Ten individuals with normal (i.e., non-osteoarthritic) knees who were age and sex-matched with the patients in the total knee arthroplasty groups were tested for gait analysis and served as controls.

Knee motion was measured noninvasively with an instrumented spatial linkage (ISL),[20,21,28] an electrogoniometer which measures the three-dimensional motion of a joint. The ISL is composed of seven metal pieces or links interconnected by six electrical hinges or potentiometers (Fig. 1). The ends of the ISL are fixed to the tibia and femur so that it spans the joint. The links and potentiometer freely change their relative positions and orientations as the knee moves. When the geometry of the links, the electrical parameters which charac-



A



B

Fig. 1. **A** Photograph of kinematic linkage device with a goniometer that has 6° of freedom (instrumented spatial linkage; ISL). **B** Diagram

terize the potentiometer, and the voltages generated by the potentiometers as the knee moves are known, the position of one end of the ISL can be computed relative to the other end.

In this study, the ISL was secured to the lateral aspect of the subjects' knees and its ends were fixed to thin aluminum plates, which were, in turn, attached to the tibia and femur by stiff elastic cuffs, 30cm in width. Although these cuffs did not provide a perfectly rigid attachment of the ISL to the tibia and femur, they reduced the amount of unwanted movement of the ISL and adjacent soft tissue over the underlying bone, which would introduce an error into the measured joint motion. The reproducibility and reliability of the ISL method have been reported by Townsend et al.[28] Shiavi et al.,[20] and Terajima et al.[27] (Table 1). Motion between the ends of the ISL was related to the anatomy of the knee through the application of a biplanar radiographic technique with the knee in full extension (Fuji Computed Radiographic System, Fuji Film, Tokyo, Japan). Using the radiographic images of the total knee arthroplasty components and the targets on the ends of the ISL (Fig. 1), we determined anatomic rotation axis directions and a point from which the tibial translations would be defined. The origin of the femur was defined as the center of both condyles, and the origin of the tibia was defined as the center of the tibial plateau (Fig. 2).[26] The motion of the tibia relative to the femur was described in terms of three clinically meaningful rotations (flexion and extension, internal and external rotation, abduction and adduction) and three translations (anterior and posterior, medial and lateral, proximal and distal). The linear accuracy of the ISL was determined by placing it in known configurations on a milling machine, and comparing the known and predicted relative positions of the ends of the ISL. The linear accuracy was determined to be ± 0.5mm, and the angular accuracy was ±0.5°.

Pressure sensors[6] were attached to the heel and great toe of the limb of interest, to define the stance and swing phases of the gait cycle. Knee motion was recorded at 100Hz by a computer data acquisition system as the subjects walked at their own free speed. Although we had planned that walking speed should be controlled, when we tried this, individuals walked at different speeds and showed nonphysiological gait. We therefore decided to use free gait, i.e., the subjects walked as usual. It has been shown that knee kinematics for free speed and fast walking are similar.[21]

Patterns for the three knee rotations and three translations were measured during three gait cycles for each subject, and were averaged to obtain a mean pattern for each motion component for each subject in the three test groups. These patterns were averaged for the subjects in each test group, and various descriptive peak magnitudes of rotations and translations were identified. A global comparison of each of these motion components over the three test groups was obtained by analysis of variance, and pairwise comparisons were made while taking multiple comparisons into account (Scheffe's method).

Table 1. Comparison between mean values for knee motion parameters during walking in two tests (reliability)

Knee measurement (n = 10)	Motion		
	Mean	SD	t*
Flexion and extension (degrees)			
Peak flexion in stance			
Test	18.8	4.1	0.412
Retest	19.3	4.3	
Peak flexion in swing			
Test	58.3	6.1	0.271
Retest	60.8	7.4	
Adduction and abduction (degrees)			
Test	11.7	1.9	0.417
Retest	11.9	2.8	
Internal and external rotation (degrees)			
Test	21.8	5.0	0.455
Retest	21.6	3.8	
Medial and lateral translation (mm)			
Test	10.0	2.0	0.376
Retest	10.0	2.2	
Anterior and posterior translation (mm)			
Test	24.1	4.5	0.476
Retest	24.2	5.2	
Proximal and distal translation (mm)			
Test	21.6	3.8	0.470
Retest	21.8	3.8	

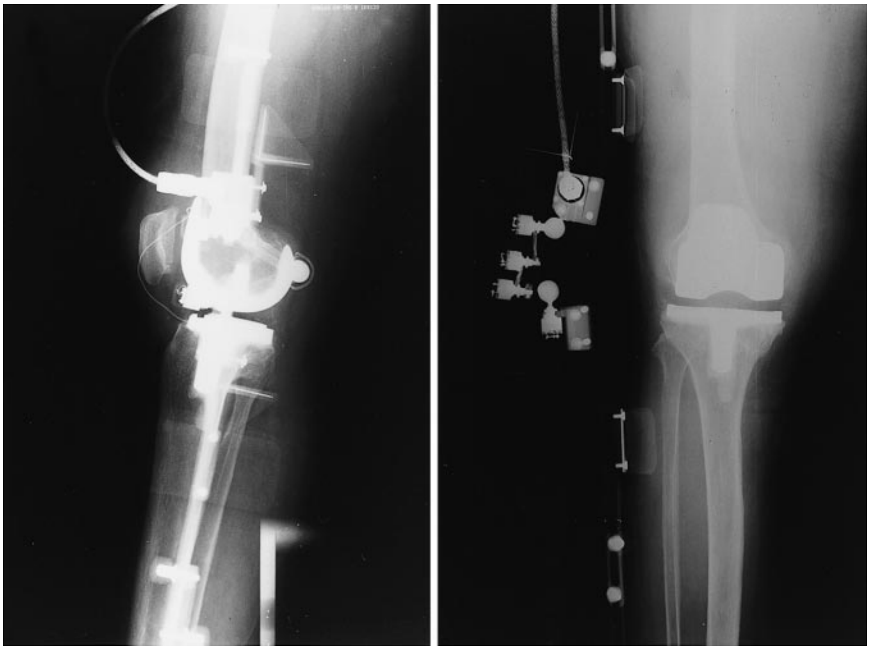
Paired student t-test indicated that the differences between the means (test and retest) were not significant at the 0.05 level for any of the six measurements

* t for P 0.05 = 2.228

Results

Full extension was not reached during the swing or the stance phases of the gait cycle in any of the three groups. In the stance phase, there was no significant difference in peak flexion (Al in Fig. 3A,B and Table 2) between the group with retention of the posterior cruciate ligament (mean ± SD, 14.4° ± 4.5°) and that with the posterior stabilizing articular surface (9.8° ± 6.6°). However, peak stance flexion in the group with retention of the posterior cruciate ligament and the group with the posterior stabilizing articular surface was less than that for healthy controls (18.0° ± 8.5°). There was no significant difference in peak flexion during the swing phase of gait (A2 in Fig. 3A,B and Table 2) between patients with retention of the posterior

A



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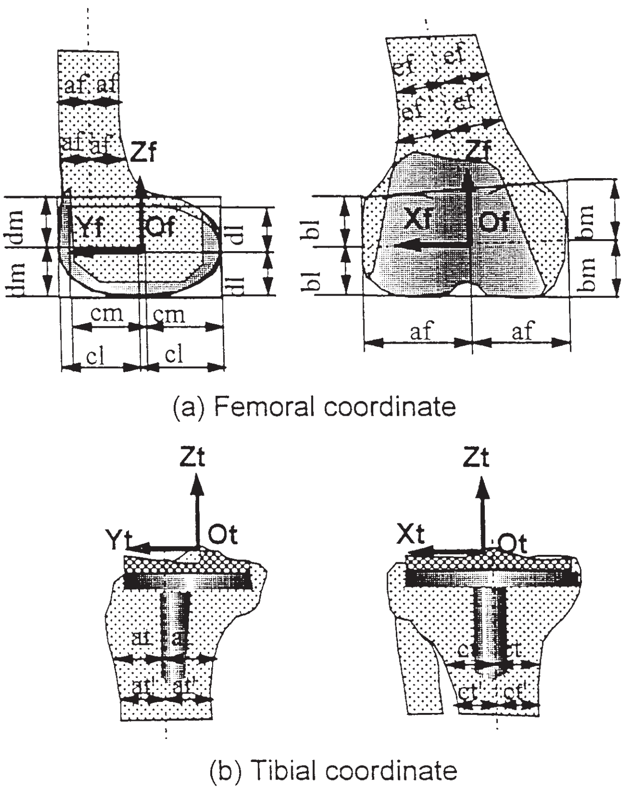


C

Fig. 2. **A** Sagittal and **B** frontal radiographic view of ISL; **C** Define initions of femoral and tibial axes and origins. Femoral coordinates: The *X-f* axis was directed laterally, and parallel to the joint line. The *Y-f* axis was perpendicular to the longitudinal axis of bone with the positive direction positioned anteriorly. The *Z-f* axis was perpendicular to both the *X-f* and *Y-f* axes and was oriented proximally. Tibial coordinates. The *Z-t* axis was parallel to the longitudinal axis of bone with the positive direction positioned proximally. The *X-t* axis was directed laterally, and parallel to the joint line. The *Y-t* axis was perpendicular to both the *Z-t* and *X-t* axes and was oriented anteriorly. Origin of bone coordinates (*a,b*). The origin of the femur (*Of*) was defined as the center of both condyles, and the origin of the tibia (*Ot*) was defined as the center of the tibial plateau. *cm*, Center of the distal aspect of the medial condyle of the femur; *dm*, center of the posterior aspect of the medial condyle of the femur; *cl*, center of the distal aspect of the lateral condyle of the femur; *dl*, center of the posterior aspect of the lateral condyle of the femur; *af*, center of the distal aspect of the femur; *bl*, center of the lateral condyle of the femur; *bm*, center of the medial condyle of the femur

cruciate ligament (49.7° ± 5.9°) and those with the posterior stabilizing articular surface (45.7° ± 10.0°), but again, peak swing flexion for both implant groups was significantly less than that for the healthy controls (60.5° ± 21.7°).

The knee was adducted throughout the gait cycle for both implant groups, with the peak adduction during the swing phase (B in Fig. 3A,B and Table 2) being less for patients with retention of the posterior cruciate ligament (4.9° ± 4.7°) than for patients with the posterior stabilizing articular surface (7.8° ± 10.3°), although the difference was not significant. In the healthy controls, adduction (7.0° ± 3.4°) occurred at the same point in the gait cycle.

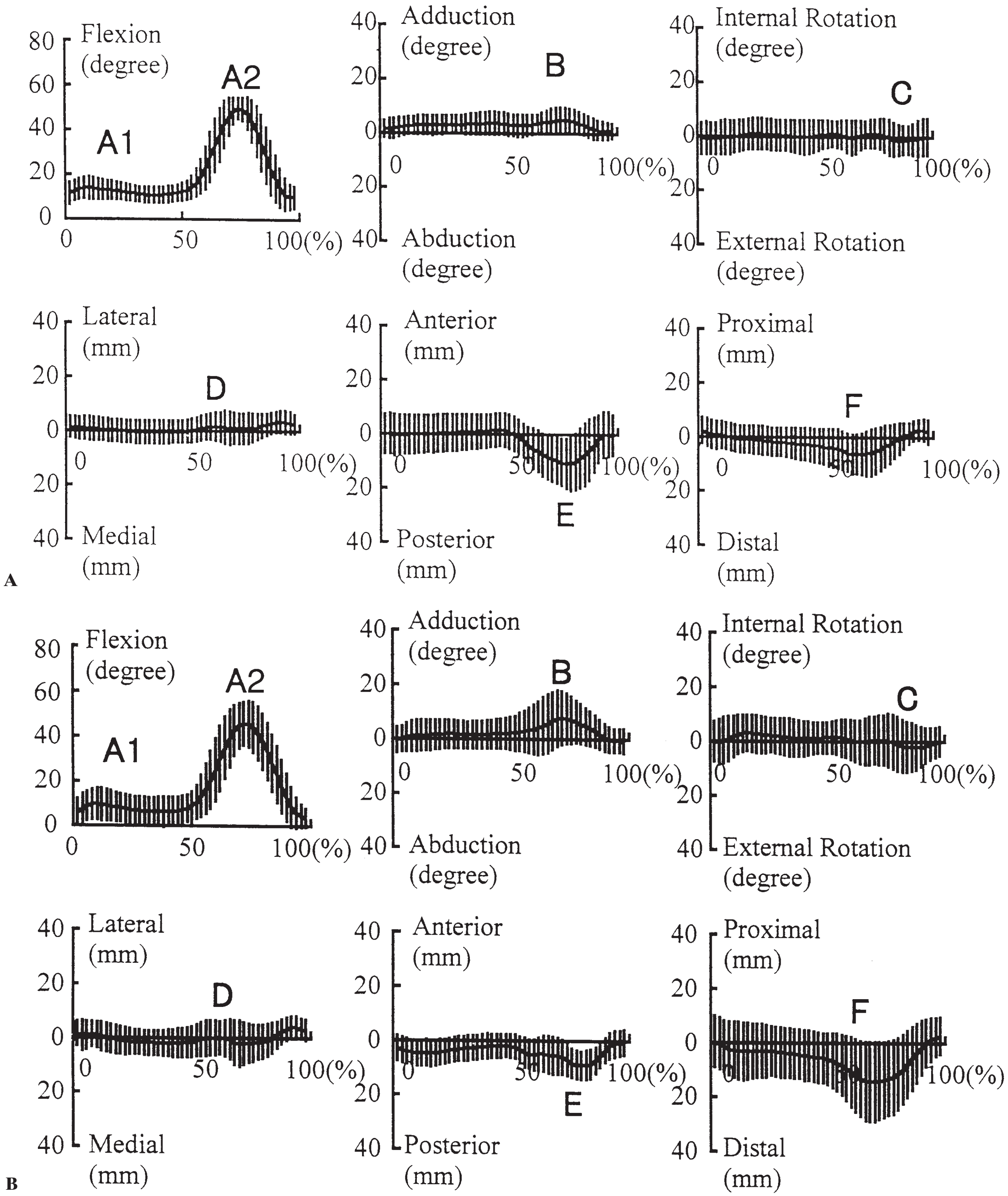
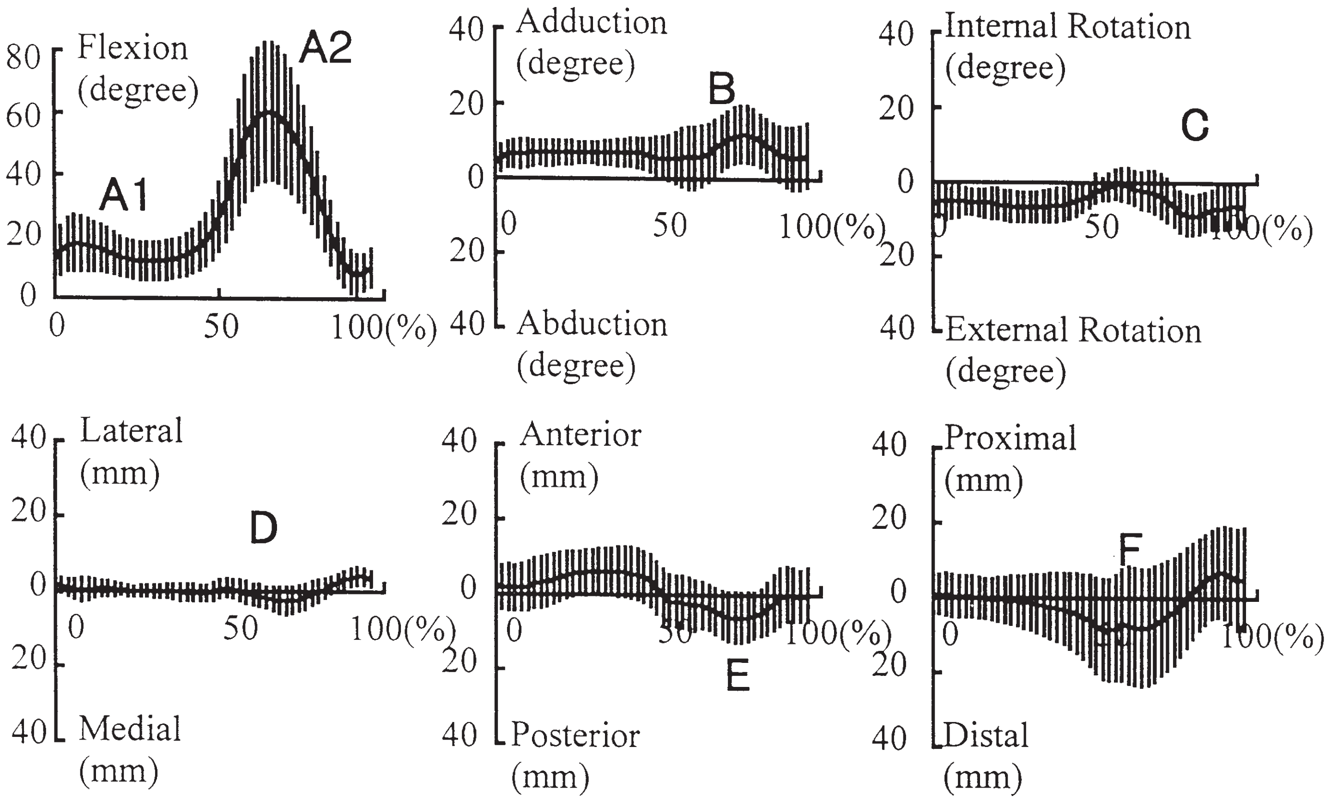


Fig. 3. **A** Average patterns of angular and linear displacement of the tibiofemoral joint during walking. In patients with total knee replacement with retention of the posterior cruciate ligament (PCL); **B** in patients with total knee replacements with PCL substituting design; **C** in controls. The patterns begin with heel strike and end with heel strike of the ipsilateral limb. Values are averages ± SD. *A1*, Peak flexion in stance phase; *A2*, Peak flexion in swing phase; *B*, Peak adduction in swing phase; *C*, internal and external rotation; *D*, range of medial and lateral translations; *E*, anterior and posterior translation during the swing phase; *F*, full flexion in swing phase



C

Fig. 3. *Continued*

Table 2. Mean values (SD) of magnitudes of three translations and three rotations

Motion component	Normal controls (n = 10)	PCL + Group (n = 11)	PCLS group (n = 9)
Flexion and extension[a]			
• Peak flexion is stance (A1)	18.0 (8.5)*	14.4 (4.5)	9.8 (6.6)*
• Peak flexion in swing (A2)	60.5 (21.7)*,**	49.7 (5.9)*	45.7 (10.0)**
Adduction (+), abduction (−)[a]			
• Peak during swing (B)	7.0 (3.4)	4.9 (4.7)	7.8 (10.3)
Internal and external rotation[a]			
• Total range in swing (C)	13.2 (3.1)*,**	5.2 (3.1)*	5.8 (2.2)**
Range of medial and lateral[b]			
• Translation over gait cycle (D)	4.2 (2.3)	3.6 (3.9)	4.1 (4.1)
Anterior and posterior translation[b]			
• Total range in swing (E)	6.1 (12.2)*	10.8 (8.6)*	9.0 (5.2)
Proximal and distal translation[b]			
• Maximum distal translation in swing (F)	6.9 (11.8)	6.3 (7.2)	14.4 (14.4)

*,** $P < 0.05$
Values are means (SD)
PCL+, Retention of the posterior cruciate ligament (PCL) design; PCLS, PCL substituting design
[a] Degrees
[b] Mm

No substantial external or internal rotation occurred during the gait cycle in either of the implant groups (C in Fig. 3A,B and Table 2). In the healthy controls, from toeoff until just before heel strike, the tibiofemoral joint rotated externally 13.2° ± 3.1°. Then internal rotation continued until toeoff (C in Fig. 3C and Table 2).

The overall maximum range of medial and lateral translations (D in Fig. 3A,B and Table 2) throughout the gait cycle was small. The controls had a range of 4.2 ± 2.3 mm. There was no significant difference between patients with retention of the posterior cruciate ligament (3.6 ± 3.9 mm) and those with the posterior stabilizing articular surface (4.1 ± 4.1 mm).

When we compared the overall anterior and posterior translation during the swing phase (E in Fig. 3A,B and Table 2), there was no significant difference between the group with retention of the posterior cruciate ligament (10.8 ± 8.6 mm) and those with the posterior stabilizing articular surface (9.0 ± 5.2 mm). The overall anterior and posterior translation during swing phase for the healthy control group was 6.1 ± 12.2 mm, significantly different from the value for the group with retention of the posterior cruciate ligament group, but not from the value for the group with the posterior stabilizing articular surface.

The knee translated distally during flexion and proximally during extension. The largest translation over the gait cycle was in the distal direction (distraction), and this occurred as the knee reached full flexion in the swing phase (F in Fig. 3 A, B and Table 2). The maximum distal translation during the swing phase was greater for the group with the posterior stabilizing articular surface (14.4 ± 14.4 mm) than for the group with retention of the posterior cruciate ligament (6.3 ± 7.2 mm). The maximum distal translation for the healthy control group was 6.9 ± 11.8 mm.

Discussion

One hypothesis to be tested in this study was that knee motion during free speed walking for patients with retention of the posterior cruciate ligament and those with posterior stabilizing articular surface knee replacements would be significantly different from the motion in healthy control subjects. The data generated in this study indicate that posterior translation during the swing phase was less in the healthy control group than in either of the total knee arthroplasty groups. These data suggest that the posterior cruciate ligament in total knee arthroplasty with retention of the posterior cruciate ligament and the tibial cam in total knee arthroplasty with a posterior stabilizing articular surface did not completely reproduce the motion of normal knees with an intact posterior cruciate ligament. It is possible that the posterior cruciate ligament in the group with retention of this ligament did not have proper tension.[19]

The knee motion in the two implant groups appeared to be more inflexible than that in the controls. This was particularly evident with rotation during the swing phase and flexion during the stance and swing phases of gait. The restricted rotation during the swing phase of gait may have been caused by the deficit of the anterior cruciate ligament in the total knee arthroplasty groups. The anterior cruciate ligament plays an important role in rotation. Another factor could be the increased friction between the metal and plastic implant components after the operation, compared with cartilage in the normal joint. Although patients in both implant groups could attain full extension and 95° of flexion passively, less than 50° flexion was exhibited in the swing phase of gait. Dorr et al.[5] and Simon et al.[22] reported similar results in their follow-up of patients with total knee arthroplasty. One explanation for the restricted flexion during the stance phase of gait may be the presence of a “patterned” gait. Since many people with arthritic knees walk with a inflexible gait for years before receiving total knee arthroplasty, they may continue this abnormal gait as a habit after total knee arthroplasty. A second possible explanation for the restricted motion during gait may be the irreversible loss of joint proprioception.[23] Proprioceptive neuropathy frequently exists to a variable degree in patients who undergo total knee arthroplasty. A third possible explanation may be partial or total denervation of position sense by surgical damage to ligaments and capsule during the arthroplasty surgery. For example, it has been shown that flexion is restricted in anterior cruciate ligament-deficient knees compared with normal healthy knees.[21] The increased friction postoperatively also could be a factor.

The other hypothesis posed in this study was that the motion in the two implant groups, those with retention of the posterior cruciate ligament and those with posterior stabilizing articular surface knees, would not be significantly different. The hypothesis was posed in this way because many of the clinical follow-ups of patients with either of these implant designs had equivalent acceptable outcomes.[2,4,7,8,12–16,18,19,25,30] In this study, the three translation and rotation patterns examined in the swing phase were similar in both groups. However, adduction and distal translation values were greater for patients with the posterior stabilizing articular surface, although these differences were not significant. These results suggest that the geometry of the posterior stabilized articular surface does not provides as much stability in these directions as total knee arthroplasties which retain the posterior cruciate ligament. These increased components of motion may lead to abnormally high compressive stresses in the trabecular bone, a subsequent increased rate of radiolucency around the tibial tray, and varus alignment of the component.[11,29] Increased radiolucency with posterior stabilizing articular surface implants, compared with radiolucency in those with retention of the posterior cruciate ligament, has been reported by Becker et al.,[2] although the radiolucency appears early but progresses minimally.[11,19,25,29,30] Furthermore, these larger motions may lead to eccentric load to the patellar component, and to an increased rate of fractures and loosening. In clinical reports, failure rates were higher with the posterior stabilizing articular surface implants (Scott et al.,[18] 5%; Insall et al.,[8] 11%) than with implants with retention of the posterior cruciate ligament (Johnson and Eastwood.,[9] 2%; Wright et al.,[30] 3%).

The gait of individuals with total knee arthroplasty has been extensively investigated.[1,3,4,10,17,22] Andriacchi et al.[1] found that patients with the less constrained cruciate-retaining total knee arthroplasty designs had more normal gait patterns during stair climbing than those with the more constrained cruciate-sacrificed implants. Although this and other studies have provided invaluable insight into the biomechanics of total knee arthroplasty, they have focused on the posterior cruciate ligament retention and sacrificed types of implants. The present study is the first, to the authors' knowledge, that has considered the gait of patients with posterior cruciate ligament retention and stabilizing total knee arthroplasty designs.

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