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GAIT ANALYSIS WITH AN ANGLE DIAGRAM TECHNIQUE

Application in Healthy Persons and in Studies of Marmor Knee Arthroplasties

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Normal step dimension data were obtained from six healthy subjects by recording step length and step frequency at different walking speeds. In addition, an externally applied goniometer system was used to measure the sagittal knee and hip joint movements in eleven persons with healthy joints. The movements were recorded on an oscilloscope in the form of a so-called angle diagram during walking. In seven patients undergoing Marmor knee arthroplasty the same gait analysis as in the healthy subjects was performed before and after operation. The results were compared by a clinical scoring system for pain and walking ability and by measurement of passive knee mobility and passive extension deficit. The angle diagram permitted recording of functional sagittal mobility and functional extension deficit during walking. The functional knee mobility during walking was found to be pain-dependent; thus increasing pain is accompanied by a gradual decrease in functional mobility despite good passive knee joint motion. In several patients the functional extension deficit during walking was increased compared with the extension deficit on passive movement. The clinical improvements after knee arthroplasty corresponded very well to the increased functional knee mobility during walking, measured on the angle diagram.

Key words: gait analysis; knee arthroplasty; rheumatoid arthritis; osteoarthritis

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The rapid technical development of arthroplastic procedures today necessitates an evaluation of the results of surgery so that comparisons between different types of implants and operative procedures can be made. The need for objective methods of measurement is clear, especially in view of the fact that different social conditions and requirements in different countries give rise to discrepancies between clinical assessments, which become coloured both by the patients' and by the examiners' subjective opinions. Furthermore, objective methods of measurement can provide support in cases where there are doubtful indications for operation and facilitate checking and evaluation of problematic joints.

Concerning the knee, Collopy et al. (1977) reported a study with gait analysis in geometric knee arthroplasty, and Stauffer et al. (1977) also emphasized the need for such an analysis in the evaluation of diseased knee joints. On the other hand, Freeman et al. (1977) have presented a sophisticated scoring system for assessment based on clinical findings alone.

In this paper the results of gait analysis in persons with healthy knees are presented first. A comparison is then made between the objective measurement results obtained by gait analysis in a group of patients with degenerative joint disease before and after Marmor knee arthroplasty (Marmor 1973), and the results of clinical assessments of these patients. The system of instrumentation for gait analysis and the method of

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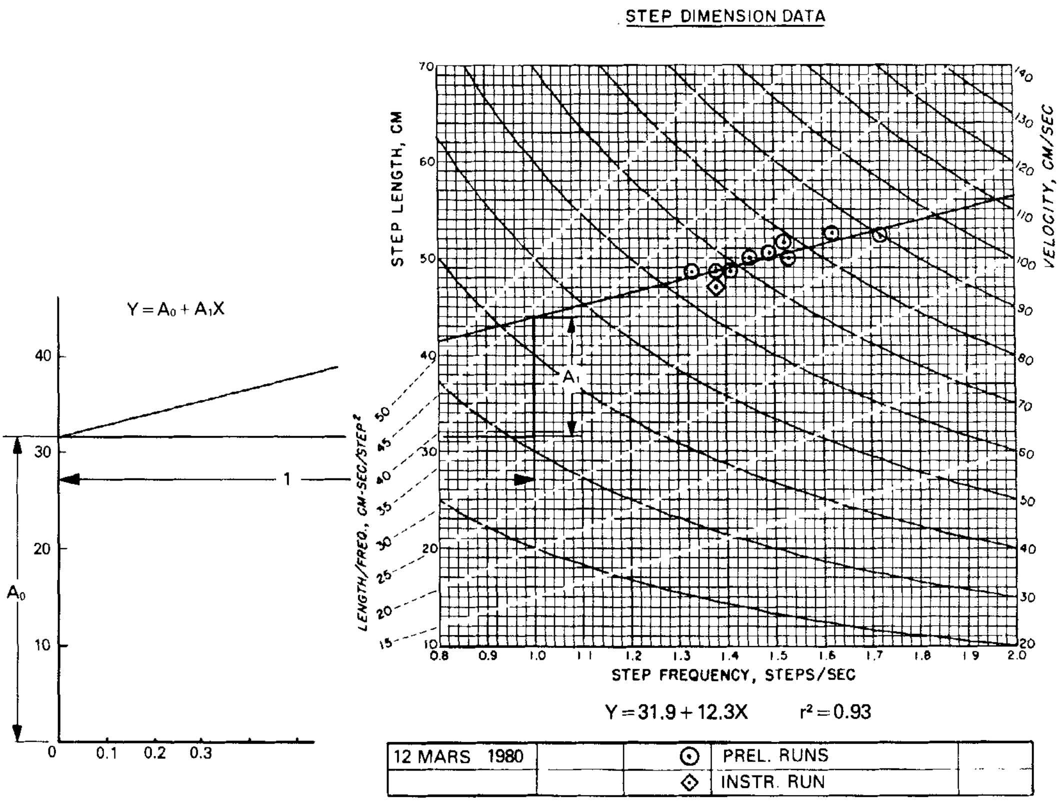

Figure 1. A step dimension graph from a knee arthroplasty patient with the pertinent linear regression line.

measurement have been reported by Öberg & Lamoureux (1979).

MATERIAL AND METHODS

The step length and step frequency were measured in the gait laboratory in six healthy subjects (ages 14–42 years, mean 29 years), an attempt being made to obtain the greatest possible variation in the speed of walking. The mean value obtained at every run on the 5 m long measurement track was plotted on a so-called step dimension graph (Figure 1), to facilitate visualization and interpretation (cf. Öberg & Lamoureux 1979). A linear regression line relating step length (l) to step frequency (f) over a person's full range of walking speeds provides a simple, objective description of the manner in which the person changes speed (speed = v = l × f) (cf. Andriacchi et al. 1977). Such a line is characterized by three variables: 1) the slope of the line, A_1, 2) the point at which the line crosses the vertical axis, A_0, and 3) the measure of how close to the regression line the data points actually lie. This measure is called the coefficient of determination and is equal to the square of the correlation coefficient, abbreviated r^2. The closer r^2 is to 1, the closer the data points come to lying on the regression line, i.e., the better is the linear correlation between step length and step frequency.

Using a specially developed system of instruments (Figure 2) (Öberg & Lamoureux 1979), electrogoniometers were then applied on eleven healthy subjects – four males, mean age 27 years (range 22–37 years) and seven females, mean age 26 years (range 20–36 years). During walking at voluntary speed the flexion angles at the knee and hip joints were recorded in the form of a hip-knee angle diagram (Grieve 1968) on an oscilloscope (Figure 3). As a rule three walking cycles were recorded for each leg and the finding was documented by photographing the oscillogram with a polaroid camera. By calibration, functional angles could be read from the oscillogram.

Seven knee arthroplasty patients – three with rheumatoid arthritis and four with osteoarthritis – underwent the same gait analysis as the normal subjects. Step dimension data A_1, r^2 and v_{max} (maximum speed)

Figure 2. The electrogoniometric instrument applied on a subject.

were calculated. Angle diagrams comprising the hip and knee joint sagittal mobility during walking at voluntary gait velocity were recorded by means of the externally applied goniometers mentioned above; the patients were also assessed clinically, independently of the gait analysis, with respect to pain, walking ability, passive knee mobility and passive extension deficit. For evaluating pain and walking ability, a classification originally presented by Merle d'Aubigné (Merle d'Aubigné et al. 1949, Merle d'Aubigné & Postel 1954) was used, with grading of these two variables from 1 to 6, a score of 1 corresponding to the most severe handicap and 6 to the normal condition (Table 1). The examinations were performed preoperatively and about 6 months and 3 years postoperatively. In the patient group the mean values for functional knee mobility during walking, obtained from the angle diagrams, and for passive knee mobility measured clinically, were tabulated according to the corresponding pain score. As a clinical correlation between pain and walking ability

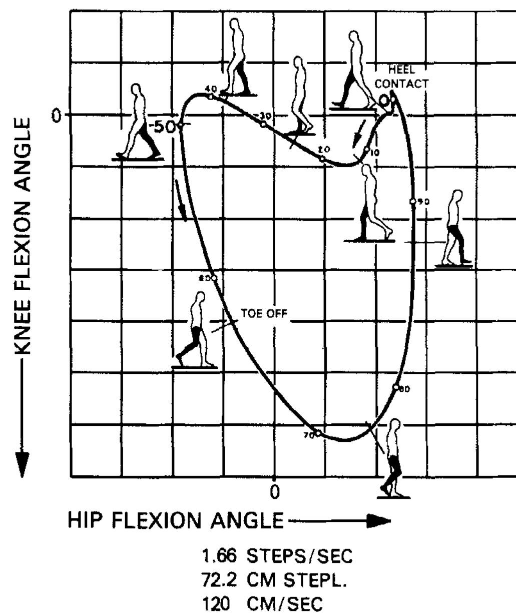

Figure 3. Hip-knee angle diagram for a normal subject walking at moderate speed with corresponding gait cycle phases.

Table 1. Merle d'Aubigné classification (modified) for grading pain and walking ability, 1–6 (cf. text)

	1	2	3	4	5	6
PAIN	Pain even at rest.	Severe when trying to walk. Prevents physical activity.	Moderate. Permits some physical activity.	Pain after physical efforts, disappears at rest.	Initial pain.	No pain.
	1	2	3	4	5	6
WALKING ABILITY	Confined to bed or some mobility when supported.	Time and range very limited with or without support.	Less than 1 km using stick. Can stand upright for considerable periods	Considerable range, using a stick, limited without.	No stick required, remaining lameness.	Normal gait.

was considered likely, these parameters were examined before and after operation in knee arthroplasty patients (70 knees).

RESULTS

Step dimension data for the group of six healthy subjects are given in Table 2, showing a good linear correlation between step length and step frequency (i.e. $r^2 \times 100 > 87$).

In the second group of 11 healthy subjects the mean functional knee mobility during walking, measured on the angle diagram, was 63 ± 4° (SD), with a range of 55–70° (Table 3) (cf. Kettelkamp et al. 1970).

The maximal functional extension during walking was also recorded in these eleven subjects. Large inter- and intraindividual variations were found (Table 3).

In the seven patients who underwent knee arthroplasty, an attempt was made to compare the step dimension data with the clinical assessment of pain and walking ability, but no correlation was found in this group. In general, neither an improvement of linear correlation nor increased maximum speed was found despite increased walking ability and freedom from pain postoperatively.

The results of the angle diagram investigations of these seven arthroplasty patients are reported separately below as an Appendix, with relevant tables and comments.

Table 4 shows that the mean functional sagittal mobility increased progressively with decreasing pain. The probability of this being due to chance

Table 2. Some step dimension data for normal subjects showing a good linear correlation between step length and step frequency

Sex	Age (years)	Average of voluntary gait velocity (cm/s)	Max. gait velocity (cm/s)	A_1 cm s	$r^2 \times 100$
F	25	135±20 (SD)	172	30.6	96
M	26	107±28 (SD)	153	44.4	92
M	30	120±27 (SD)	172	46.2	93
M	35	110±28 (SD)	160	44.4	95
M	42	117±30 (SD)	162	27.6	88
M	14	150±55 (SD)	269	31.0	92

Table 3. Functional range of motion and extension of the knee joints found in 11 healthy subjects

Sex	Age (years)	Gait velocity (cm/s)	Functional range of motion (degrees)		Functional extension (degrees)	
			Left	Right	Left	Right
M	37	115	63	67	+2	+5
M	22	140	70	70	0	+3
M	26	100	60	60	0	+2
M	22	129	60	65	+3	0
F	31	124	70	67	+5	+5
F	22	140	60	55	0	–5
F	20	110	58	60	+5	+10
F	28	114	65	62	+5	+1
F	20	142	65	63	0	–5
F	36	109	63	55	–5	–6
F	22	127	63	63	–2	–5

Table 4. Mean values of functional and passive range of motion at corresponding pain scores for the patient group throughout the observation time

Pain score	Functional range of motion (mean)	Passive range of motion (mean)
1	0.0°	90°
2	7.5°	80°
3	28.6°	86°
4	37.0°	90°
5	38.3°	105°
6	49.3°	117°

is 1 in 6! = 1 in 1·2·3·4·5·6 = 1 in 720 = 0.0014 (i.e. $P < 0.01$). That it is due to chance is thus highly unlikely and there is therefore the greatest probability that a positive correlation exists between increased pain and reduced functional mobility (cf. Kettelkamp et al. 1972, Stauffer et al. 1977). It is also evident from Table 4 that even when there was minimal or no functional mobility, the passive movement was good. Observations made on three different occasions on nine knees in seven patients are presented graphically in Figure 4. A regression line has been inserted in order to indicate the positive slope and thus the positive correlation, but there were too few independent observations to allow any conclusion to be drawn as to the position of the regression line in the diagram in the case of a large number of independent observations.

A positive correlation was not only found between knee pain and functional knee mobility during walking, but also between the patients' walking ability and their functional knee mobility. However, this correlation was probably secondary to a strongly positive correlation between decreasing pain and increasing walking ability as shown in Figure 5. This figure summarizes the clinical findings with respect to pain and walking ability pre- and postoperatively in the whole group of patients (= 70 knee joints). Ten knees before and after operation, altogether 20 observations, are excluded from the figure because of irrelevant hindrance to walking that had no connection with knee pain; for example, asthma, gangrene of a toe, pain from other joints,

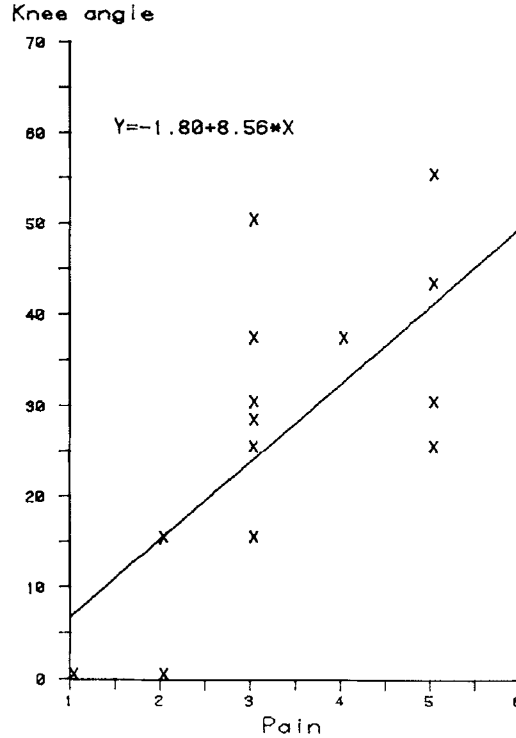

Figure 4. Pain assessment with corresponding knee mobility as found on the angle diagram and with the pertinent linear regression line. Some of the observations are superimposed on each other.

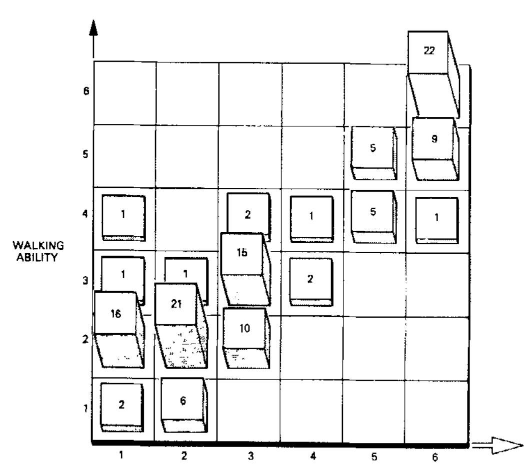

Figure 5. Relation between pain and walking ability. The figures in the graph indicate the number of observations. Thus less pain results in better walking ability.

hypothyroidism, and a residual condition after a fracture of the femoral neck. As seen in the figure, with decreasing pain the walking ability improved. Thus, there is a positive correlation between pain and walking ability scores.

DISCUSSION

This study, as others, shows that in healthy subjects there is a linear correlation between step length and step frequency, with a correlation coefficient close to 0.9 or higher. In the group of patients, on the other hand, no linear correlation was found. Neither was any relationship found in the patients between clinically assessed walking ability and step dimension data. This is probably due to the fact that in the clinical evaluation of a patient's walking ability, less consideration is paid to the gait pattern and to the capacity to increase the speed of walking. The main concern is the patient's ability to cover a certain distance at a speed reasonable for his age.

There is at present no way of measuring the intensity of pain objectively. The observations in this study revealed that with progressively increasing pain the knee mobility during walking decreased accordingly, although the passive mobility was good. This is in accordance with clinical observations. *The results therefore indicate that the functional sagittal mobility of a knee with degenerative disease might be a quantitative measure of the intensity of the pain.*

No definite correlation between passive mobility and pain was found, and the same was reported by Stauffer et al. (1977), but in this context the duration of the pain should be taken into consideration. It seems reasonable to assume that prolonged severe pain in the knee joint due to degenerative disease will gradually also have a negative effect on the passive range of movement.

The large individual variations in functional extension of the knee joint during walking, found in this study, may imply that the technique for application of the instrument on the patient's leg needs to be altered, as some observations showed that functional hyperextension occurred even in patients without hyperextension during passive measurements (see Table 3). Such an adjustment of the 0° point on the oscilloscope (extended knee), however, does not influence the value obtained for functional mobility.

A comparison of the functional knee mobility in the pain-free patients who had undergone a knee arthroplasty (48° ± 7°; mean ± SD) and that in the healthy subjects (63° ± 4°; mean ± SD), showed a clear difference (cf. Chao et al. 1980). The difference may be due partly to age-dependent differences in muscle power between the two groups, and also possibly to muscle disease in the former group (rheumatoid arthritis) (Stauffer et al. 1977), but another conceivable reason is the mechanics of the artificial knee joint, which can never achieve the same complex pattern of motion as a healthy, natural joint.

Measurements of functional knee mobility by the angle diagram technique might provide a valuable supplementary examination in the assessment of the mechanical function of different prostheses. Poor function is undoubtedly one of the important causes of loosening of a joint implant.

APPENDIX

The results of the angle diagram investigations of seven arthroplasty patients.

Table I

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	1/2 y postop.	3 y postop.	Preop.	1/2 y postop.	3 y postop.
M	72	RA	30°–60°	20°–50°	25°–50°	15°–100°	15°–100°	15°–125°

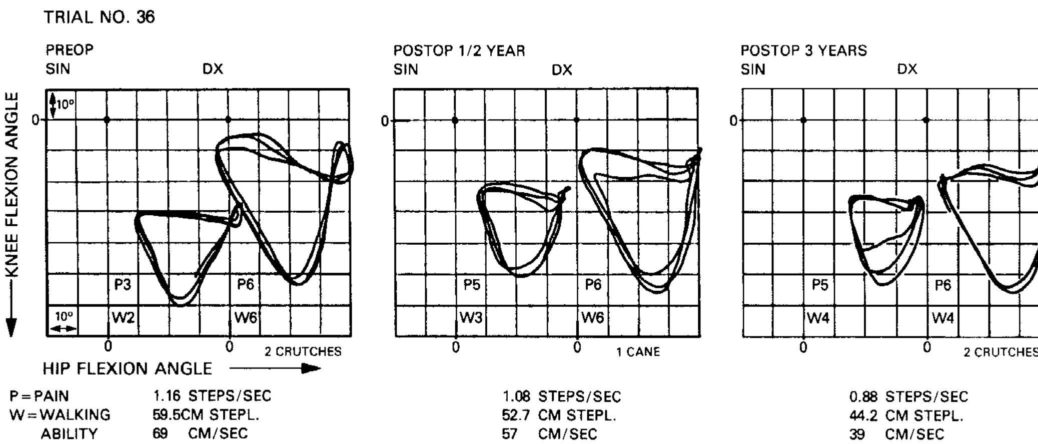

Table I and Figure I. Marmor arthroplasty of the left knee performed in November 1976. The functional mobility recorded from the angle diagram of the left knee was clearly reduced to about 30° throughout the period of observation, whereas the functional extension deficit decreased somewhat postoperatively. The passive mobility of the knee was 85° to 110° the whole time. Hypothyroidism, diagnosed postoperatively, was considered an important factor which influenced the patient's training and muscle function and thus probably also the gait pattern.

Table II

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	1/2 y postop.	3 y postop.	Preop.	1/2 y postop.	3 y postop.
F	58	RA	0°–50°	+5°–55°	+5°–45°	0°–105°	0°–110°	0°–105°

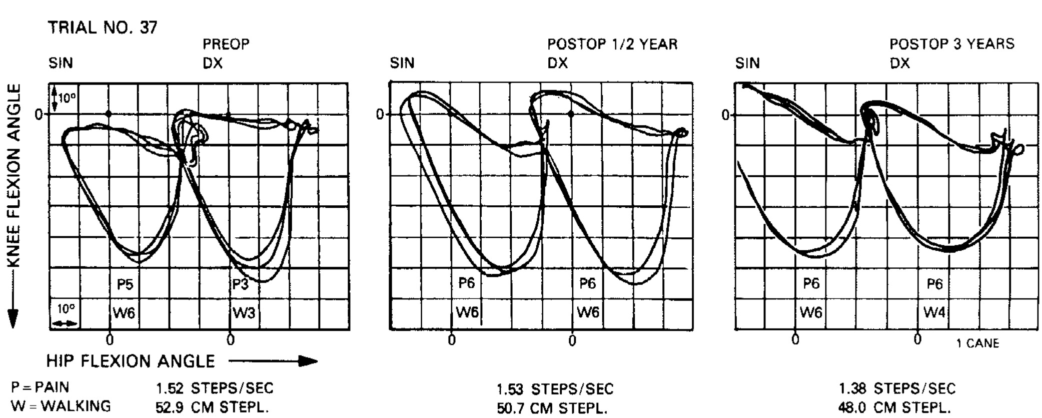

Table II and Figure II. Multiple joint involvement, treated with cortisone; Charnley arthroplasty of the right hip in 1975, Marmor arthroplasty of the right knee in November 1976, left hip arthroplasty in December 1978 and left ankle arthroplasty in April 1979. At the time of preoperative gait analysis (1976) the patient had synovitis in the left nonoperated knee, which probably affected the functional mobility. In both knees the passive mobility was very good at all examinations. Postoperatively the synovitis in the left knee subsided. The first postoperative analysis shows very good functional mobility, while at the second one it is decreased by 10°. This is probably a manifestation of the patient's feeling of an increasing instability. No objective instability of the knee was found at clinical examination.

Table III

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	1/2 y postop.	3 y postop.	Preop.	1/2 y postop.	3 y postop.
M	73	RA	30°–30°	20°–60°	20°–65°	10°–100°	0°–110°	0°–120°

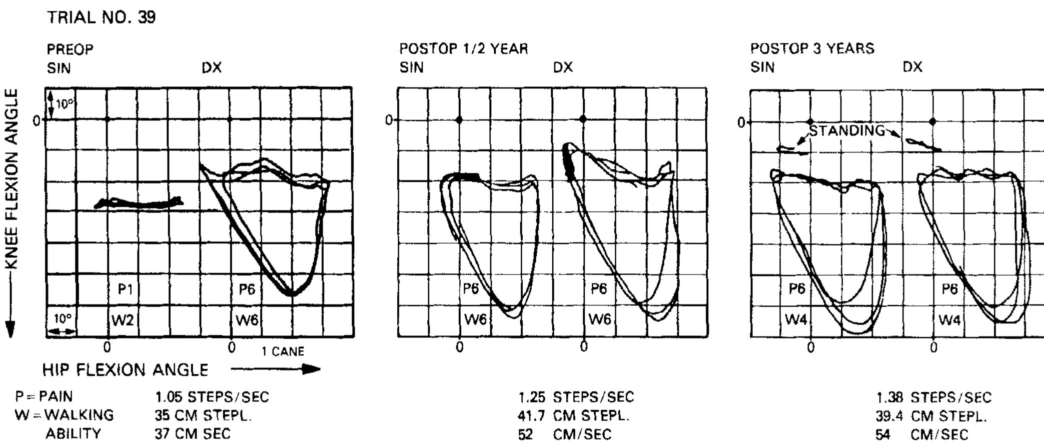

Table III and Figure III. Before knee arthroplasty the left knee was very painful, with almost no functional mobility despite a passive range of movement of 90°. There was also an increased functional extension deficit compared with the unaffected right knee. At the 3-year follow-up knee extension on standing is indicated; thus there was an extension deficit of 10°, but no passive extension deficit. On walking there was a functional extension deficit of 20°, measured on the angle diagram. As a result of late-onset diabetes with increasing ischaemia in the right foot, the walking ability deteriorated gradually and about 2 months after the 3-year follow-up, below-knee amputation was performed because of gangrene.

Table IV

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	1/2 y postop.	3 y postop.	Preop.	1/2 y postop.	3 y postop.
F	72	OA	22°–47°	12°–55°	5°–60°	0°–90°	0°–110°	0°–115°

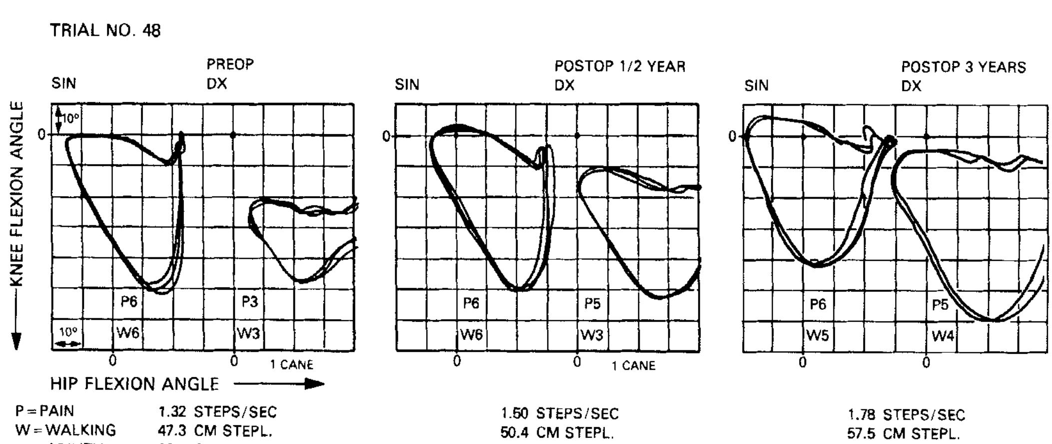

Table IV and Figure IV. Because of increasing pain, with a score of 3 preoperatively, Marmor arthroplasty of the right knee was performed in January 1977. The functional range of movement gradually increased postoperatively and the functional extension deficit gradually decreased. The walking ability was poor as a result of severe sciatica.

Table V

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	½ y postop.	3 y postop.	Preop.	½ y postop.	3 y postop.
F	61	OA	10°–47°	10°–47°	2°–50°	+10°–95°	0°–90°	0°–95°

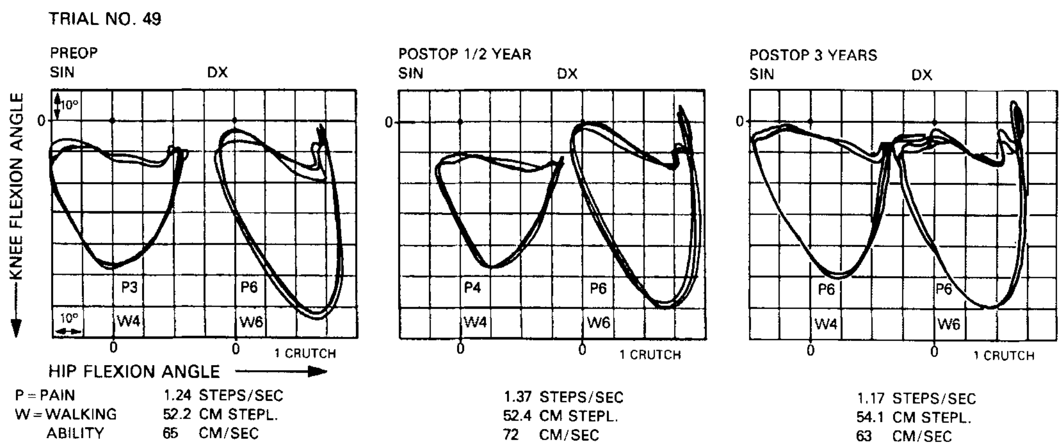

Table V and Figure V. In 1973 a St. Georg "sledge" prosthesis (Engelbrecht 1971) was inserted medially in the left knee, because of a fracture of the tibial condyle. In 1974 the patient sustained a trochanteric fracture of the left femur, which was nailed by the Ender method (Ender & Weidner 1970). This fracture resulted in leg shortening of 4 cm and muscle inefficiency. Because of increasing pain in the lateral knee compartment, complementary lateral Marmor arthroplasty of the knee was performed in February 1977. Postoperatively the functional mobility improved to nearly 50° at the 3-year follow-up. The walking ability was still reduced because of sequelae to the hip fracture mentioned above.

Table VI

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	½ y postop.	3 y postop.	Preop.	½ y postop.	3 y postop.
F	75	RA sin	0°	10°–55°	5°–55°	25°–90°	0°–110°	0°–110°

Table VI b

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			½ y preop.	Preop.	3 y postop.	½ y preop.	Preop.	3 y postop.
F	75	RA dx	5°–60°	15°–43°	10°–50°	0°–120°	10°–90°	0°–115°

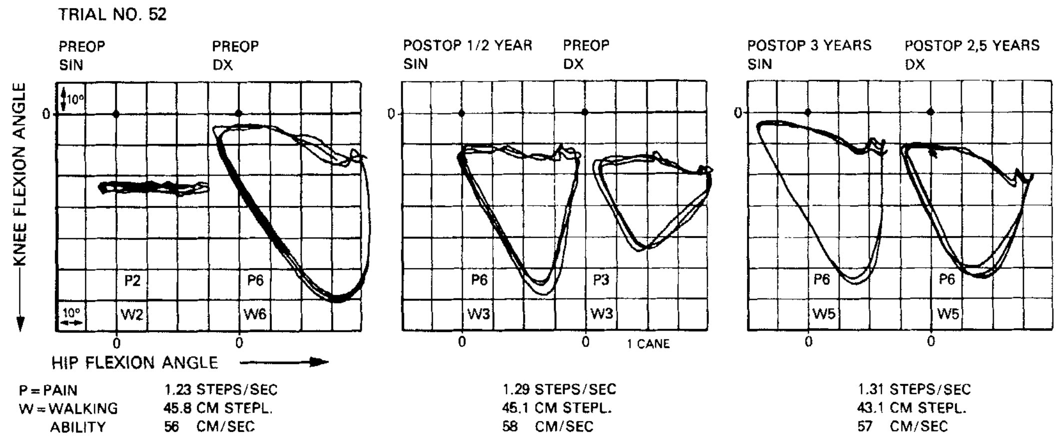

Table VI a, b and Figure VI. Marmor arthroplasty of the left knee was performed in February 1977 because of severe pain. Six months postoperatively this knee was free from pain and the functional mobility was 45°. In the meantime the right knee had become increasingly painful (pain score 3), with increasing joint degeneration, and the functional mobility of the right knee, which was previously 55°, had now decreased to about 30°, although the passive range of movement was still 10–90°. Marmor arthroplasty of the right knee was performed in October 1978 and thus at the 3-year examination both knees had undergone the operative procedure and the functional mobility was clearly improved on both sides compared with preoperatively.

Table VII a

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			Preop.	½ y postop.	3 y postop.	Preop.	½ y postop.	3 y postop.
F	35	RA sin	0°–15°	+10°–35°	+3°–50°	0°–100°	0°–90°	0°–95°

Table VII b

Sex	Age (years)	Diagn.	Functional range of motion			Passive range of motion		
			½ y preop.	Preop.	3 y postop.	½ y preop.	Preop.	3 y postop.
F	35	RA dx	+5°–10°	+5°–10°	+10°–50°	0°–70°	5°–100°	0°–105°

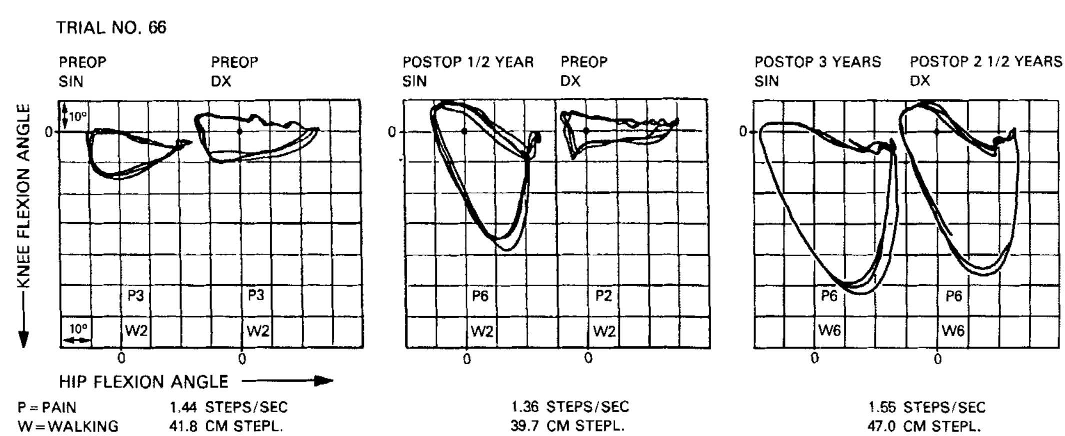

Table VII a, b and Figure VII. Preoperatively both knees were severely affected by rheumatoid arthritis and the left knee was considered most painful, although both knees were assessed as having the same pain score. The left knee was therefore operated on first in May 1977. Six months later the first gait analysis was performed and the functional mobility had now increased to 45°, while the functional mobility in the nonoperated knee was unchanged. Shortly afterwards, Marmor arthroplasty was performed on the right knee, which at that time had a pain score of 2, and at the later follow-up the patient had two completely pain-free knees with an unlimited walking ability and good functional knee mobility bilaterally.

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