



## Original Research

## Gait Analysis Comparing Kinematic, Kinetic, and Muscle Activation Data of Modern and Conventional Total Knee Arthroplasty

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## ABSTRACT

**Background:** To provide normal knee function, a total knee arthroplasty (TKA) implant with an anatomic surface shape and an adequate sagittal position has been developed. However, it is unclear how this modern implant influences knee joint kinetics and muscle activation during a gait. Therefore, we evaluated this modern TKA prosthesis and compared it with a conventional TKA prosthesis for gait analysis in terms of kinetics and muscle activation.

**Methods:** Subjects were patients (>60 years of age) with knee osteoarthritis who had undergone unilateral TKA. Twelve patients received the modern TKA prosthesis (group modern), and the other 12 patients received a conventional TKA prosthesis (group conventional). The subjects underwent motion capture analyses with a force plate, and kinematic and kinetic data were acquired from a 10-m gait test. Electromyography data of 6 lower limb muscles were simultaneously collected during the gait test. The 2 groups were compared using unpaired t-tests.

**Results:** In group modern, gait speed was faster, step length was longer, and the knee flexion angle during the initial stance phase was larger. Furthermore, in group modern, the maximum knee extension moment was higher; however, the quadriceps muscle activity tended to be lower than that in group conventional.

**Conclusions:** Gait characteristics of group modern were more like a normal gait, and knee joint extension moments were greater. This finding indicates that the quadriceps muscles can be more effectively activated, and the anterior stability function of the anterior cruciate ligament may be reproduced with the shape of the modern implant.

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## Introduction

Total knee arthroplasty (TKA) is performed in patients with severe knee osteoarthritis (OA) to restore knee function. This procedure shows good clinical results [1,2] and relieves pain just as well as total hip arthroplasty (THA). However, it is not as effective as THA for improving joint function and quality of life [3]. Furthermore, responses to patient-based questionnaires show that patients are not satisfied with their ability to walk, stand, kneel, and

squat after conventional TKA [4,5]. This may reflect the paradoxical motion of the knee joint after TKA. In vivo knee joint kinematics after TKA are usually evaluated using a 2D-3D registration method by fluoroscopy [6]. This method assesses joint motion precisely and can detect abnormal dynamics, such as paradoxical motion [7]. However, 2D-3D fluoroscopy has some disadvantages, including a limited imaging range and difficulty in performing dynamic evaluation. In addition, in patients with poor post-TKA results, imaging does not provide a complete picture of the problem, and additionally, quadriceps weakness affects the postoperative results of TKA [8,9]. Therefore, evaluation of the knee joint function based on kinetics and muscle activity is considered very important.

In recent years, an implant (Journey II; Smith and Nephew, Memphis, TN) with a shape that restores the normal anteroposterior stability provided by the cruciate ligaments has been

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developed. This implant has an insert with an asymmetrical and anatomic joint surface shape, and a natural frontal inclination of the joint line is attained by changing the thickness of the medial and lateral side of the insert and femoral condyles. The bicruciate stabilized (BCS) type of implants has a unique dual cam-post mechanism and provides anterior-posterior stability. In kinematic evaluations using the 2D-3D registration method, the joint dynamics of the BCS implant were similar to those of normal knees [10,11]. However, it is still unclear how an implant with a shape that mimics that of the normal knee joint affects kinetics and muscle activity. Therefore, the purpose of this study was to evaluate a modern TKA prosthesis that imitates the normal knee using motion capture analysis synchronized with a force plate and surface electromyogram (EMG) and to evaluate not only the kinematics but also the kinetics and muscle activity involved in knee joint function. A gait analysis of patients with modern TKA prostheses was performed and compared with the gait analysis in patients who received conventional TKA. Our hypothesis was that after TKA, patients who received the modern prosthesis would show more normal gait characteristics and different kinetics and muscle activation when compared with patients with a conventional prosthesis.

## Material and methods

### Subjects

The subjects were patients older than 60 years with knee OA who had undergone unilateral TKA at our hospital or an affiliated hospital. All gait measurements were performed 6 months after surgery. Twelve patients received the modern TKA prosthesis designed to mimic a normal knee (Journey II; Smith and Nephew, Memphis, TN) (group modern), and 12 patients received a conventional TKA prosthesis (Legion; Smith and Nephew, Memphis, TN) (group conventional). There were no specific criteria for implant selection, as the surgeon did not selectively use a modern or conventional design for specific preoperative conditions. Patients with a history of lower limb surgery and fracture, neuromuscular disease, collagen disease, skin disorders preventing the application of markers, and a knee range of motion of less than 100° and patients who could not walk for 10 m were excluded. The study protocol was approved by our institutional review board (IRB number H29-243), and written informed consent was obtained from all patients before inclusion in the study.

### Surgery and postoperative therapy

All operations were performed by the senior coauthor or with the senior coauthor as the first assistant, and thus, all surgeries were performed using the same procedure. A midline longitudinal incision was made, and a retinacular incision was made using a medial parapatellar approach. The distal femoral cut was set at a 6° valgus angle with an intramedullary alignment rod, and the tibial cut was set at a 90° angle to the mechanical axis. The anterior cruciate ligament (ACL) was resected in all cases, and the posterior cruciate ligament was resected in cases with advanced degeneration. The measured resection technique was used to obtain a balanced flexion and extension gap. The patella was resurfaced depending on the extent of damage. Patellar tracking was balanced in all cases, and lateral retinacular releases were not required. After the operation, it was confirmed that the knee could bend from 0° to 110° by gravity-assisted flexion. Rehabilitation began immediately after surgery, and range-of-motion exercises and full weight bearing were performed within the pain limit of the patient.

### Gait analysis

Gait analysis was performed using a motion capture system (Vicon MX; Vicon Motion System Inc., Oxford, UK), which was synchronized with a force plate (AccuGait; AMTI Inc., Watertown, MA) and a wireless EMG (Trigno Lab; Delsys, Inc., Boston, MA). The patient walked at a comfortable speed on a 10-m platform until he or she was able to touch both lower limbs 3 times on the force plate. Sixteen infrared cameras (MX-T20; Vicon Motion System Inc., Oxford, UK) were installed, and the sampling frequency was set to 100 Hz. Forty markers (14 mm) were attached in accordance with the Plug-in Gait model [12]. Two force plates were synchronized with this system, and the ground reaction force (GRF) was measured during walking at a 1000-Hz sampling frequency. The muscle activity of 6 muscles (vastus medialis, rectus femoris, vastus lateralis, semitendinosus, biceps femoris, and gluteus medius) was measured at a sampling frequency of 2000 Hz using EMG. The placement of the wireless surface EMG was based on a previous study [13]. Before the gait task, EMG data were measured during maximum voluntary isometric contraction of hip abduction, knee flexion, and knee extension. The Knee Injury and Osteoarthritis Outcome Score [14] was also evaluated.

### Data collection and statistical analysis

The analysis section comprised 6 m, excluding the first and last 2 m of the 10-m platform, and the moment was analyzed in the section where connection was made with the force plate. Gait parameters such as gait speed, gait cycle, and maximum knee joint flexion and extension angles were measured. GRF and knee joint moment (flexion, extension, varus, and valgus) were calculated using the VICON motion system. The raw EMG data were filtered at 30–400 Hz and converted to locally integrated values with a time constant of 0.1 second. From the EMG data, the ratio of the maximum voluntary contraction (% MVC) of each muscle using the integrated value in the stance phase and the swing phase during walking was calculated. EMG processing was performed using custom scripts on MATLAB, version 8.4.0.150421 (R2014b) (MathWorks, Inc., Natick, MA). An unpaired t-test was used to compare the means between the 2 groups. A *P*-value of less than 0.05 was considered significant. Numerical data were expressed as mean ± standard deviation. All statistical analyses were performed with Microsoft Excel 2016 (Microsoft Corp, Redmond, WA).

## Results

Details of the 2 groups are given in Table 1. Although there were no significant differences between the 2 groups, the body mass index was lower in group modern than in group conventional, whereas the scores in the sport and quality-of-life domains of the Knee Injury and Osteoarthritis Outcome Score tended to be higher in group modern.

### Kinematics

The gait speed was  $1.1 \pm 0.2$  m/s in group modern, which was significantly faster than that in group conventional ( $0.9 \pm 0.2$  m/s,  $P = .03$ ). The step length was  $0.54 \pm 0.07$  m in group modern, which was significantly longer than that in group conventional ( $0.45 \pm 0.11$  m,  $P = .03$ ). Nine of 12 cases (75%) in group modern and 10 of 12 cases (83%) in group conventional showed double flexion peaks during the gait cycle, known as double knee action [15]. On the other hand, the knee flexion angle in the initial stance phase was  $10.9 \pm 3.0^\circ$  in group modern, which was significantly greater than that in group conventional ( $8.0 \pm 2.6^\circ$ ,  $P = .04$ ) (Table 2, Fig. 1).

**Table 1**  
Patient demographic data.

Variable	Group modern	Group conventional	P-value
Age (y)	69.4 ± 4.9	70.0 ± 6.4	.81
Sex (male/female)	2/10	4/8	
Side (right/left)	6/6	7/5	
Height (m)	1.55 ± 0.06	1.56 ± 0.08	.64
Body mass index (kg/m <sup>2</sup> )	23.5 ± 3.6	26.5 ± 4.4	.09
Postoperative time (months)	13.1 ± 6.7	16.8 ± 6.3	.20
ROM (°)			
Flexion	126.1 ± 9.8	126.2 ± 5.8	.98
Extension	-0.4 ± 1.0	-1.0 ± 1.2	.23
Preoperative tibiofemoral radiograph axis (°)	184.4 ± 5.3	180.3 ± 11.0	.27
Tibiofemoral radiograph axis (°)	176.5 ± 1.6	175.5 ± 2.8	.31
KOOS			
Symptoms	80.7 ± 15.1	82.8 ± 8.3	.70
Pain	86.6 ± 9.1	84.1 ± 14.2	.64
ADL	88.6 ± 8.2	87.7 ± 8.1	.80
Sport	66.7 ± 21.2	50.6 ± 16.9	.06
QOL	79.2 ± 12.8	68.8 ± 15.1	.10

ROM, range of motion; KOOS, Knee Injury and Osteoarthritis Outcome Score; ADL, activities of daily living; QOL, quality of life.

Data are expressed as average ± standard deviation.

### Kinetics

The maximum knee extension moment was  $0.55 \pm 0.24$  Nm/kg in group modern, and this was significantly greater than that in group conventional ( $0.34 \pm 0.19$  Nm/kg,  $P = .04$ ). There were no significant differences in the vertical GRF and knee joint varus, valgus, or flexion moment (Table 3).

### Electromyogram

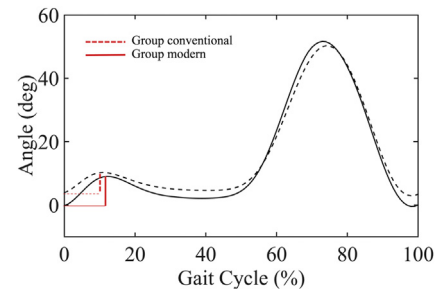
In the stance phase, the average maximum EMG activity (%MVC) of the vastus medialis was  $29.4 \pm 10.2$  (% MVC) in group modern and  $40.9 \pm 20.9$  in group conventional ( $P = .12$ ). For the rectus femoris, it was  $16.3 \pm 8.5$  in group modern and  $21.6 \pm 11.0$  in group conventional ( $P = .22$ ), and for the vastus lateralis, it was  $38.3 \pm 17.2$  in group modern and  $43.6 \pm 16.7$  in group conventional ( $P = .47$ ). Although there were no significant differences, the quadriceps muscle activity in group modern tended to be lower than that in group conventional (Table 4). Similar results were found during the swing phase in the 2 groups (vastus medialis:  $13.1 \pm 5.1$  vs  $16.9 \pm 6.7$  [ $P = .16$ ]; rectus femoris:  $8.2 \pm 4.5$  vs  $10.8 \pm 4.7$  [ $P = .19$ ]; and vastus lateralis:  $12.0 \pm 4.6$  vs  $16.1 \pm 6.4$  [ $P = .10$ ]). As seen in the stance phase, the quadriceps muscle activity was lower in group modern than in group conventional (medial hamstring:  $25.5 \pm 8.3$  vs  $39.7 \pm 51.4$  [ $P = .38$ ]; lateral hamstring:  $23.0 \pm 8.7$  vs  $31.0 \pm 12.7$  [ $P = .10$ ]; and for the gluteus medius:  $12.5 \pm 7.5$  vs  $13.6 \pm 11.6$  [ $P = .79$ ]) (Table 5).

**Table 2**  
Comparison of kinematic data of gait parameters.

Gait parameter	Group modern	Group conventional	P-value
Gait speed (m/s)	1.1 ± 0.2	0.9 ± 0.2	<b>.03</b>
Gait duration (s)	1.03 ± 0.07	1.08 ± 0.10	.14
Step length (m)	0.54 ± 0.07	0.45 ± 0.11	<b>.03</b>
Swing duration (s)	0.45 ± 0.46	0.46 ± 0.05	.82
Max knee flexion (°)	53.2 ± 7.1	52.8 ± 7.1	.90
Max knee extension (°)	2.9 ± 4.0	-0.5 ± 4.6	.08
Double knee action (+/-)	9/3	10/2	
Max knee flexion angle at initial stance phase (°)	10.9 ± 3.0	8.0 ± 2.6	<b>.04</b>

Significant P-values are provided in bold.

Data are expressed as average ± standard deviation.



**Figure 1.** The solid line indicates group modern and the dotted line indicates group conventional. The average knee flexion-extension angle during the walking cycle of the 2 groups is shown. There is a significant difference in the knee flexion angle in the initial stance phase.

### Discussion

This study revealed that patients who underwent TKA with a modern TKA prosthesis had a faster gait speed, a longer step length, and a greater knee flexion angle during the initial stance phase when compared with patients with a conventional TKA prosthesis. In addition, the average peak knee joint extension moment during the normal gait cycle was larger in patients with a modern TKA, whereas the quadriceps muscle activity was lower.

TKA shows good long-term clinical results for end-stage knee OA [1,2]. However, there is still room for improvements, including that in patients' ability to perform activities of daily living and satisfaction levels, which are low compared with those seen in THA [3]. Various implants have been developed with the goal of obtaining better knee joint function.

Journey II (Smith and Nephew, Memphis, TN) is a guided motion implant that has an anatomic joint surface shape, provides an adequate position in the sagittal plane, and guides normal knee joint motions such as medial pivot and posterior rollback. The BCS insert has a characteristic post-cam structure that mimics the functions of the ACL and posterior cruciate ligament. So far, it has been reported that kinematic evaluation of cadaver knees [16] and in vivo dynamic analysis using fluoroscopic images [10] show knee joint movement similar to that of normal knees. Conversely, it is not clear how this implant affects kinetics and muscle activity.

Healthy subjects show a double knee action during gaits. Double knee action is characterized by the knee joint showing double flexion peaks during the gait cycle. The first flexion and extension movements in the initial stance phase reduce the impact at the time of heel contact and reduce the amplitude of vertical movement of the center of gravity. This is a characteristic of a normal gait. Studies suggest that patients with knee OA have a slower gait speed and reduced double knee action when compared with healthy subjects [17-19]. Other reports suggest that gait parameters improve after TKA and are better than that in patients with OA; however, compared with healthy subjects, patients who underwent TKA have

**Table 3**  
Average peak knee moment and vGRF.

Moment	Group modern	Group conventional	P-value
Peak knee extension moment (Nm/kg)	0.55 ± 0.24	0.34 ± 0.19	<b>.04</b>
Peak knee flexion moment (Nm/kg)	0.32 ± 0.15	0.35 ± 0.22	.71
Peak knee varus moment (Nm/kg)	0.52 ± 0.14	0.51 ± 0.12	.93
Peak knee valgus moment (Nm/kg)	0.09 ± 0.06	0.09 ± 0.10	.89
vGRF (N/kg)	10.9 ± 0.6	10.7 ± 0.5	.48

vGRF, vertical ground reaction force.

Significant P-values are provided in bold.

Data are expressed as average ± standard deviation.

**Table 4**  
Average maximum EMG value (% MVC) during the stance phase.

Muscle	Group modern	Group conventional	P-value
Vastus medialis	29.4 ± 10.2	40.9 ± 20.9	.12
Rectus femoris	16.3 ± 8.5	21.6 ± 11.0	.22
Vastus lateralis	38.3 ± 17.2	43.6 ± 16.7	.47
Medial hamstring	42.4 ± 11.6	70.4 ± 121.3	.46
Lateral hamstring	52.6 ± 23.5	43.9 ± 23.2	.39
Gluteus medius	42.9 ± 32.9	33.3 ± 19.7	.42

EMG, electromyography; % MVC, % of the maximal voluntary contraction. Data are expressed as average ± standard deviation.

slower walking speeds, shorter strides, and reduced double knee action [20,21]. In this study, patients who received modern TKA showed faster gait speeds and longer step lengths than patients who received conventional TKA. In contrast, patients who received conventional TKA tended to have a smaller maximum knee flexion angle in the initial stance phase [22]; however, patients who received modern TKA showed a larger knee flexion angle in the initial stance phase than patients who received conventional TKA. Although a clinically meaningful difference in gait parameters may not be reflected in daily activities, the gait parameter values of patients who received modern TKA were close to normal. However, the results observed may have been affected by preoperative differences in patient gait parameters between the 2 groups.

The maximum extension moment during the gait cycle was larger in patients who received modern TKA. There are many reports that suggest that conventional TKA results in a lower extension moment than that in healthy subjects [23,24]. Journey II (Smith and Nephew, Memphis, TN) reproduces the normal anteroposterior position in terms of implant shape more effectively than conventional implants. It is considered that the femoral implant is positioned more anteriorly than the conventional implant, the lever arm in the extension mechanism is enlarged, and the extensor muscle is activated effectively [25]. In addition, it is known that when quadriceps strength decreases, the gait speed becomes slower and the stride length is reduced [26,27]. Therefore, it is possible that patients who received modern TKA are able to demonstrate quadriceps muscle action more effectively than patients who received conventional TKA.

Conversely, regarding muscle activity, patients who received modern TKA showed less quadriceps muscle activity in both the stance and swing phases and less hamstring muscle activity in the swing phase. It has been reported that in patients who received TKA, the required muscle activity of the quadriceps is 3 times that of the normal knee, and prolonged activity of the rectus femoris during the stance phase is required, meaning that the amount of quadriceps muscle activity is greater after TKA surgery [28,29]. Patients who received modern TKA were able to walk with less quadriceps muscle activity. This muscle activation pattern is thought to be due not only to greater knee extension moment but also to the fact that knee extension is easy to perform owing to the anterior-posterior positioning being similar to that of the normal

**Table 5**  
Average maximum EMG value (% MVC) during the swing phase.

Muscle	Group modern	Group conventional	P-value
Vastus medialis	13.1 ± 5.1	16.9 ± 6.7	.16
Rectus femoris	8.2 ± 4.5	10.8 ± 4.7	.19
Vastus lateralis	12.0 ± 4.6	16.1 ± 6.4	.10
Medial hamstring	25.5 ± 8.3	39.7 ± 51.4	.38
Lateral hamstring	23.0 ± 8.7	31.0 ± 12.7	.10
Gluteus medius	12.5 ± 7.5	13.6 ± 11.6	.79

EMG, electromyography; % MVC, % of the maximal voluntary contraction. Data are expressed as average ± standard deviation.

knee. Furthermore, previous dynamic analysis has demonstrated that one of the factors involved in smooth gait motion after TKA is induction of joint motion similar to that in normal knees [10]. The knee extension moment was smaller and hamstring muscle activity was greater in patients who received conventional TKA. This result is consistent with the so-called quadriceps avoidance gait seen in ACL-deficient knees [30,31]. In both patients who received modern TKA and those who received conventional TKA, the ACL is removed, and thus, they are all considered to be with ACL-deficient knees. The patients who received modern TKA showed a nearly normal kinetic and muscle activity pattern, similar to that in ACL-intact knees. This is because the modern TKA prosthesis was able to reproduce anterior-posterior stability, which is a part of the ACL function, by acquiring an appropriate anterior-posterior position owing to the characteristic implant shape and the presence of a post-cam mechanism in the BCS insert.

There were several limitations to this study. First, although there was no significant difference between the subjects in the 2 groups, there may have still been some selection bias. It is possible that the bias may make it difficult to evaluate whether it was preoperative patient selection or the knee prosthesis that caused the difference in gait parameters. Second, the study design was retrospective, with a small number of cases. A power analysis showed a power of 0.55 or more for detecting significant differences in gait parameters. Therefore, we can assume a certain level of statistical power. Third, there was a mixture of cruciate retaining (CR) and BCS implants in the patients who received modern TKA and a mixture of CR and posterior-stabilized implants in the patients who received conventional TKA. Different inserts may influence muscle activity around the knee, and this may have affected the outcomes of hamstring and quadriceps muscle activity [32]. In addition, the presence of CR and BCS may have affected anterior-posterior stability in patients who received modern TKA. However, in accordance with the report by Murakami et al [11], during gait analysis, the BCS shows less anteroposterior translation, and there is less post-cam contact. Regarding the anteroposterior stability of the BCS, it is highly likely that the entire implant shape is involved, not just the post-cam; it is unlikely that this had a significant impact on the results of this study. Fourth, our assessments were performed at an average of 13 months after surgery in the patients who received modern TKA and at an average of 16 months in the patients who received conventional TKA, and thus, we were unable to evaluate the medium- and long-term outcomes. In the future, we plan to undertake presurgery and postsurgery evaluations and increase the number of patients.

## Conclusions

This is the first study to evaluate postoperative kinetics and muscle activity after insertion of a modern TKA prosthesis (Journey II; Smith and Nephew, Memphis, TN) that has an anatomic joint surface shape and provides cruciate ligament function. Compared with patients who received conventional implants, those who received the modern TKA prosthesis showed a near-normal gait pattern and greater knee joint extension moment.

This suggests that the quadriceps muscles can be more effectively activated and that the anterior stability function of the ACL can be reproduced with the shape of the modern implant.

## Conflict of interest

The authors declare there are no conflicts of interest.

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