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Changed gait pattern in patients with total knee arthroplasty but minimal influence of tibial insert design

Gait analysis during level walking in 39 TKR patients and 18 healthy controls

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Introduction **Previous radiostereometric studies have revealed abnormal anterior-posterior translation of the femur in patients operated with AMK (DePuy, Johnson and Johnson, Leeds, UK) total knee arthroplasty (TKA). Based on these observations, we hypothesized that patients with TKA have an abnormal gait pattern, and that there are differences in kinematics depending on the design of the tibial joint area.**

Method **We used a gait analysis system to evaluate the influence of joint area design on the kinematics of the hip and knee during level walking. 39 TKA patients (42 knees) and 18 healthy age-matched controls were studied. Patients with 5° varus/valgus alignment or less were randomized to receive either a relatively flat or a concave tibial insert with retention of the posterior cruciate ligament. Patients who had more than 5° varus-valgus alignment and/or extension defect of 10° or more were randomized to receive the concave or a posterior-stabilized tibial component with resection of the posterior cruciate ligament.**

Results **Patients with TKA tended to have less hip and knee extension and decreased knee and hip extension moment than controls. They also tended to walk more slowly. TKA altered the gait pattern, but choice of implant design had little influence.**

Interpretation **In patients with a similar degree of degenerative joint disease and within the limits of the constraints offered by the prostheses under study, the choice of joint area constraint has little influence on the gait pattern.**

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Earlier gait analysis studies (Andriacchi et al. 1982, Dorr et al. 1988, Goh et al. 1993, Chassin et al. 1996, Hilding et al. 1996, Bolanos et al. 1998, Ishii et al. 1998, Hilding et al. 1999, Lee et al. 1999, Otsuko et al.1999) have shown that the gait pattern of patients with total knee arthroplasty (TKA) differs from that of healthy people. Andriacchi et al. (1982) found that TKA patients had shorter than normal stride length, reduced mid-stance knee flexion, and abnormal patterns of external flexion-extension moment of the knee. Kramers-deQuervain et al.(1997) reported that patients with TKA had gait velocity below normal values. They also spent a decreased percentage of time in single-limb stance and had abnormal sagittal plane knee motion, with decreased peak values and decreased range of motion during stance and swing.

The influence of TKA design on level or stair walking is controversial. Several authors (Hilding et al. 1996, Bolanos et al. 1998) could not document any influence of TKA design, whereas others observed more pronounced deviations from normal with increasing prosthetic constraint and

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resection of the posterior cruciate ligament (PCL). Andriacchi et al. (1982) reported that patients with unconstrained cruciate retaining inserts had more normal gait during stair climbing than those with the more constrained cruciate-sacrificing designs. Dorr et al. (1988) found that knees with cruciate-sacrificing TKA (Total Condylar, Johnson and Johnson, Braintree, MA) had more flexion and increased flexion and varus moments during loading than knees with posterior cruciate-retaining TKA. Kramers-deQuervain et al. (1997) showed that knees with unconstrained inserts had significantly higher values for peak knee flexion than knees with semiconstrained inserts. Cloutier (1983) found greater knee flexion during stair walking in patients with non-constrained prostheses than in those with semiconstrained total condylar prostheses.

Uvehammer et al. (2000a, b) used dynamic radiostereometry to study the kinematics of 4 variations of the AMK prosthesis during a single step up. All designs showed anterior femoral subluxation with increasing flexion, and to varying extents. Surprisingly, the most stable designs showed the most pronounced AP displacements. We aimed to evaluate if the differences detected during a standardized extension of the knee, also implied changed knee function during level walking. Most previous studies of gait pattern after total knee replacement have been based on selected patient material that only included cases with good or excellent clinical results (Andriacchi et al. 1982, Simon et al. 1983, Chassin et al. 1996). Thus, these studies might reflect the peak performance of a certain prosthetic design, but may be less informative concerning expected overall functional results. In our study, the patients were not primarily selected by clinical outcome.

We studied 39 patients (42 knees) who were operated with different variations (flat, concave and posterior stabilized design) of the AMK total knee replacement, and 18 healthy age-matched controls. Hip and knee flexion-extension and adduction-abduction angles and moments were evaluated during level walking. Based on previous observations quoted above (Andriacchi et al. 1982, Cloutier 1983, Dorr et al. 1988, Kramers-deQuervain et al. 1997, Uvehammer et al. 2000), we hypothesized that patients with TKA have abnormal gait pattern, and that the knee kinematics differ depending on the design of the tibial joint area.

Patients and methods

Gait analysis

All patients had participated in a prospective randomized study (Uvehammer et al. 2001 a, b). In that study, 83 patients (87 knees) with non-inflammatory arthrosis of the knee were operated with the cemented AMK total knee prosthesis. Patients with a 5° or less varus/valgus malalignment were randomized to receive either a relatively flat or a concave tibial plateau. The posterior cruciate ligament (PCL) was retained. Patients who had more than 5° varus-valgus malalignment and/or extension defect of 10° or more were randomized to receive either concave or a posterior-stabilized tibial component. The posterior cruciate ligament was sacrificed. The alignment was measured in radiographs as hip-knee-ankle (HKA) angle (Hagstedt et al. 1980). The fixation of the tibial component, and the clinical results up to two years after the operation have been reported previously (Uvehammer et al. 2001 a, b). The Ethics Committee of Göteborg University approved the study.

Motion analysis was done one to two years after surgery. 50 patients (53 knees) from the primary study material agreed to participate in motion analysis. Statistical analysis did not reveal any differences in HSS scores between the patients who were willing and those not willing to participate in the study. 4 of these 50 patients were excluded because of ipsilateral total hip arthroplasty, 1 patient because of Parkinson disease, and one who could not follow our instructions during the examination. 19 age-matched controls agreed to participate. They had no history or symptoms of musculoskeletal disease or knee problems. Tracking problems, i.e. difficulties in detecting markers by the software, left 38 patients (41 knees) and 18 controls for final analysis (Table 1).

Our motion laboratory is equipped with six infrared cameras recording at 240 Hz (MCU 240 Qualisys AB, Qualisys Medical AB, Göteborg, Sweden). The camera system was calibrated to a measurable space of 9.2 m^3 (2 m × 2 m × 2.3 m). 20 retroreflective spherical markers were attached to the

Table 1. Patient data and clinical results. Median (range)

	PCL retained		PCL resected		Controls
	Flat	Concave	Concave	PS	
Male/female	1 / 10	4 / 5	7 / 5	5 / 4	9 / 9
Age (years)	73 (61–80)	70 (62–81)	72.5 (54–89)	72 (54–83)	69.5 (50–87)
Weight (kg)	77 (46–118)	88 (67–110)	77 (59–126)	72 (67–126)	72 (59–98)
BMI	28 (20–4)	31 (22–34)	27 (21–40)	27 (24–40)	26 (22–33)
HSS score					
Preoperatively	69 (51–79)	61 (56–76)	64 (54–73)	56 (51–79)	
1 year	81 (72–94)	85 (73–94)	89 (61–96)	85 (61–95)	
2 years	84 (72–97)	86 (79–97)	95 (77–97)	95 (77–97)	

BMI, body mass index; PS, posterior stabilized insert; PCL, posterior cruciate ligament.

skin over bony landmarks (acromion, 12th thoracic vertebra, sacrum, anterior superior iliac spine, greater trochanter, lateral knee joint line, proximal to the superior border of the patella, tibial tubercle, heel, lateral malleolus and between the second and third metatarsals). Markers were placed bilaterally. Euler angles were calculated (Kadaba et al. 1990, Davis et al. 1991) using the proximal segment as fixed and the distal as moving. Markers attached to the pelvis were used for calculation of the center, and markers attached to the lower leg and ankle were used to identify the knee and the ankle joints. The longitudinal axis of the thigh segment passes through the knee and hip joints. In the lower leg, it passes through the calculated center of the knee and ankle joint. The anterior-posterior axis of the foot segment passes through the heel marker and toe markers.

Two force plates (Kistler 9281C, Kistler Instrumente AG, Winterthur, Switzerland) were used to record ground reaction forces during level walking (Vaughan et al. 1992). QGait 2.0 (Qualisys Medical AB, Göteborg, Sweden) was used for calculation of joint angles and joint moment of force. The moments were obtained by solving from the most distal segment (ankle) proximally. Each segment (foot, leg, thigh) defined by skin markers was isolated from the other segments as a free body for the calculations. Qgait 2.0 software was used to calculate the center of the joints using the 3-dimensional coordinates of skin markers. 8 piezoelectric sensors in each force plate recorded the magnitude, direction and position of the ground reaction force. The mass of each segment was calculated as a percentage of body mass. The QGait software also calculated the segmental moment of inertia and thereafter internal moments about the most distal joint (ankle). The calculated internal moments about the more distal joint were used as input when calculating the corresponding moments about the more proximal joints. The joint moments were normalized for the individual weight of the subjects (Nm/kg). Images from the 6 cameras and the forces were recorded synchronously.

Recordings of motion were achieved using QtracC version 2.51 software (Qualisys Medical AB, Göteborg, Sweden). Reconstruction from two-dimensional into three-dimensional data was made with QtracV version 2.60 (Qualisys Medical AB). QGait 2.0 was used to calculate rotations of the hip and knee joint in relation to the three cardinal axes. In this report, only motions in the sagittal (flexion/extension) and frontal (abduction/adduction) planes are reported. Patient data are presented only for the operated limb. In the controls, measurements of both limbs were recorded and the median of the sum of measurements of both limbs is presented.

The patients and controls were asked to walk without targeting on the force plates at self-selected speed. Several trials preceded the actual measurements to define a starting line, which facilitated stepping on both force plates according to the step length of the individual patient. The results are presented as maximum values for each parameter. Walking speed, stride length and cadence were calculated. Three successful measurements were recorded for each patient, and the most optimum of them was used for further analysis.

Table 2. Cadence, speed and stride length. Median (range)

	PCL retained		PCL resected		Controls
	Flat	Concave	Concave	PS	
Cadence (steps/min)	98 (61–122)	97 (63–120)	90 (78–123)	95 (83–115)	109 (86–122)
Speed (m/s)	0.9 (0.5–1.2)	1.0 (0.5–1.5)	1.0 (0.7–1.4)	1.0 (0.7–1.3)	1.2 (0.8–1.3)
Stride length (m)	1.1 (1.0–1.3)	1.3 (0.8–1.5)	1.3 (1.0–1.4)	1.2 (1.1–1.4)	1.3 (1.1–1.5)

PS, posterior stabilized insert; PCL, posterior cruciate ligament.

Clinical and radiographic evaluations

In the TKA patients, the Hospital for Special Surgery (HSS) knee score (Ranawat and Shine 1973) was recorded preoperatively and two years after operation. The hip-knee-ankle (HKA) angle (Hagstedt et al. 1980) was measured preoperatively and two years after operation.

Statistics

We used non-parametric tests, as most of the result parameters showed a skewed distribution. According to the study design, the two groups of patients operated with and without resection of the PCL were analyzed separately and compared with the control group using non-parametric ANOVA (Kruskall-Wallis test). If this test revealed a difference, further analysis between the groups within each stratum was done using Mann-Whitney test. To compensate for repeated testing, p-values less than 0.025 were considered to represent statistically significant differences.

Results

Clinical results and HKA angle

The HSS scores recorded preoperatively, and at one and two years of follow-up, did not differ between the TKA groups within each stratum ($p > 0.3$). The HKA angle determined two years after operation did not differ either ($p > 0.7$) (Table 1).

Flat and concave tibial insert with retained PCL

Velocity, stride length and cadence. In the group with flat tibial insert, velocity and stride length were reduced compared to the controls ($p = 0.003$ and $p < 0.001$, respectively) (Table 2). The velocity and stride length did not differ between the patients with concave insert and the control group ($p > 0.09$), or between the patient groups ($p > 0.1$). Cadence did not differ between the groups ($p = 0.08$).

Hip. The patients with concave tibial insert flexed their hip more than the patients with flat insert and the controls (concave vs. controls, $p = 0.006$, concave vs. flat insert, $p = 0.03$) (Table 3). They also extended their hip less than did the controls ($p = 0.002$), whereas patients with flat insert showed hip extension closer to the controls ($p = 0.1$). The difference in maximum hip extension between patients with flat insert and concave insert did not reach significance ($p = 0.04$).

There were no statistically significant differences in maximum hip adduction/abduction or extension/flexion moments, or hip adduction/abduction angles between the two groups with retained PCL, or between the groups with retained PCL and the controls ($p > 0.09$) (Table 3).

Knee. In both patient groups, there was a tendency to less knee extension compared to the controls, but a significant difference was only found in the group with concave tibial insert (flat vs. controls, $p = 0.2$, concave vs. controls, $p = 0.01$) (Table 3). There was no difference in maximal knee extension between the patient groups ($p = 0.03$). No statistically significant differences were seen in maximal knee flexion between the patient groups, or between the patients groups and the controls ($p > 0.1$). Compared to the controls and the patients with the concave component, maximum knee abduction was decreased in the group with the flat component ($p = 0.004$ and $p = 0.02$, respectively). The flat-insert group also had increased maximum knee adduction, and this difference was statistically significant compared to the controls

Table 3. Maximum angles and moments. Median and range are presented PCL retained

	PCL retained		PCL resected		Controls
	Flat	Concave	Concave	PS	
Angles (°)					
Hip flexion	30 (19–39)	37 (27–46)	33 (20–52)	34 (28–52)	29 (19–43)
Hip extension	8 (1– 21)	5 (-6–19)	5 (-8–24)	3 (-8–10)	16 (5–22)
Hip adduction	5 (2–29)	6 (2–13)	5 (2–38)	7 (1–9)	6 (0–9)
Hip abduction	3 (-1–6)	2 (-1–12)	2 (-3–7)	3 (0–7)	5 (1–7)
Knee flexion	56 (21–63)	60 (43–70)	58 (29–74)	66 (54 –74)	60 (47–68)
Knee extension	0 (-4–5)	-8 (-19–5)	-7 (-19–7)	-11 (-19–-2)	3 (-12–10)
Knee adduction	7 (-2–22)	3 (-2–8)	5 (-6–10)	4 (-5–9)	3 (-3–9)
Knee abduction	0 (-7–17)	5 (1–15)	6 (-4–16)	6 (-4–13)	6 (0–13)
Moments (Nm/kg)					
Hip flexion	1.0 (-0.1–1.7)	0.9 (0.5–1.7)	1.1 (0.0–2.0)	1.1 (0.9–2.1)	1.3 (0.8–2.0)
Hip extension	0.6 (0.2–1.2)	0.6 (0.3–1.4)	0.5 (0.3–1.0)	0.4 (0.3–0.7)	0.6 (0.4–0.9)
Hip adduction	0.2 (0.1–0.3)	0.2 (0.1–0.5)	0.1 (-0.1–0.1)	0.1 (0.1–0.6)	0.2 (0.1–0.5)
Hip abduction	0.9 (0.1–1.1)	1.0 (0.6–1.2)	0.9 (0.3–1.5)	1.0 (0.8–1.1)	0.9 (0.7–1.0)
Knee flexion	0.2 (0.1–0.6)	0.4 (0.2–2.1)	0.3 (0.2–0.6)	0.4 (0.2–0.5)	0.3 (0.2–0.7)
Knee extension	0.5 (0.0–0.7)	0.3 (0.1–0.8)	0.4 (0.0–0.9)	0.4 (0.3–0.8)	0.6 (0.2–1.0)
Knee adduction	0.2 (0.1–0.6)	0.4 (0.2–2.1)	0.3 (0.2–0.6)	0.4 (0.2–0.5)	0.3 (0.2–0.7)
Knee abduction	0.5 (0.0–0.7)	0.3 (0.1–0.8)	0.4 (0.0–0.9)	0.4 (0.3–0.8)	0.6 (0.2–1.0)

(flat vs. controls, $p = 0.009$, flat vs. concave, $p = 0.03$).

Both patient groups showed reduced knee extension moment (Table 3) compared to the controls (flat vs. controls, $p = 0.02$, concave vs. controls, $p = 0.01$). There was no difference in knee extension moment between the patient groups ($p = 0.5$). The other peak moments (flexion, adduction and abduction) did not differ between the patient groups, or between the patients groups and the controls ($p > 0.2$).

Concave vs. posterior stabilized inserts with resected PCL and controls

Velocity, stride length and cadence. Patients with concave tibial insert and resected PCL had decreased cadence ($p = 0.004$) and velocity ($p = 0.006$) compared to the controls. These parameters were also numerically reduced in the group with PS design, but this difference was not significant ($p > 0.06$). There were no differences in cadence and velocity between the patient groups ($p > 0.2$). There were no statistically significant differences in stride length ($p = 0.4$).

Hip. Both TKA groups had less hip extension than the controls (Table 3) (concave vs. controls, $p = 0.02$, PS vs. controls, $p < 0.001$), but there was no difference between the TKA groups ($p = 0.3$). The maximum hip flexion did not differ between the patient groups, or between the patient groups and the controls ($p = 0.08$).

The maximum hip abduction/adduction movements and moments did not differ between the patient groups, or between the patient groups and the controls ($p > 0.05$) (Table 3).

The group with posterior stabilized insert had lower peak hip extension moment than the controls ($p = 0.003$) (Table 3). There were no other differences in hip extension-flexion moments ($p > 0.05$).

Knee. Patients with posterior stabilized insert extended their knee less than the controls ($p < 0.001$) (Table 3). There was no significant difference in knee extension between the patient groups ($p = 0.1$) or between the group with concave insert and the controls ($p = 0.1$). The other knee parameters analyzed did not differ between the patient groups, or between the patients groups and the controls ($p > 0.05$).

Discussion

The gait pattern of TKA patients differed from that observed in a control population. The TKA patients tended to have lower velocity compared to controls, as observed previously (Andriacchi et al. 1982, Kramers-deQuervain et al. 1997, Bolanos et al. 1998, Lee et al. 1999). Small differences in hip and knee joint movements were found, and they appeared mainly as reduced hip and/or knee extension.

The presence of knee arthrosis commonly results in reduced extension of the knee. Thus, the abnormal gait pattern in the patients operated with TKA might have been acquired preoperatively (Andriacchi et al.1982, Ishii et al. 1998). The patients may also have abnormal muscular function caused by a partial loss of proprioceptive control, or by reduction or imbalance in muscle capacity after the TKA (Andriacchi et al. 1982). Loss of one or both of the cruciate ligaments is probably also of importance, but these ligaments may not have functioned normally preoperatively either. Decreased knee extension was seen in knees with concave insert and retained PCL, and knees with PS insert. Three of the patient groups (excluding those with flat tibial insert) also had reduced hip extension. Patients with retained PCL and concave tibial insert also had increased flexion of the hip.

Abnormal anterior/posterior displacement of the distal femur might be reduced by avoidance of full knee extension and limitation of knee flexion, which will have a secondary effect on the motions and moments of the hip. Patients without full extension of their knee might also have had reduced their hip extension to maintain balance.

Both groups with retained PCL had decreased maximum knee extension moment, as previously shown also in patients with arthrosis of the knee (Kaufman et al. 2001, Gök et al. 2002). Since contact forces in the knee joint are proportional to net external reaction moment, Kaufmann et al. (2001) speculated that OA patients reduced pain by reducing knee extensor moment. In knees operated with TKA, it is more probable that reduction of extension moment has other causes. Previous dynamic radiostereometric studies (Uvehammer et al. 2000 a, b) have shown that the femoral condyles become displaced anteriorly in the AMK prosthesis, with increasing flexion. This abnormal pattern of motion was observed in all joint area designs studied. Change of the tibiofemoral relationship influences the lever arm for the quadriceps tendon, and also induces high patellar pressures and anterior knee pain (Andriacchi et al.1986, D'Lima et al. 2001), which can change knee extension moment. The decreased hip extension moment seen in patients with PS insert reflects the same need as decreased knee extension moment, i.e. the need to stabilize the knee at stance (heel contact).

Wexler et al. (1998) studied patients with anterior cruciate ligament (ACL) deficiency. These patients had significantly decreased external knee flexion and increased knee extension moments compared with control subjects. These changes were interpreted as avoidance of quadriceps and accentuation of hamstring use. Increased flexion angle of the knee for a certain knee flexion moment at midstance was also observed. The pattern of knee extension-flexion moment in the TKA patients in the present study is partly similar to that of ACL- deficient patients in the study of Wexler et al. Decreased internal knee extension moment was found, but there was no difference in internal knee flexion moment.

Hooper et al. (2002) studied patients with chronic posterior instability of the knee using gait analysis and the Flandry score. They hypothesized that reduced extension moment was a compensatory mechanism to reduce posterior knee instability. In their patients, they found lower internal peak knee extensor torque during stance phase in less satisfied patients. This is in line with the results of the present study. Lower internal knee extensor moment was observed during the stance phase in patient groups with little preoperative deformity.

Most previous studies of gait pattern after TKA were based on selected patient material that only included cases with good or excellent clinical results (Andriacchi et al.1982, Simon et al. 1983, Chassin et al. 1996). Thus, these studies might reflect the peak performance of a certain prosthetic design, but are less informative concerning the expected overall functional results. The patients in our study were recruited preoperatively from the waiting list and were not selected according to clinical results. However, relatively low acceptance to participate may have caused some bias. Another confounding factor in the present—and probably in any unselected patient population with total knee prosthesis—is the presence of associated degenerative joint disease. Patients with knee arthrosis frequently have bilateral disease, and also have an increased incidence of hip arthrosis, factors which might influence gait. Our study could not address this problem, because involvement of the opposite knee and/or hip was found frequently. According to the study protocol, presence of ipsilateral THR was an exclusion criteria, because any reduction of hip offset or rotational malposition of the stem or the cup could also be expected to influence the function of the knee.

Walking speed may influence gait parameters such as hip and knee angles and moments (Andriacchi et al. 1977). However, a consistent reduction of velocity was not observed in the present study. Correlation between velocity and the gait parameters appeared inconsistently. Based on this finding, the abnormalities observed in some groups cannot be explained only by changes in walking speed.

To achieve as normal knee kinematics as possible, the design of knee prosthesis should allow extension close to that of normal knees. All variations in design that were studied were associated with gait patterns different from normal, mainly as reduced hip and/or knee extension. Overall, there were no or neglible differences in the gait pattern, which could be related to the design of the joint area in the AMK prosthesis.

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