

Compensation by nonoperated joints in the lower limbs  
during walking after endoprosthetic knee replacement  
following bone tumor resection

腫瘍用人工膝関節置換術後患者の  
歩行時の手術膝以外の下肢関節による代償戦略

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1 Compensation by nonoperated joints in the lower limbs during walking after endoprosthetic knee  
2 replacement following bone tumor resection

3

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24

25 Word count for the abstract: 245

26 Word count for the main text (excluding reference): 2829

27 Number of Tables: 3

28 Number of Figures: 3

29 **Abstract**

30 **Background:** Endoprosthetic knee replacement is often used to preserve joint function in patients  
31 with bone tumors of the distal femur or proximal tibia. Recently, because of improved oncologic  
32 outcome, surgeons are focusing more on the functional outcome of patients with musculoskeletal  
33 tumors. We hypothesized that patients who have undergone endoprosthetic knee replacement are  
34 forced to compensate for deficiency in their operated joint during walking. In this study, we  
35 investigated differences in gait kinematics, kinetics, and energetics between patients with  
36 endoprosthetic knee replacement and healthy subjects.

37 **Methods:** We performed gait analysis for 8 patients who underwent endoprosthetic knee  
38 replacement after bone tumor resection and 8 matched healthy subjects. Gait kinematics, kinetics,  
39 and energetics of patients' ipsilateral and contralateral limbs were compared with those of healthy  
40 subjects by using Dunnett's test.

41 **Findings:** Compared with healthy subjects, patients showed increased negative joint power around  
42 the ipsilateral ankle, greater second peak in the contralateral vertical ground reaction forces, and  
43 abnormal hip movement on both sides after initial contact.

44 **Interpretation:** Patients tended to compensate for dysfunction of the reconstructed knee by muscles  
45 around the ipsilateral ankle and contralateral hip, with increased load on the contralateral limb  
46 during walking. These differences could lead to secondary impairments. Further analysis, including

47 musculoskeletal simulation and assessment of long-term functional outcome with regard to  
48 secondary musculoskeletal impairment, is needed to verify the significance of the change in gait and  
49 to determine the need for special care for secondary musculoskeletal dysfunction in these patients.

50 1. Introduction

51 Endoprosthetic knee replacement is often used to preserve joint function in patients with bone  
52 tumors of the distal femur or proximal tibia. Recently, surgeons are focusing more on the functional  
53 outcome of patients with musculoskeletal tumor because of improved oncologic outcome (Whelan et  
54 al., 2011) with the help of advanced diagnostic imaging, chemotherapeutic agents, and surgical  
55 techniques. For orthopedic surgeons, gait function is one of the most important components of  
56 functional outcome in patients treated for a tumor in the lower extremity. Previous studies have  
57 reported slower walking speed (Carty et al., 2009; De Visser et al., 2000; Otis et al., 1985), longer  
58 step length of the nonoperated limb (Rompen et al., 2002), and decreased foot pressure (Tsuboyama  
59 et al., 1994), all of which can be attributed to insufficient muscle strength around the reconstructed  
60 knee.

61         These patients have to compensate for deficiency of the reconstructed joint by using  
62 muscles around adjacent or contralateral joints during walking. This compensation can be  
63 quantitatively evaluated by analyzing gait kinematics (e.g., joint angular movement), kinetics (e.g.,  
64 ground reaction forces and internal joint moment), and energetics (e.g., joint power). However,  
65 because there is little knowledge on how joint kinematics, kinetics, and energetics change after  
66 endoprosthetic knee replacement following bone tumor resection, it is difficult to consider the  
67 potential overload on musculoskeletal tissue around the lower limb joints other than the

68 reconstructed knee. Previous studies have suggested the possibility of increased load on nonoperated  
69 joints during locomotion after bone or joint reconstruction (Beaulieu et al., 2010; Foucher and  
70 Wimmer, 2012; Taddei et al., 2011). The aim of this study was to verify compensation by  
71 nonoperated joints during walking in patients who underwent endoprosthetic knee replacement  
72 following bone tumor resection by evaluating differences in lower limb gait biomechanics between  
73 patients and healthy subjects.

74

## 75 2. Methods

### 76 2.1. Study design

77 This was a single-center, cross-sectional study based on measurements obtained from a group of  
78 patients and a group of healthy control subjects. Patients aged >15 years who underwent  
79 endoprosthetic knee replacement after bone tumor resection, were without neurologic  
80 musculoskeletal pathology that affected gait function, and were routinely followed-up at Kyoto  
81 University Hospital were included. Exclusion criteria were concurrent metastasis, local recurrence,  
82 unstable implant, period of less than 1 year since last surgery, daily use of walking aid or orthopedic  
83 shoes, and more than 3 cm of discrepancy in limb length. All eligible patients were asked to  
84 participate in the study at the outpatient clinic, and, if they agreed to be part of the study,  
85 measurements were obtained at a motion analysis laboratory on another day. After collecting the



86 patients' data, we recruited matched healthy subjects whose data were compared with the patients'  
87 data. All procedures were approved by the Ethical Review Board of Kyoto University Graduate  
88 School of Medicine, and written informed consent was obtained from all subjects.

89

## 90 2.2. Data collection and processing

91 We performed gait analysis using a 7-camera 3-dimensional motion analysis system (Vicon MX;  
92 Vicon, Oxford, United Kingdom) with 2 force plates (9286A; Kistler Japan, Tokyo, Japan). All  
93 participants (patients and healthy subjects) walked along a 6-m walkway at a self-selected speed  
94 with 35 retroreflective markers on their body landmarks, according to the Plug-in Gait protocol  
95 (Vicon). All healthy subjects also walked at a slightly slower speed because patients who have  
96 undergone endoprosthetic knee replacement may walk more slowly than healthy subjects (Carty et  
97 al., 2009; De Visser et al., 2000; Otis et al., 1985). The walking speed of each healthy subject (either  
98 self-selected or slower) that was closer to the mean walking speed of the patients was used in  
99 analysis. At least 5 successful trials were collected for each walking speed (self-selected for both  
100 groups and slower for healthy subjects) to assure repeatability of the results. Data were collected at a  
101 sampling rate of 100 Hz for marker trajectories and 1,000 Hz for force plates.

102 Marker trajectories were filtered using a Woltring filter (Woltring, 1986), with a  
103 mean-squared error value of 10. Joint kinematics and kinetics were generated using inverse

104 dynamics analysis within Nexus version 1.7.1 software (Vicon). Joint moments were filtered using a  
105 0-lag fourth-order Butterworth filter. Joint powers were calculated from the dot product of the joint  
106 angular velocities and joint moments on the sagittal plane. Joint moments and powers were  
107 normalized to body weight and height. Joint power is the energy generated (positive value) or  
108 absorbed (negative value) around a joint per unit of time. All data were processed using Nexus  
109 software and MATLAB 2012a (MathWorks, Natick, MA).

110

### 111 2.3. Statistical methods

112 Walking speeds were reported as the mean and SD for patients and healthy subjects. Ground reaction  
113 forces, joint angles, joint moments, and joint powers were averaged for each of 3 groups (ipsilateral  
114 and contralateral sides of the patients, and the right side of healthy subjects). We compared the joint  
115 kinematic, kinetic, and energetic parameters described in Table 1 between the 3 groups using  
116 Dunnett's multiple comparison test, performed on R version 2.41.0 (R Development Core Team,  
117 <http://www.R-project.org>) with an R library multcomp (Hothorn et al., 2008), setting the right side of  
118 healthy subjects as the control group. Significance was set at  $P < .05$ . The patients' ipsilateral limb  
119 was not compared with the contralateral limb because the presence of a compensatory mechanism  
120 cannot be determined by comparing data obtained from the same patient. All graphics were  
121 generated by R.

122

### 123 3. Results

124 Of 17 eligible patients, 9 were excluded: because of implant instability in 3, daily use of crutches or  
125 a cane in 2, metastasis in 1, and refusal to participate in 3. Finally, 8 patients (mean [SD, range] age,  
126 30 [12, 19–59] years; height, 1.67 [0.7, 1.58–1.78] m; weight, 59.9 [20.2, 45.0–108.5] kg) who  
127 underwent endoprosthetic knee replacement following bone tumor resection participated in this  
128 study at a mean (SD) of 91 (41) months after primary endoprosthetic replacement. Demographic  
129 data of the patients are shown in Table 2. Of the 8 patients, 6 had osteosarcoma, 1 had giant cell  
130 tumor, and 1 had chondrosarcoma. Five patients had a tumor in the distal femur and 3 in the  
131 proximal tibia. Four patients had undergone revision surgery; only a femoral component had been  
132 replaced in 1, only a tibial component had been replaced in 1, and all components had been replaced  
133 in 2. All patients were continuously disease free and could walk without an assistive device. Three  
134 types of endoprosthesis were used for reconstruction: Kyocera Limb Salvage System (KYOCERA  
135 Medical Corp., Osaka, Japan) in 3 patients, Howmedica Modular Resection System (Stryker  
136 Orthopaedics, Mahwah, NJ) in 3, and Japan Medical Materials K-MAX KNEE System K-5  
137 (KYOCERA Medical Corp.) in 2 (Fig. 1). Eight matched healthy subjects (mean [SD, range] age, 30  
138 [10, 23–53] years; height, 1.70 [0.06, 1.62–1.78] m; weight, 62.2 [10.9, 48.6–85.0] kg) were enrolled.  
139 Mean (SD) walking speed was 1.21 (0.15) m/s for patients and 1.20 (0.08) m/s for healthy subjects.

140

141 3.1. Ground reaction forces

142 Ground reaction forces of patients and healthy subjects are shown in Figure 2. The first (GR3) and  
143 second (GR4) peaks of vertical ground reaction forces were smaller on the ipsilateral side in the  
144 patients than in the healthy subjects, whereas the second peaks of vertical ground reaction forces  
145 were greater on the contralateral side in the patients than in the healthy subjects (Fig. 2, Table 3).

146

147 3.2. Joint angles, moments, and powers

148 Compared with healthy subjects, patients showed a tendency to flex the contralateral hip after initial  
149 contact, (Table 3, H5), whereas the ipsilateral hip of the patients simply extended after initial contact  
150 (Fig. 3, Table 3, H1-2). The ipsilateral knee of the patients generally remained extended during early  
151 stance (Fig. 3, Table 3, K1-3). Of the 8 patients, 5 (3 with femoral replacement) kept their operated  
152 knee extended during early stance, whereas 2 (1 with femoral replacement) exhibited a normal knee  
153 movement pattern. One patient with femoral replacement flexed the ipsilateral knee after initial  
154 contact but extended it during late stance, similar to a normal knee. The maximal plantarflexion  
155 angle during early stance was greater on the ipsilateral side of the patients than in the healthy  
156 subjects, and the maximal dorsiflexion angle was smaller on the ipsilateral side of the patients than  
157 in the healthy subjects (Fig. 3, Table 3, A2-3). The maximal knee extension moment during early

158 stance was smaller on the ipsilateral side of the patients than in the healthy subjects (Fig. 3, Table 3,  
159 KM). The maximal plantarflexion moment was smaller on the ipsilateral side of the patients than in  
160 the healthy subjects (Fig. 3, AM2). The patients' ipsilateral knee exerted little joint power during  
161 early stance (Fig. 3, Table 3, KP1-2). During stance, the mean negative ankle joint power of the  
162 patients' ipsilateral side was greater than that of the healthy subjects (Fig. 3, Table 3, AP2).

163

#### 164 4. Discussion

165 We hypothesized that patients who have undergone endoprosthetic knee replacement are forced to  
166 compensate for deficiency in their operated joint during walking. In this study, we verified  
167 differences in gait kinematics, kinetics, and energetics between patients and healthy subjects  
168 matched by age, sex, size (height and weight), and walking speed. Some studies have investigated  
169 joint angles, joint moments, and joint power during gait (Benedetti et al., 2000; Carty et al., 2009).  
170 However, these studies only discussed the reduction in joint motion or kinetic value and not the  
171 increased load on residual intact muscles or joints. We focused on the increases in joint angular  
172 movement, moment, and power from the viewpoint of compensation. Defining parameters of interest  
173 allowed us to identify the approximate time point at which each maximum (or minimum) value was  
174 obtained; this helped us to estimate the potential problems experienced by the patients during  
175 walking.

176           The walking speed of patients after endoprosthetic knee replacement differs between  
177 studies (De Visser et al., 2000; Colangeli et al., 2007; Carty et al., 2009), possibly because of  
178 variable experimental settings (level or treadmill walking) and/or differences in patient age or tumor  
179 treatment. The mean walking speed of patients in the present study is similar to that in a recent study  
180 (Carty et al., 2009).

181

#### 182 4.1. Ipsilateral knee kinematics

183 We observed 3 major patterns in the patients' ipsilateral knee kinematics, as previously reported  
184 (Carty et al., 2009; Rompen et al., 2002): (1) no ipsilateral knee flexion during early stance  
185 (extended-knee gait, 5 patients), (2) no ipsilateral knee extension during late stance (flexed-knee gait,  
186 1 patient), and (3) 2 distinct peaks of knee flexion, the so-called double-knee action, during a stride  
187 (normal gait, 2 patients). The causes of the first 2 gait patterns are not clear, although weakness in  
188 ipsilateral knee extensors (Rompen et al., 2002), need for knee stabilization during loading response,  
189 and compensation for a painful knee (Carty et al., 2009) may be contributing factors, ~~as previous~~  
190 ~~studies have discussed~~. Removal of the vastus medialis with relative preservation of the vastus  
191 lateralis and vastus intermedius (Benedetti et al., 2000) or guarding the operated knee (Tsuboyama et  
192 al., 1994) might be associated with extended-knee gait (also referred to as stiff-legged pattern).

193 Extended- and flexed-knee gait similarly exhibit smaller sagittal knee excursion, which might lead

194 to increased ipsilateral ankle excursion and ankle joint power during stance. The differences  
195 described above were more clearly exhibited by patients with extended- or flexed-knee gait than  
196 those with a normal gait pattern.

197

#### 198 4.2. Compensation by ipsilateral limb

199 The results of this study suggest the presence of compensation around the ipsilateral ankle. Increased  
200 negative joint power around the ipsilateral ankle implies a greater load on ankle dorsiflexors during  
201 loading response and ankle plantarflexors during midstance. Activation of the gastrocnemius occurs  
202 for a greater time in patients who have undergone endoprosthetic knee replacement than in healthy  
203 people (Carty et al., 2010); this also suggests that patients put a greater load on ipsilateral ankle  
204 muscles. Decreased ipsilateral knee flexion during early stance, regardless of gait pattern, may alter  
205 ankle energetics because greater angular acceleration and deceleration are required if the knee flexes  
206 little after initial contact. This reduction in knee flexion may be associated with increased ipsilateral  
207 plantarflexion after initial contact. Patients tended to extend the ipsilateral hip continuously from  
208 terminal swing to loading response, regardless of their ipsilateral knee kinematics. We do not believe  
209 that this continuous hip extension increases hip joint load. Reduced ipsilateral ground reaction forces  
210 may enable patients to extend the ipsilateral hip after initial contact. Weakness in ipsilateral hip  
211 extensors in patients who underwent endoprosthetic knee replacement, which has been reported

212 previously (Beebe et al., 2009), may be associated with weaker ipsilateral body support during early  
213 stance; however, we did not measure hip muscle strength in the patients. In these patients, we did not  
214 observe increased hip extension, which has been reported previously (Rompen et al., 2002), possibly  
215 because of the small sample size.

216

#### 217 4.3. Compensation by the contralateral limb

218 A greater second peak in the contralateral vertical ground reaction forces suggests that patients'  
219 contralateral limbs are generally exposed to greater load at push-off. We also found that compared  
220 with healthy subjects, patients tended to flex the contralateral hip after initial contact. This  
221 contralateral hip flexion may be due to the slight discrepancy in limb length (0.75 cm shorter than  
222 the contralateral side, on average) or compensation for reduced body support by the ipsilateral limb  
223 during late stance, which corresponds to contralateral loading response. Although kinetic and  
224 energetic analyses did not reveal the effect of this increased contralateral flexion, this kinematic  
225 change may affect the contralateral hip by abnormal loading. One patient occasionally experienced  
226 contralateral hip pain after a long walk; this pain may indicate the effect of increased flexion on the  
227 contralateral hip.

228

#### 229 4.4. Limitations



230 Our study has several limitations, most due to the characteristics of the subjects. First, we could  
231 conveniently recruit only 8 patients and could not guarantee the statistical power of each  
232 comparison; this restricted our investigation to only the differences we could detect. Second, the  
233 heterogeneous characteristics of the patients, including age, weight, implant design, bone resection  
234 length, and resected muscles, made the target population less specific. This heterogeneity may have  
235 increased variability in gait parameters and weakened the statistical power. Four of the 8 patients  
236 underwent revision surgery, which could compromise the functional outcome. However, we could  
237 not exclude these patients, because it would have significantly reduced the statistical power, and  
238 comparison using a statistical test would have been impractical. Patients with revision surgery  
239 appeared to have gait function comparable to that of patients without revision surgery, possibly  
240 because of inclusion criteria, such as the ability to walk without an assistive device. Further studies  
241 with strict inclusion criteria that specify the type of prosthesis and size and location of the tumor are  
242 required for further understanding gait pathology. Third, there may be a selection bias; patients who  
243 participated in this study achieved good functional outcome (e.g., they could walk without an  
244 assistive device). Therefore, the results of this study should be regarded as a reference of the patients  
245 who achieved good functional outcome. Comparing patients after endoprosthetic replacement with  
246 those who underwent simple knee replacement for other orthopedic diseases (e.g., osteoarthritis)  
247 would also help clarify the gait characteristics of both patient populations. Fourth, the inverse

248 dynamics analysis used in this study did not allow consideration of the detailed joint load with  
249 muscle forces. Detection of change in joint load using electromyography may be difficult because of  
250 the changes in properties of patients' lower limb muscles, which hamper intersubject comparison of  
251 electromyographic findings. Musculoskeletal modeling may be useful to verify the joint load and  
252 muscle forces in these patients. Nevertheless, the information obtained from the present study can be  
253 used to explain the gait pattern in patients who undergo endoprosthetic knee replacement and to  
254 predict the potential problems during walking for these patients.

255

## 256 5. Conclusions

257 We observed that patients tended to compensate for dysfunction of the reconstructed knee by  
258 muscles around the ipsilateral ankle and contralateral hip, with increased load on the contralateral  
259 limb during walking. These changes may cause secondary impairments. Further analysis, including  
260 musculoskeletal simulation and assessment of long-term functional outcome, is required to verify the  
261 significance of the change in gait and to determine the requirement of special care for secondary  
262 musculoskeletal dysfunction in these patients. Quantification of the musculoskeletal load after  
263 surgery is important because some patients who undergo joint reconstruction after tumor resection  
264 live with the implant for more than 20 years.

265

266 Acknowledgement

267 This work is partially supported by Grant-in-Aid for Japan Society for the Promotion of Science

268 Fellows. We thank KYOCERA Medical Corp. and Stryker Japan Corp. for kindly providing

269 information and samples of their endoprosthesis implants.

270

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Table 1. Kinematic, kinetic, and energetic gait parameters of interest

Name	Description
<i>Ground reaction forces</i>	
GF1	Max. aft force
GF2	Max. fore force
GF3	Max. vertical force during early stance
GF4	Max. vertical force during late stance
<i>Joint angles</i>	
H1	Hip flexion at initial contact
H2	Max. hip flexion during early stance
H3	Max. hip extension
H4	Max. hip flexion during swing
H5	H2 – H1
K1	Knee flexion at initial contact
K2	Max. knee flexion during early stance
K3	Knee flexion at toe-off
K4	Max. knee flexion during late stance
A1	Ankle dorsiflexion at initial contact

---

A2 Max. plantarflexion during early stance

A3 Max. dorsiflexion during stance

A4 Ankle plantarflexion at toe-off

*Internal joint moments*

HM1 Max. hip extension moment during stance

HM2 Max. hip flexion moment during stance

Max. knee extension moment during early  
KM  
stance

AM1 Max. dorsiflexion moment during stance

AM2 Max. plantarflexion moment

*Joint powers*

HP1 Max. hip joint power during early stance

HP2 Min. hip joint power during late stance

KP1 Min. knee joint power during early stance

KP2 Max. knee joint power during early stance

AP1 Min. ankle joint power

AP2 Mean negative ankle power during stance

AP3 Max. ankle joint power

---



Abbreviations: Max., maximum; Min., minimum.

Table 2. Patient characteristics at time of measurement

No.	Sex/age, y	Follow-up, mo*	Diagnosis	Site	Endoprosthesis (hinge type)	Revision	Resected muscles and bone length, cm
1	M/59	47	CS	Tibia	HMRS (rotating)	Yes	None, 13
2	M/19	51	OS	Femur	JMM-K5 (hingeless)	No	VL (lateral part), 12
3	M/34	81	GCT	Femur	KLS (fixed)	Yes	None, 12
4	M/24	29	OS	Tibia	HMRS (rotating)	Yes	Soleus (lateral part), 7
5	F/24	34	OS	Femur	KLS (rotating)	No	VI, VM, 13
6	M/24	12	OS	Femur	KLS (rotating)	Yes	VI, VL, 19
7	M/27	61	OS	Femur	JMM K-5 (hingeless)	No	VI (lateral part), VL, 16
8	M/30	111	OS	Tibia	HMRS (rotating)	No	None, 12

\*Interval from last surgery (primary or revision).

Abbreviations: CS, chondrosarcoma; GCT, giant cell tumor; HMRS, Howmedica Modular Resection System; JMM-K5, Japan Medical Materials K-MAX KNEE System K-5; KLS, Kyocera Limb Salvage System; OS, osteosarcoma; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis.

Table 3. Sagittal kinematics, kinetics, and energetics

	Ipsilateral,	Contralateral,	Healthy,	<i>P</i> value (vs. healthy)*	
	mean (SD)	mean (SD)	mean (SD)	Ipsilateral	Contralateral
Ground reaction forces, %BW					
GF1	16.3 (7.1)	18.5 (2.8)	20.4 (4.5)	.21	.67
GF2	17.8 (4.1)	24.3 (3.8)	20.7 (1.2)	.18	.08
GF3	99.9 (5.7)	110.1 (5.9)	116.7 (7.4)	< .001	.09
GF4	101.6 (3.9)	116.7 (4.4)	109.1 (2.6)	.001	.001
Joint angles, °					
H1	33.2 (5.8)	35.6 (6.2)	33.0 (7.4)	.99	.63
H2	33.2 (5.8)	37.4 (7.4)	33.6 (7.4)	.99	.46
H3	9.5 (6.6)	10.4 (7.5)	11.2 (7.7)	.85	.97
H4	38.4 (7.7)	37.6 (7.5)	34.3 (7.5)	.47	.60
H5	0.0 (0.0)	1.8 (1.6)	0.7 (0.9)	.33	.09
K1	4.4 (5.4)	8.6 (3.6)	10.0 (2.6)	.02	.72
K2	9.2 (8.3)	24.7 (3.2)	25.3 (4.5)	<.001	.98
K3	27.2 (7.0)	36.0 (4.6)	37.8 (2.7)	.001	.70
K4	62.9 (11.4)	64.9 (4.9)	65.7 (2.9)	.67	.96

A1	-2.1 (6.8)	1.6 (3.3)	3.0 (5.1)	.11	.80
A2	11.3 (5.6)	3.5 (2.5)	0.1 (5.2)	<.001	.27
A3	13.9 (4.3)	15.7 (5.2)	20.1 (4.0)	.02	.11
A4	12.2 (8.3)	13.8 (11.2)	7.6 (6.6)	.30	.49
Joint moments, Nm/(kg·m)					
HM1	0.28 (0.11)	0.37 (0.21)	0.24 (0.07)	.75	.15
HM2	0.55 (0.15)	0.57 (0.13)	0.57 (0.12)	.93	.99
KM	0.14 (0.08)	0.40 (0.15)	0.45 (0.12)	<.001	.63
AM1	0.10 (0.07)	0.06 (0.05)	0.05 (0.03)	.17	.82
AM2	0.69 (0.06)	0.89 (0.09)	0.83 (0.06)	.001	.17
Joint powers, W/(kg·m)					
HP1	0.41 (0.20)	0.52 (0.53)	0.24 (0.17)	.53	.21
HP2	-0.68 (0.26)	-0.57 (0.16)	-0.51 (0.17)	.19	.79
KP1	-0.07 (0.08)	-0.52 (0.27)	-0.49 (0.28)	.003	.95
KP2	0.11 (0.08)	0.51 (0.12)	0.52 (0.13)	<.001	.98
AP1	-0.58 (0.10)	-0.51 (0.15)	-0.47 (0.08)	.15	.78
AP2	-0.28 (0.05)	-0.19 (0.06)	-0.19 (0.02)	.001	.97
AP3	2.3 (0.7)	3.0 (0.8)	2.6 (0.4)	.51	.27

\*Dunnett's test

## Figure Legends

Fig. 1 Knee endoprotheses used for the patients. A: Kyocera Limb Salvage System. B: Japan Medical Materials K-MAX KNEE System K-5. C: Howmedica Modular Resection System.

Fig. 2. Ground reaction forces during walking. The solid line and dashed line represent the ipsilateral and contralateral sides, respectively, of the patients. Both lines are the mean values for each group. The gray band represents mean  $\pm$  1 SD of the healthy subjects. All data were time-normalized for a gait cycle. \* $P < .05$  for comparison between the ipsilateral side of the patients and healthy subjects. † $P < .05$  for comparison between the contralateral side of the patients and healthy subjects.

Fig. 3. Gait kinematics, kinetics, and energetics of each group. The solid line and dashed line represent the ipsilateral and contralateral sides, respectively, of the patients. Both lines are the mean values for each group. The gray band represents mean  $\pm$  1 SD of the healthy subjects. All data were time-normalized for a gait cycle. \* $P < .05$  for comparison between the ipsilateral side of the patients and healthy subjects. † $P < .05$  for comparison between the contralateral side of the patients and healthy subjects.

Fig. 1



Fig. 2

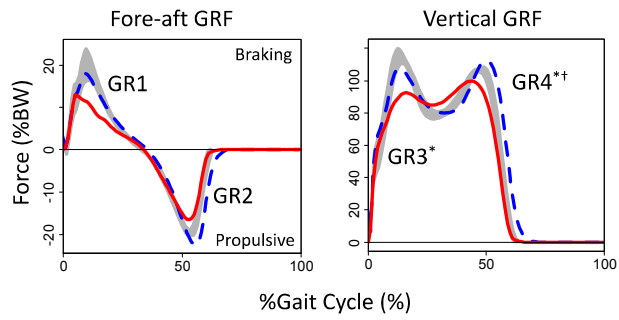




Fig. 3

