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Quantitative evaluation of gait pattern in patients with osteoarthrosis of the knee before and after total knee arthroplasty. Gait analysis using a pressure measuring system

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Abstract: Using a pressure measuring system, we quantitatively evaluated gait pattern in patients with osteoarthrosis (OA) of the knee before and after total knee arthroplasty (TKA). In the OA group, the stance time was longer, and the average vertical component of the floor reaction force (AVF) was lower than the values in normal age-matched subjects. These gait parameters correlated with the clinical score. These results suggest that changes in the gait parameters reflect gait patterns that reduce load on the knee. The center of pressure (COP) under the foot was correlated with the axial alignment of the lower limb in the mid-stance phase. In the TKA group, the clinical scores and gait parameters were improved 12 months after surgery compared with the preoperative values. The COP in the mid-stance phase moved inward after the TKA. However, in patients examined more than 2 years after a TKA, stance time and AVF did not reach normal levels, despite the patients' good clinical scores. These findings indicate that the gait pattern before surgery continues although pain on walking is reduced early after a TKA. Gait evaluation with a simple pressure measuring system revealed the changes in gait that are difficult to define by subjective clinical assessment.

Key words: gait analysis, osteoarthrosis of the knee, total knee arthroplasty, pressure measuring system

Introduction

Total knee arthroplasy (TKA) is a widely used surgical treatment for osteoarthrosis (OA) which provides consistently good postoperative clinical results. Surgical techniques and knee prostheses have improved in recent years to provide more satisfactory reconstruction in regard to functional capacity of knee joints and improved walking ability.

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Evaluation of the functional capacity of knee joints has been performed by static radiographic examination and by clinical scoring systems. However, these methods are not suitable for preoperative evaluation and postoperative observation, as OA manifests its symptoms in dynamic situations. Chao and Stauffer[8] and Stauffer et al.[19] first reported quantitative gait analysis for patients with prosthetic knee replacements. Since those studies, there have been a number of studies of the relationship between changes in gait parameters and clinical symptoms or the axial alignment of the lower extremities.[2,7,11,14,20]

However, since a large measurement apparatus is required for gait analysis, it has not been widely used for pre- and postoperative evaluations. In the present study, we performed gait analysis of patients with OA of the knee, using a simple pressure measuring system, and we quantitatively evaluated changes in gait pattern in these OA patients after TKA.

Subjects and methods

Study design

Study 1: Gait analysis in patients with OA of the knee

The subjects were 53 women with OA of the knee who were examined at Tottori University Hospital in the period November 1995 to October 1997 (OA group; mean age, 68.2 years; range, 50–85 years). Of these 53 patients, 38 showed bilateral involvement, and in these patients the more severely affected knee (as shown by radiography) was evaluated.

Fourteen age-matched healthy women without physical or radiographically shown disorders in the bilateral lower extremities were tested as controls (control group; mean age, 68.0 years; range, 61–78 years), and the left lower extremity of each subject was evaluated.

After radiographic and clinical evaluations, gait analysis of each subject was performed with a pressure measuring system. Gait parameters in the OA and control groups were compared, and the relationships between the gait parameters and the clinical scores or the axial alignment of the lower extremity, measured by radiography, were analyzed.

Study 2: Gait analysis in TKA patients

TKA patients were divided into TKA groups A and B according to whether the first gait analysis had been performed before TKA.

TKA group A

The subjects were 16 women who had undergone TKA for OA at our hospital in the period December 1995 to September 1997. They were aged 64–84 years (mean, 73.0 years) at surgery. Four patients underwent TKA in the contralateral knee within 6 months after the first surgery. Gait analysis and clinical evaluation of these patients were performed just before surgery and at one or more of the following times postoperatively; 3 months (12 patients), 6 months (15 patients), and 12 months (12 patients).

TKA group B

The subjects were 22 women who had undergone TKA for OA at our hospital in the period December 1985 to October 1995. Of the 22 patients, 11 had undergone bilateral TKA, and in these patients the lower extremity that was first operated on was evaluated. In 2 of the 22 patients, high tibial osteotomy had been performed in the contralateral knee. They were aged 60–82 years (mean, 72.2 years) at the time of first evaluation and gait analysis and clinical evaluation were performed at the time of follow-up observation (mean postoperative period, 4.8 years; range: 2.0–10.8 years).

TKA was performed by conventional techniques, and the patella was replaced in all patients. Full-weight walking started 2 or 3 weeks after the operation. A semiconstrained type of implant was placed in all knees for evaluation. An Osteonics (Allendale, NJ, USA) implant was used in all 16 knees in group A, and 10 PCA (Howmedica, Rutherford, NJ, USA) and 12 Osteonics implants were used in group B.

Clinical evaluation

The walking ability of the patients was evaluated clinically in terms of pain on walking (Table 1) according to the criteria for evaluating osteoarthritis of the knee proposed by the Japanese Orthopedic Association,[12] and passive range of motion of the knee was measured on physical examination. Clinical results are shown in Table 2. Single-stance anteroposterior radiographs of the lower extremities were used for evaluation. The severity of OA was evaluated according to Ahlbäck's classification,[1] and the anatomical femorotibial angle (FTA) was measured by the method of Bauer et al.[4] Table 3 shows the radiographic results in all groups.

Table 1. Clinical evaluation of walking ability[a]

Pain on walking	Points
Walking 1 km or more usually with no pain, without regard to mild pain, rarely felt with certain activities	30
Walking 1 km or more regardless of pain	25
Walking 500 m or more, but less than 1 km without regard to pain	20
Walking 100 m or more, but less than 500 m without regard to pain	15
Walking indoors or nearby, but less than 100 m without regard to pain	10
Inability to walk	5
Inability to stand	0

[a] According to the criteria for evaluating osteoarthritis of the knee (1988: The Comittee on Assessment Criteria for Knee Diseases and Treatments of the Japanese Orthopaedic Association). A normal subject's score is 30 points

Gait analysis

Apparatus

The apparatus used was a pressure measuring system (MP-4800; Anima, Tokyo, Japan). The measurement plate (280 mm × 392 mm) had 2240 measuring sensors with a pressure sensitivity ranging from 0.1 to 4.0 kg/cm^2. The center of pressure (COP) was simultaneously determined by load-cells positioned at the four corners of the plate.

Measurement methods

In the center of the 6-m-long and 60-cm-wide walkway, two measurement plates were placed to be adjusted to the step length of each subject. Free walking with bare feet on the walkway was repeated several times, and the foot pressure distribution was sampled at 20 Hz. The data obtained at each sampling time were processed, and combined frames of the footprint and the path of the COP were determined (Fig. 1a). The following parameters were calculated from the pressure distribution data obtained while the subjects were walking with the least restriction:

(a) Stance time: Duration between heel strike and toe-off.
(b) Percent pre-stance, percent mid-stance, and percent terminal stance phases: The times of heel strike, foot flat (grounding of the fifth metatarsal head region), heel-off and toe-off, determined from the sequential instant foot print, and the durations

Table 2. Cinical results and gait parameters in each study group

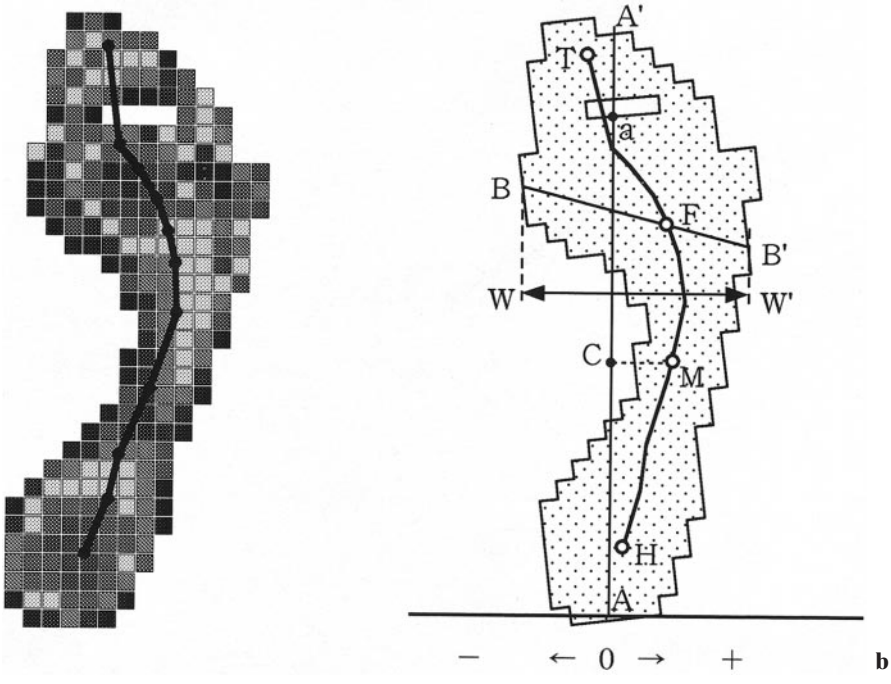
	(A) Control (n = 14)	(B) OA (n = 53)	TKA group A				(C) TKA group B (n = 22)	Significance[a]	
			Preop. (n = 16)	3 months (n = 12)	6 months (n = 15)	12 months (n = 12)		A vs. B	A vs. C
Clinical score (points)	30.0	20.7 ± 5.8	15.3 ± 4.3	23.3 ± 4.4*	26.0 ± 3.4*	28.3 ± 3.3*	28.2 ± 2.9	<0.0001	0.026
ROM (degrees)									
Extension	0	−7.3 ± 6.7	−9.7 ± 7.2	−5.4 ± 4.0*	−4.3 ± 4.2*	−3.8 ± 3.8*	−3.9 ± 3.4	<0.0001	0.042
Flexion	155.4 ± 1.7	132.0 ± 17.2	117.5 ± 13.3	99.2 ± 12.2*	101.0 ± 12.4*	102.1 ± 10.1*	101.8 ± 15.5	<0.0001	<0.0001
Stance time (ms)	748 ± 91	922 ± 174	1030 ± 219	980 ± 201	952 ± 237	864 ± 153*	873 ± 114	0.0006	0.0015
%Pre-stance	13.9 ± 3.4	10.7 ± 4.0	9.2 ± 3.0	9.1 ± 3.3	10.0 ± 4.1	11.5 ± 3.8	10.4 ± 3.7	0.0068	0.0082
%Mid-stance	42.8 ± 10.2	52.6 ± 12.8	54.3 ± 13.8	59.8 ± 12.8	61.1 ± 11.2	58.4 ± 11.9	53.8 ± 10.5	0.0096	0.0039
%Terminal-stance	43.5 ± 9.0	36.8 ± 11.5	36.5 ± 12.4	31.1 ± 10.9	28.9 ± 9.4	30.1 ± 12.0	35.8 ± 12.0	0.047	0.047
Average vertical force (BW%)	74.7 ± 3.1	70.5 ± 5.8	68.8 ± 2.5	70.1 ± 2.3	71.0 ± 2.7*	72.7 ± 2.7*	72.0 ± 4.2	0.01	0.042
Location of COP (mm)									
Heel	8.9 ± 4.0	9.7 ± 5.8	8.1 ± 5.9	6.6 ± 3.9	7.8 ± 4.9	5.7 ± 5.9	8.7 ± 5.6	0.67	0.90
Midfoot	4.8 ± 1.3	8.5 ± 6.5	11.6 ± 6.2	2.8 ± 3.9*	3.0 ± 5.1*	4.3 ± 6.1*	4.8 ± 4.6	0.40	0.93
Forefoot	1.8 ± 3.7	5.5 ± 7.2	9.6 ± 5.5	1.1 ± 7.9*	−0.3 ± 5.3*	2.1 ± 9.2*	3.2 ± 4.6	0.07	0.35
Toe	−9.5 ± 3.4	−8.5 ± 9.8	−5.6 ± 12.5	−14.4 ± 12.4	−11.9 ± 8.7	−12.0 ± 8.4	−5.9 ± 6.2	0.71	0.06

*Significant difference from preoperative value in TKA group A (unpaired t-test)
Values are presented as means ± SD
OA, osteoarthrosis, TKA, total knee arthroplasty; ROM, range of motion; COP, center of pressure
[a]Analyzed by unpaired t-test

Table 3. Radiographic evaluation results in each study group

	OA (n = 53)	TKA group A (n = 16)		TKA group B (n = 22)	Control (n = 14)
		Preop.	Postop.		
Ahlbäck class[a] (No.)	I (28), II (8), III (17)	II (4), III (12)	—	—	0 (14)
FTA (degrees)	185.7 ± 7.4	190.1 ± 7.8	173.3 ± 2.5	175.5 ± 5.0	177.2 ± 2.9

Values are means ± SD
OA, Osteoarthrosis; TKA, total knee arthroplasty
FTA, Femorotibial angle measured according to Bauer's method
[a] Classfication according to Ahlbäck [1] classes 0–III: class 0, less than 50% joint space narrowing (no arthrosis); class I, equal to or greater than 50% joint space narrowing; class II, 100% joint space narrowing; class III, attrition of the subchondral bone
Values in parentheses are numbers of knees



a **b**

Fig. 1. a Footprint during gait in the combined frame obtained with a pressure measuring system (MP-4800; Anima, Tokyo, Japan). The curve shows the path of the center of pressure (COP). **b** Measurement method for location of the COP, measured in the heel (H), midfoot (M), forefoot (F), and toe (T), corrected by the foot width (WW'), and quantified as the distance from the axis of the foot (AA'). The COP outside the axis of the foot is expressed as positive, and that inside the axis of the foot as negative. A, Midposterior heel border; A', midtip of the second toe; a, base of the second toe; B, medial edge of the forefoot; B', lateral edge of the forefoot; C, mid-point between Aa

of the pre-stance, mid-stance, and terminal stance phases were calculated, and the fraction of each to the stance time was determined.

(c) Average vertical force (AVF): The integral of the vertical component of the floor reaction force was divided by the stance time.

(d) Location of COP on the footprint: The COP was quantified in the heel, midfoot (midpoint of the midposterior heel border and the base of the second toe), forefoot (site of the maximum foot width), and toe on the footprint of the combined frame. The location of the COP, expressed as the distance from the axis of the foot (COP outside the axis of the foot was expressed as positive and COP inside the axis of the foot as negative), i.e. the line between the midposterior heel border and the midtip of the second toe, was corrected by the foot width (Fig. 1b).

Statistical analysis

Comparisons between groups were performed by unpaired t-test. Correlations between the clinical evaluation and gait parameters were examined by regression analysis. A value of $P < 0.05$ was considered significant.

Results

Study 1: Gait analysis in patients with OA of the knee

Clinical evaluation

In the OA group the mean clinical score was 20.7 points (range, 10–30 points), (Table 2) and the mean FTA was 185.7° (range, 175–208°) (Table 3).

Gait parameters

The mean stance time in the OA group was 922 ms, significantly longer than that in the control group

Table 4. Correlation between clinical score and gait parameters in osteoarthrosis (OA) group

Spearman rank correlation	Stance time (ms)	%Pre-stance	%Mid-stance	%Terminal-stance	Average vertical force (BW%)
Correlation coefficient	−0.356	0.129	−0.173	0.200	0.595
P value	0.01	0.35	0.21	0.149	<0.0001

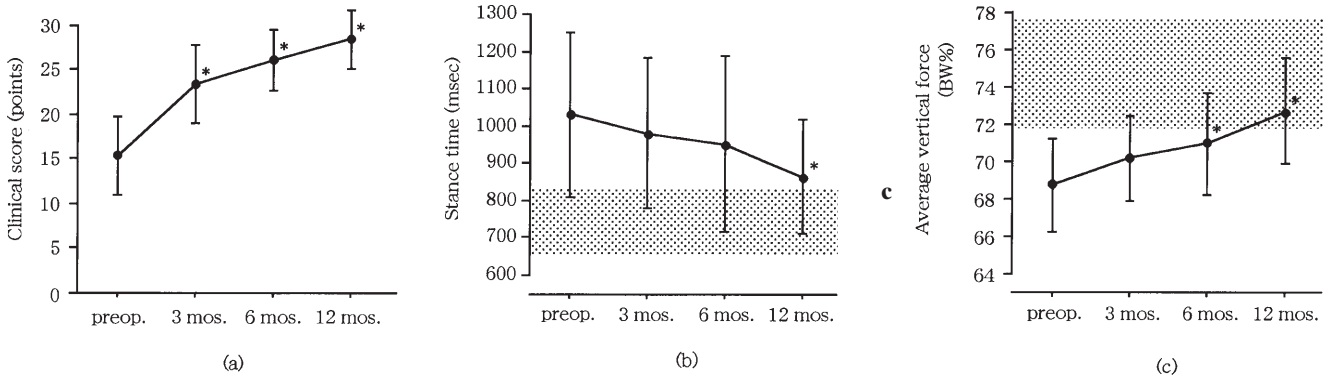


Fig. 3a–c. Clinical score and gait parameters in total knee arthroplasty (TKA) group A. **a** Clinical score; **b** stance time; **c** average vertical force. Values are expressed as means ± SD. *Shaded area* shows control variation (means ± SD). *Significant difference from preoperative value (unpaired *t*-test)

Table 5. Correlation between femorotibial angle (FTA) and location of the center of pressure (COP) in OA group

Pearson correlation	Location of COP			
	Heel	Midfoot	Forefoot	Toe
Correlation coefficient	0.023	0.486	0.474	0.243
P value	0.88	0.0002	0.0003	0.08

(748 ms; $P = 0.0006$). The percent pre-stance, mid-stance, and terminal stance phases in the OA group were significantly lower ($P = 0.0068$), higher ($P = 0.0096$), and lower ($P = 0.047$), respectively, than the values in the control group. The mean AVF was 70.5 body weight % (BW%) in the OA group and 74.7 BW% in the control group, the difference being significant ($P = 0.01$) (Table 2).

Correlations between clinical evaluation and gait parameters

The clinical score was negatively correlated with stance time ($P = 0.01$), and positively correlated with the AVF ($P < 0.0001$) (Table 4). No correlations were observed between location of the COP and the FTA in the heel and toe, while there was a significant correlation in the midfoot ($P = 0.0002$) (Fig. 2) and forefoot ($P = 0.0003$) (Table 5).

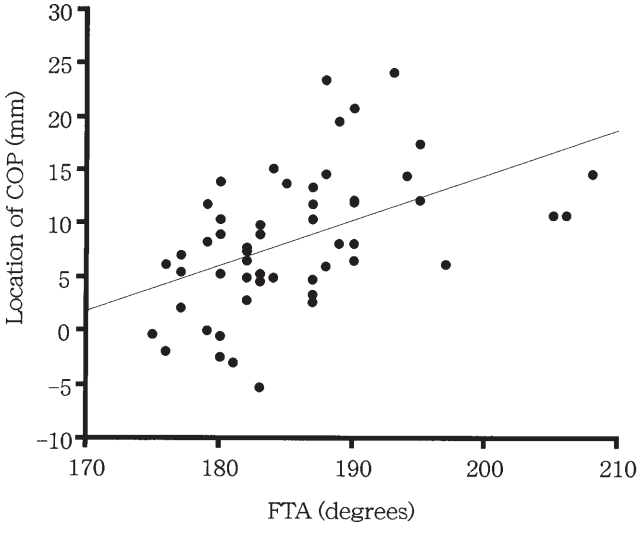


Fig. 2. Correlation between location of the COP on the midfoot and the femorotibial angle (*FTA*) in the osteoarthrosis (OA) group ($n = 53$). The correlation coefficient (r), determined by Pearson correlation, was 0.486; $P = 0.0002$

Study 2: Gait analysis in TKA patients

TKA group A (Table 2, Fig. 3)

Clinical evaluation. The clinical score was significantly improved 3, 6, and 12 months after TKA compared with the preoperative score ($P < 0.0001$).

Gait parameters. A continuous decrease in the stance time was evident from 3 months after surgery, reaching a mean stance time of 864 ms 12 months after surgery; this was significantly lower than the preoperative value (1030 ms; $P = 0.03$). No significant difference was observed in the percent pre-stance, mid-stance, or terminal stance phases before and after surgery. The mean AVF was 71.0 BW% 6 months after surgery, significantly higher than the preoperative value (68.8 BW%; $P = 0.025$). In the midfoot and forefoot, the location of the COP had moved significantly inward after TKA compared with results before surgery ($P < 0.01$ and $P < 0.05$, respectively).

TKA group B (Table 2)
Clinical evaluation. The mean clinical score was significantly lower than that in the control group ($P = 0.026$).

Gait parameters. The mean stance time was 873 ms, significantly greater than that in the control group ($P = 0.0015$). The percent pre-stance, mid-stance, and terminal stance phases were significantly lower ($P = 0.0082$), higher ($P = 0.0039$), and lower ($P = 0.047$), respectively, than these values in the control group, which were similar to those in the OA group. The mean AVF was 72.0 BW%, significantly lower than that in the control group ($P = 0.042$). The location of COP at all examined sites was not different from that in the control group.

Discussion

Since the study done by Chao et al.,[8] in 1974, there have been many quantitative evaluations of gait in patients with OA of the knee and patients before and after TKA.[2,3,5–7,9–11,13–17,21,22] These studies have revealed certain characteristic gait patterns (i.e., changes in time-distance parameters such as prolongation of stance time and reduction in gait velocity) and changes in kinetic parameters such as reduction in the vertical component of the floor reaction force. In the present study, using a pressure measuring system, we showed prolongation of stance time and reduction in the vertical component of floor reaction force in the OA group, as shown in the previous studies. Stauffer et al.[20] reported a correlation between clinical status and gait parameters in patients with OA of the knee. We observed prolongation of stance time and a reduction in the AVF, both of which were correlated with a reduction in clinical score determined by pain and walking ability. These results suggest that these changes in the gait parameters in the OA group reflect gait patterns that prevent pain and reduce load on the knee.

The pressure measuring system used in this study has advantages in that it can clearly distinguish subphases among the stance phases by instantaneously analyzing the footprints, and it can detect the COP under the foot. Our study demonstrated that the percent mid-stance phase was high in the OA group. The location of the COP was correlated with the FTA in the mid-stance phase. In this phase, the COP under the foot, which is the most distal site of load transmission, was found to deviate outward in patients with a severe varus knee condition, suggesting that such patients have a large difference between load distribution in the knee as determined during gait and estimates of load distribution in the knee based on static radiographs.

Collopy et al.[10] and Andersson et al.[2] reported that although gait velocity was higher 1 year after TKA than before sugery, it did not reach the normal level. A number of studies have shown differences in gait parameters between normal subjects and patients after TKA, even though clinical results were satisfactory, and there were no symptoms of arthrosis.[3,5,6,11,13,15,16,21] In the present study, the clinical scores were improved 3 months after TKA and 2 years after the operation, the patients had satisfactory clinical scores. The range of motion of the knee joint had improved after TKA by about 5 degrees in extension and with a decrease of about 15 degrees in flexion.

The stance time and AVF had improved 1 year after TKA, but more than 2 years after the operation, the patients' stance time was longer and the AVF was lower than in the control group. The percent stance phases did not change significantly throughout the period before and after TKA, and the percent mid-stance phase in the patients after TKA was higher than that in the control group, as was observed in the OA group.

These results indicate that the gait pattern observed before TKA continues, although pain during walking is reduced and the passive range of motion of the knee is sufficient for gait after TKA.[3,8,10,15,20] These abnormalities in gait after TKA may be explained by the continuation of a preoperative gait habit,[9] irreversible loss of joint proprioceptive function due to osteoarthritis,[18] and the influence of slightly limited extension of the knee.[10] Another cause of these abormalities may be the prosthetic design. However, several investigators have reported that it was difficult to determine design-specific functional variables during level walking.[3,13,16]

As a method for evaluation of the severity of OA, clinical evaluation is important for the quantification of subjective symptoms, and radiography is necessary for the evaluation of deformity. However, these methods are not sufficient for the objective evaluation of improvement in clinical symptoms in dynamic situations and in walking ability. Abundant information has been

made available by gait analyses using a large-scale measurement system. However, it is difficult to use this method for routine examinations because the required measurement and data analysis are complicated and time-consuming. In the present study, we performed gait analysis using a pressure measuring system as a test for its clinical use; this system requires only simple techniques and minimal restrictions imposed on the subject. There was a correlation between the gait parameters obtained by our method and the clinical evaluation results. We found that these gait parameters detected and quantified changes in gait patterns after a TKA. We therefore believe that quantitative gait analysis with a simple system is useful for the postoperative evaluation of TKA.

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References

1. Ahlbäck S. Osteoarthrosis of the knee. A radiographic investigation. Acta Radiol 1968;277(Suppl):1–71.
2. Andersson GBJ, Andriacchi TP, Galante JO. Correlations between changes in gait and in clinical status after knee arthroplasty. Acta Orthop Scand 1981;52:569–73.
3. Andriacchi TP, Galante JO, Fermier RW. The influence of total knee-replacement design on walking and stair-climbing. J Bone Joint Surg Am 1982;64:1328–35.
4. Bauer GCH, Insall J, Koshino T. Tibial osteotomy in gonarthrosis. Osteoarthritis of the knee. J Bone Joint Surg Am 1969;51: 1545–63.
5. Berman AT, Zarro VJ, Bosacco SJ, et al. Quantitative gait analysis after unilateral or bilateral total knee replacement. J Bone Joint Surg Am 1987;69:1340–45.
6. Berman AT, Bosacco SJ, Israelite C. Evaluation of total knee arthroplasty using isokinetic testing. Clin Orthop 1991;271:106–13.
7. Brugioni DJ, Andriacchi TP, Galante JO. A functional and radiographic analysis of the total condylar knee arthroplasty. J Arthroplasty 1990;5:173–80.
8. Chao EY, Stauffer RN. Biomechanical evaluation of geometric and polycentric knee arthroplasty. Instn Mech Engrs 1974:52–60.
9. Chao EY, Laughman RK, Stauffer RN. Biomechanical gait evaluation of pre- and postoperative total knee replacement patients. Arch Orthop Traumat Surg 1980;97:309–17.
10. Collopy MC, Murray MP, Gardner GM, et al. Kinesiologic measurements of functional performance before and after geometric total knee replacement: One-year follow-up of 20 cases. Clin Orthop 1977;126:196–202.
11. Gore DR, Murray MP, Sepic SB, et al. Correlations between objective measures of function and a clinical knee rating scale following total knee replacement. Orthopedics 1986;9:1363–67.
12. Koshino T, Ikeuchi H, Niwa J, et al. Assessment criteria for knee diseases and treatments. Tokyo: Kanehara Shuppan, 1994:183.
13. Kramers-de Quervain IA, Stüssi E, Müller R, et al. Quantitative gait analysis after bilateral total knee arthroplasty with two different systems within each subject. J Arthroplasty 1997;12:168–79.
14. Kroll MA, Otis JC, Sculco TP, et al. The relationship of stride characteristics to pain before and after total knee arthroplasty. Clin Orthop 1989;239:191–5.
15. Laughman RK, Stauffer RN, Ilstrup DM, et al. Functional evaluation of total knee replacement. J Orthop Res 1984;2:307–13.
16. Rittman N, Kettelkamp DB, Pryor P, et al. Analysis of patterns of knee motion walking for four types of total knee implants. Clin Orthop 1981;155:111–7.
17. Simon SR, Trieshmann HW, Burdett RG, et al. Quantitaitve gait analysis after total knee arthroplasty for monoarticular degenerative arthritis. J Bone Joint Surg Am 1983;65:605–13.
18. Skinner HB, Barrack RL, Cook SD, et al. Joint position sense in total knee arthroplasty. J Orthop Res 1984;1:276–83.
19. Stauffer R, Kettelkamp DB, Thompson C, et al. The MacIntosh prosthesis. Prospective clinical and gait evaluation. Arch Surg 1975;110:717–20.
20. Stauffer RN, Chao EYS, Györ AN. Biomechanical gait analysis of the diseased knee joint. Clin Orthop 1977;126:246–55.
21. Steiner ME, Simon SR, Pisciotta JC. Early changes in gait and maximum knee torque following knee arthroplasty. Clin Orthop 1989;238:174–82.
22. Wilson SA, McCann PD, Gotlin RS, et al. Comprehensive gait analysis in posterior-stabilized knee arthroplasty. J Arthroplasty 1996;11:359–67.