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Original article

Knee biomechanics of patients with total knee replacement during downhill walking on different slopes

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Abstract

Purpose: The purpose of this study was to compare knee biomechanics of the replaced limb to the non-replaced limb of total knee replacement (TKR) patients and healthy controls during walking on level ground and on decline surfaces of 5˚, 10˚, and 15˚.
Methods: Twenty-five TKR patients and 10 healthy controls performed 5 walking trials on different decline slopes on a force platform and an instrumented ramp system. Two analyses of variance, 2 × 2 (limb × group) and 2 × 4 (limb × decline slope), were used to examine selected biomechanics variables.
Results: The replaced limb of TKR patients had lower peak loading-response and push-off knee extension moment than the non-replaced and the matched limb of healthy controls. No differences were found in loading-response and push-off knee internal abduction moments among replaced, non-replaced, and matched limb of healthy controls. The knee flexion range of motion, peak loading-response vertical ground reaction force, and peak knee extension moment increased across all slope comparisons between 0˚ and 15˚ in both the replaced and non-replaced limb of TKR patients.
Conclusion: Downhill walking may not be appropriate to include in early stage rehabilitation exercise protocols for TKR patients.

Keywords: Decline surface; Knee adduction moment; Knee joint moment; Total knee arthroplasty

1. Introduction

Total knee replacement (TKR) or total knee arthroplasty is a common surgical procedure for disabling knee osteoarthritis (OA).[1] It has been shown to be effective in reducing pain and improving range of motion (ROM) for patients suffering severe knee OA.[2,3] The peak internal knee abduction moment (KAbM) in the replaced limb of TKR patients has been shown to be either similar to or smaller than the KAbM in non-replaced and healthy limbs during level walking, suggesting that the surgery has successfully corrected excessive knee malalignment and abnormal loading conditions in the frontal plane associated with knee OA.[4] However, the replaced limb of TKR patients showed reduced knee extension moment (KEM) and knee flexion ROM during level walking compared to the KEM and knee flexion ROM in the non-replaced limb and their age-matched healthy controls,[5,6] indicating that deficits of the replaced knee still exist.

A large number of TKR patients are expected to stay active after surgery by engaging in recreational activities and maintaining aerobic fitness.[7] An additional benefit for TKR patients is that aerobic exercises such as walking and hiking have shown positive effects on cardiovascular health.[8] A previous study has also suggested that walking uphill at a 5˚ incline may be a safe exercise for unilateral TKR patients, since that incline has similar medial knee joint loading compared to level walking.[9] However, muscle soreness[10] and high loading on the knee joint[11,12] may cause pain and injury during downhill walking in healthy adults.[13,14] The results of previous studies[11,15−17] have shown that the peak knee flexion angle and knee flexion ROM are greater during downhill walking compared to level walking during the stance phase in young healthy individuals, indicating that the knees are kept at a more flexed position and receive higher loads during downhill walking compared to level walking. Studies have also shown that the loading-response vertical ground reaction force (VGRF) increases as the angle of slope increases for downhill walking.[11,16−20] The peak KEM is also greater in downhill

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walking compared to level walking.[16–18,21] Kuster et al.[11] reported that the peak KEM during 10° downhill walking is nearly twice as much as that obtained in level walking when participants walked at the same step frequency. However, no study has reported knee kinematics and kinetics in frontal and transverse planes during downhill walking. Whether and at what degree of slope in downhill walking is safe for unilateral TKR patients remains to be investigated.

Two previous studies[22,23] have reported knee kinematics and kinetics in sagittal plane for downhill walking in TKR patients. Reynolds[22] compared knee biomechanical characteristics between TKR patients and age-matched healthy individuals during downhill walking at their self-selected speed on a 7° slope. For TKR patients, the knee flexion ROM and peak knee flexion angle of the replaced limb was 11.9% and 26.3%, respectively, which was less than the knee flexion ROM and peak knee flexion angle of healthy participants. In addition, the peak KEM of the replaced limb was 22.7% lower than the non-replaced limb in TKM patients and was 36.2% lower than the matched limb in healthy controls. Simon et al.[23] compared the knee biomechanics and electromyographic activities of quadricep and hamstring muscles between patients who received 2 different types of TKR implants during downhill walking on a 7° slope at their self-selected speed. However, the researchers did not compare and report the differences between TKR patients and healthy controls or the differences between the replaced and non-replaced limbs.

To our knowledge, no studies have explored knee biomechanics during downhill walking on different downhill slopes in TKR patients. Thorough investigation of specific gait impairment after TKR surgery on different downhill slopes may help improve rehabilitation strategies and identify the slopes at which unsafe walking conditions occur during hiking among TKR patients. Thus, the purpose of this study was to compare knee biomechanics of the replaced limb to that of the non-replaced limb of TKR patients and with the matched limbs of healthy controls during downhill walking on decline surfaces of 0° (level walking), 5°, 10°, and 15°. We hypothesized that (1) the peak KEM would be lower and the peak KAbM would be similar in the replaced limb of TKR patients compared to the matched limbs of healthy controls, (2) the peak KEM would be lower and peak KAbM would be similar in the replaced limb compared to the non-replaced limb of TKR patients, and (3) the peak KEM and the knee flexion ROM would increase across all slope comparisons between 0° and 15° in both the replaced and non-replaced limb among TKR patients.

2. Methods

2.1. Participants

Twenty-five TKR patients between the ages of 50 and 75 years were recruited from a local orthopedic clinic (age = 68.8 ± 4.9 years, height = 170.2 ± 10.6 cm; mass = 83.2 ± 15.5 kg; months since surgery = 22.1 ± 11.7 months (range: 7−46 months)). TKR patients were recruited if they had a unilateral TKR (conducted by a single surgeon) in the past 6−60 months. Participants were excluded if they had had any additional lower extremity joint replacements, any additional diagnosed OA of the hip or ankle, more than 75% radiographic joint space narrowing and chronic pain at the contralateral knee of the TKR side, a body mass index (BMI) greater than 38 kg/m^2, or any neurological diseases. Ten older adults between the ages of 50 and 75 years without any lower extremity pathology were recruited in the study as healthy controls (age = 69.1 ± 4.6 years, height = 174.0 ± 12.0 cm, mass = 75.0 ± 23.0 kg) (Table 1).

The sample size to detect differences in measurements between TKR patients and healthy controls was estimated using peak KEM data and an effect size of 0.859, which has been previously reported in the literature.[22] To obtain an α of 0.05 and a β of 0.80, a minimum of 10 participants were needed for each group. All participants signed an informed consent document approved by the Institutional Review Board of the University of Tennessee.

2.2. Instrumentation

Three-dimensional (3D) kinematics were collected using a 12-camera motion analysis system (240 Hz; Vicon Motion Analysis Inc., Oxford, UK). Participants were asked to wear tight-fitting workout clothing and a pair of standardized laboratory running shoes (Noveto; Adidas, Portland, OR, USA) during data collection. Reflective anatomical markers were placed bilaterally on the second toe, first and fifth metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of 4 reflective tracking markers mounted on a semi-rigid thermoplastic shell was placed on the lateral aspect of shanks, thighs, pelvis, and posterior trunk. Four discrete tracking markers were place on the lateral and posterior heel counter of the shoe.

A customized instrumented ramp system was used in the study to measure the ground reaction forces (GRF) and the moments of forces during downhill walking (Fig. 1A and 1B). The ramp system (Fig. 1A) consisted of 5 segments. Segment A provided a transition from the floor to the main ramp walkway (Segment B), which was 1-m wide and 3-m long. A platform (Segment C) was hinged to the end of Segment B and mounted on a support structure (Segment E), which had 3-sets of mounting holes at 3 different heights to accommodate for ramp grades of 5°, 10°, and 15°, respectively. The 2 separate walking surfaces/structures (Segment D), which were isolated from the rest of the ramp structure but flush with the rest of the ramp surface, were bolted onto 2 force platforms

Table 1
Descriptive statistics (mean ± SD).

	TKR	Healthy	p
Age (year)	68.8 ± 4.9	69.1 ± 4.6	0.869
Height (cm)	170.2 ± 10.6	174.4 ± 12.0	0.309
Mass (kg)	83.2 ± 15.5	75.0 ± 23.0	0.231
BMI (kg/m^2)	28.7 ± 4.2*	24.1 ± 4.4	0.014

* $p < 0.05$, compared with healthy controls.
Abbreviations: BMI = body mass index; TKR = total knee replacement.

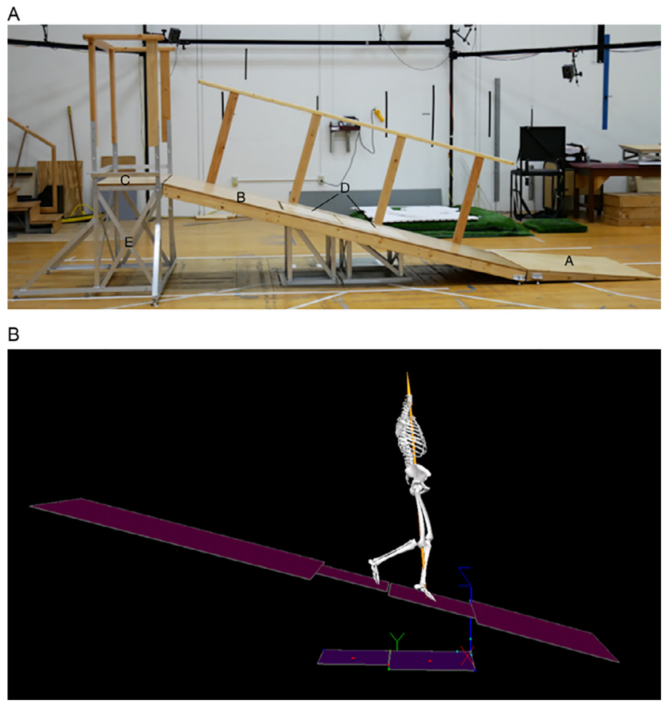

Fig. 1. (A) The mechanical structure of the ramp system. The mechanical structure of the ramp system consists of 5 segments. Segment A provides a transition from the floor the main ramp walkway (Segment B). A platform (Segment C) is hinged to the end of Segment B and mounted on a support structure (Segment E). Segment C can be adjusted at 3 different heights to accommodate for ramp grades of 5°, 10°, and 15°, respectively. The 2 separate walking structures (Segment D) are bolted on to 2 force platforms independently, with their surfaces flush with the rest of ramp surface. (B) The ramp force structure in Visual3D for the 15° decline.

independently (BP600600 and OR-6-7, 1200 Hz; American Mechanical Technology Inc., Watertown, MA, USA). Gait speeds were monitored by 2 sets of photocells (63501 IR; Lafayette Instrument Inc., Lafayette, IN, USA) and 2 electronic timers (54035A; Lafayette Instrument Inc.). The photocells were placed 3 m apart for level walking and 1.5 m apart at shoulder height for ramp walking.

2.3. *Experimental procedures*

Both healthy controls and TKR patients completed an information sheet that collected demographic and injury history information. They also completed the Physical Activity Readiness Questionnaire.[24] Following completion of the information sheet and survey, participants performed a 3-min walking trial on a treadmill at a self-selected speed as warm-up.

All participants were asked to perform 5 walking trials for each limb on each of 4 different slope conditions: 0° (level walking), 5°, 10°, and 15° (downhill). The testing order of 3 decline ramp conditions (5°, 10°, and 15°) was randomized first, which was then followed by the randomization of right and left foot within each slope condition. Level walking was performed after decline-walking conditions. The testing order of right and left leg was randomized within each decline condition. To reduce the total testing time, the ramp conditions were tested first due to the need for its setup prior to participants coming to the lab. Participants were asked to practice downhill and level walking trials at a self-selected speed for each ramp decline condition. The participants found their comfortable starting position during the practice trials. A cone was then used to mark that position. Once participants were comfortable with downhill walking during the practice trials (about 3 trials each), the participants were asked to perform downhill and level walking at their self-selected speed range (mean ± 5%) obtained during the practice trials for each ramp condition. Participants was asked to repeat a trial if they did not make a full contact within the force platform with the targeted foot and were not able to reach the pre-determined speed. A handrail was provided on the right side for balance purposes if needed, but participants were not encouraged to use it. A numerical visual analog pain scale was used to assess pain in both knees for healthy controls and for TKR patients prior to the warm-up and at the end of each test condition.

2.4. *Data analyses*

The Visual3D biomechanical analysis software suite (Version 2.6; C-Motion, Inc., Germantown, MD, USA) was used to compute the 3D kinematic and kinetic variables. The 2 ramp surfaces connected to the force platforms were modeled as force structures in Visual3D (Fig. 1B). An X-Y-Z Cardan rotational sequence was used in the 3D angular kinematics computations, and a right-hand rule was used to determine the conventions of angular kinematic and kinetic variables. Joint moments were calculated as internal moments in the proximal segment and normalized to the participant's body mass, yielding a unit of N·m/kg. Positive values indicate knee extension ROM. For kinetic variables, positive values indicate knee extension, adduction moments, and internal rotation moments. Kinematic and GRF data were smoothed at a cutoff frequency of 8 Hz using a fourth-order, zero-lag Butterworth low-pass filter. Raw GRF data were filtered alone using a fourth-order low-pass Butterworth filter with a cut-off frequency of 50 Hz for GRF data. Peak angles and moments were determined and organized for statistical analysis using customized programs (VB_V3D and VB_Table, MS Visual BASIC; Microsoft, Redmond, WA, USA). The GRFs were normalized to the participant's body weight, and joint moments were normalized to the participant's body mass (N·m/kg).

2.5. *Statistical analyses*

A one-way analysis of variance (ANOVA) was used to identify differences in demographic and survey data between TKR patients and healthy controls. A 2 × 4 (group (TKR and healthy controls) × decline slope (0°, 5°, 10°, and 15°)) ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls. To test the first 2 hypotheses, a 2 × 2 (limb (replaced and non-replaced limb) × group (TKR patients and healthy controls)) ANOVA was used to examine the interactions and main effects of knee flexion ROM; peak loading-response and push-off VGRF, KEM, KAbM; and peak internal rotation moment for each slope condition (SPSS Version 24.0; IBM Corp., Armonk, NY, USA). To test the third hypothesis, the peak KEM and the knee flexion ROM would increase across all slope comparisons between 0° and 15° in both the replaced and non-replaced limb among TKR patients, a 2×4 (limb (replaced and non-replaced limb of TKR patients) × slope (0°, 5°, 10°, and 15°)) ANOVA was used to examine the same selected biomechanics parameters. A Kruskal-Wallis non-parametric test was used to examine the difference in visual analog pain scale between replaced, non-replaced, and healthy limb for each decline slope condition. The left and right limb of healthy controls was randomly selected as Limb 1 or Limb 2 to match with the TKR replaced and non-replaced limb, respectively. An *a priori* α level was set to 0.05. When the two-way ANOVA showed a significant interaction or main effect, *post hoc* comparisons with Bonferroni adjustments were used to detect differences between limbs, groups, and decline angles, respectively. In order to focus on the effects on TKR patients and to streamline result reporting, when there was a significant limb effect, we only reported results of *post hoc* comparisons related to the TKR group.

3. Results

3.1. Differences in demographic information between TKR patients and healthy controls

Differences in age, height, and mass between TKR patients and healthy controls were not significant (Table 1). TKR patients had a significantly greater BMI than healthy controls ($p = 0.014$). Participants walked significantly faster on level ground compared to all 3 decline walking conditions ($p < 0.0001$ for all comparisons, Table 2). In all walking conditions, both limbs of TKR patients showed higher visual analog pain scale scores than the limbs of healthy controls ($p < 0.0001$ for all comparisons).

3.2. The results of 2 × 2 (group × limb) ANOVA

The peak loading-response VGRF was greater in the non-replaced limb compared to the replaced limb during 10° ($p = 0.013$) and 15° downhill walking ($p = 0.017$) (Table 3). The peak push-off VGRF was greater in the non-replaced limb compared to the replaced limb only in 10° downhill walking ($p = 0.038$). A significant limb × group interaction was present in both peak loading-response ($p = 0.024$) and push-off ($p = 0.007$) KEM at 15° downhill walking (Table 3). The replaced limb showed lower peak KEM during loading-response ($p = 0.025$) and push off ($p = 0.020$) than the matched limb of healthy controls at 15°. The TKR patients presented lower peak loading-response KEM than healthy controls in all slopes ($p < 0.036$ for all comparisons).

Table 2
Walking speed and VAS (mean ± SD).

	0°	5°	10°	15°
Walking Speed (m/s)[a,*,#,†]				
TKR	1.08 ± 0.14	0.94 ± 0.14	0.89 ± 0.15	0.92 ± 0.18
Healthy	1.17 ± 0.20	1.02 ± 0.19	0.99 ± 0.22	0.94 ± 0.18
VAS (mm)				
TKR[‡]				
Replaced	4.0 ± 7.0	5.0 ± 9.6	5.9 ± 11.8	9.6 ± 17
Non-replaced	3.6 ± 7.3	3.6 ± 7.3	4.6 ± 7	4.1 ± 7.3
Healthy				
Limb 1	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Limb 2	0 ± 0	0 ± 0	0 ± 0	0 ± 0

[a] Significant decline slope main effect.
* $p < 0.0001$, significantly different between 0° and 5°.
[#] $p < 0.0001$, significantly different between 0° and 10°.
[†] $p < 0.0001$, significantly different between 0° and 15°.
[‡] $p < 0.0001$, significantly different from healthy controls.
Abbreviations: BMI = body mass index; TKR = total knee replacement; VAS = visual analogue pain scale.

3.3. The results of 2 × 4 (limb × slope) ANOVA

Mean ensemble curves of key kinematic and kinetic variables for the replaced and non-replaced limbs of TKR patients are presented in Fig. 2; the mean data for limbs across the 4 decline slopes can also be found in Table 3. Significant results for all the ANOVA and *post hoc* comparisons are presented in the text of paper and in Fig. 3. A significant decline slope main effect was found for knee flexion ROM ($p < 0.001$). It significantly increased across all pairwise comparisons between 0° and 15° of decline angle ($p < 0.001$ for all comparisons, Fig. 2A and 2B).

A significant slope main effect was found for peak loading-response VGRF ($p < 0.001$). It significantly decreased across all comparisons between 0° and 15° of decline angle ($p < 0.035$ for all comparisons, Fig. 2C and 2D).

A significant slope main effect was present for peak push-off VGRF ($p = 0.001$). The peak push-off VGRF was greater in level walking compared to all downhill walking conditions ($p < 0.005$ for all comparisons). It was also lower during 15° compared to 5° ($p = 0.003$) and 10° ($p = 0.005$, Fig. 2C and 2D).

A significant limb × slope interaction was present in both peak KEM during loading-response ($p = 0.004$, Fig. 3A) and push-off ($p = 0.011$, Fig. 3B) for TKR patients. Both peak moments increased significantly across most slope comparisons in both replaced and non-replaced limbs ($p < 0.026$ for all comparisons, Fig. 2E and 2F). The non-replaced limb had greater peak loading-response KEM than the replaced limb in all downhill walking conditions ($p < 0.040$ for all comparisons), and it also had greater peak push-off KEM than the replaced limb during 10° and 15° downhill walking ($p < 0.003$ for all comparisons).

The peak push-off KAbM was lower in level walking than at 5°, 10°, and 15° downhill walking ($p < 0.020$ for all comparisons). It was also lower during 5° downhill walking compared to 15° downhill walking ($p = 0.023$). The peak knee internal rotation moment was greater during 15° compared to 0°, 5°, and 10° downhill walking; and it was greater during 10° compared to 0° and 5° ($p < 0.001$ for all comparisons) downhill walking.

4. Discussion

The purpose of this study was to compare knee biomechanics of the replaced limb of TKR patients to their non-replaced limb and to the healthy limb of controls during decline walking

Table 3
Knee flexion ROM (°), peak GRF (body weight), and knee moments (N·m/kg) during level and downhill walking (mean ± SD).

Variable	Group	Limb	0°	5°	10°	15°
Knee flexion ROM	TKR	Replaced	−41.3 ± 5.3	−51.2 ± 5.8	−59.0 ± 5.9	−65.8 ± 6.0
		Non-replaced	−43.1 ± 6.3	−53.5 ± 5.7	−60.0 ± 5.5	−66.7 ± 6.3
	Healthy	Limb 1	−43.4 ± 5.2	−53.6 ± 8.3	−62.8 ± 7.5	−71.0 ± 6.5
		Limb 2	−44.9 ± 8.4	−54.2 ± 8.2	−62.9 ± 6.9	−71.0 ± 6.1
Peak loading-response VGRF	TKR	Replaced	1.03 ± 0.08	1.11 ± 0.12	1.17 ± 0.13[#]	1.23 ± 0.18[#]
		Non-replaced	1.05 ± 0.07	1.14 ± 0.10	1.23 ± 0.13	1.30 ± 0.17
	Healthy	Limb 1	1.07 ± 0.07	1.13 ± 0.09	1.19 ± 0.09	1.20 ± 0.11
		Limb 2	1.09 ± 0.07	1.15 ± 0.07	1.22 ± 0.11	1.22 ± 0.15
Peak push-off VGRF	TKR	Replaced	1.01 ± 0.07	0.98 ± 0.06	0.95 ± 0.06[#]	0.91 ± 0.07
		Non-replaced	1.03 ± 0.06	1.00 ± 0.04	0.98 ± 0.06	0.94 ± 0.09
	Healthy	Limb 1	1.05 ± 0.05	0.97 ± 0.06	0.92 ± 0.08	0.90 ± 0.08
		Limb 2	1.06 ± 0.04	0.98 ± 0.04	0.93 ± 0.06	0.90 ± 0.08
Peak loading-response KEM	TKR	Replaced	0.35± 0.21[†]	0.44 ± 0.22[†]	0.58 ± 0.24[†]	0.75 ± 0.27*[,†]
		Non-replaced	0.38 ± 0.22	0.53 ± 0.24	0.75 ± 0.29	0.94 ± 0.39
	Healthy	Limb 1	0.49 ± 0.29	0.57 ± 0.30	0.81 ± 0.40	1.00 ± 0.41
		Limb 2	0.57 ± 0.26	0.68 ± 0.22	0.89 ± 0.26	0.96 ± 0.41
Peak push-off KEM	TKR	Replaced	0.15 ± 0.11	0.37 ± 0.17	0.69 ± 0.23	0.98 ± 0.23*[,†]
		Non-replaced	0.16 ± 0.17	0.43 ± 0.16	0.83 ± 0.27	1.12 ± 0.31
	Healthy	Limb 1	0.18 ± 0.07	0.34 ± 0.07	0.73 ± 0.18	1.20 ± 0.25
		Limb 2	0.21 ± 0.07	0.38 ± 0.08	0.74 ± 0.13	1.12 ± 0.25
Peak loading-response KAbM	TKR	Replaced	−0.36 ± 0.12	0.35 ± 0.14	−0.36 ± 0.15	−0.38 ± 0.14
		Non-replaced	−0.41 ± 0.20	−0.42 ± 0.21	−0.44 ± 0.22	−0.44 ± 0.23
	Healthy	Limb 1	−0.43 ± 0.14	−0.42 ± 0.11	−0.45 ± 0.12	−0.42 ± 0.13
		Limb 2	−0.43 ± 0.15	−0.41 ± 0.15	−0.41 ± 0.19	−0.42 ± 0.20
Peak push-off KAbM	TKR	Replaced	−0.29 ± 0.12	−0.32 ± 0.15	−0.35 ± 0.14	−0.38 ± 0.15
		Non-replaced	−0.32 ± 0.17	−0.36 ± 0.19	−0.40 ± 0.19	−0.40 ± 0.20
	Healthy	Limb 1	−0.25 ± 0.13	−0.28 ± 0.14	−0.30 ± 0.15	−0.33 ± 0.15
		Limb 2	−0.27 ± 0.18	−0.31 ± 0.18	−0.32 ± 0.20	−0.36 ± 0.18
Peak knee internal rotation moment	TKR	Replaced	0.09 ± 0.05	0.10 ± 0.05	0.12 ± 0.05	0.17 ± 0.06
		Non-replaced	0.12 ± 0.05	0.13 ± 0.06	0.17 ± 0.07	0.21 ± 0.08
	Healthy	Limb 1	0.10 ± 0.07	0.11 ± 0.07	0.15 ± 0.07	0.18 ± 0.08
		Limb 2	0.13 ± 0.05	0.14 ± 0.05	0.17 ± 0.06	0.20 ± 0.10

Note: Positive moment values indicate knee extension, adduction, and internal rotation moments.
* $p < 0.05$, significant limb × group interaction.
[#] $p < 0.05$, compared with non-replaced limb.
[†] $p < 0.05$, compared with healthy controls.
Abbreviations: GRF = ground reaction force; KAbM = Knee abduction moment; KEM = knee extension moment; ROM = range of motion; TKR = total knee replacement; VGRF = vertical ground reaction force.

on different slopes. We formulated 3 hypotheses regarding the way in which knee biomechanics were related to TKR.

The first hypothesis was that TKR patients would exhibit lower peak KEM and similar peak KAbM in their replaced limb compared with the matched limb of healthy controls. The results of this study support this hypothesis. Compared with the healthy controls, TKR patients demonstrated an average of 27.9% lower peak loading-response KEM in all walking conditions. The peak push-off KEM was also 18.3% lower in the replaced limb of TKR patients compared with matched limb of healthy controls in 15° downhill walking. These findings demonstrate that both the replaced and non-replaced limb had a reduction in sagittal plane knee kinetics compared with the matched limb of healthy controls in both level and downhill walking. Similar discrepancies were reported in Reynolds' study,[22] which showed 36.3% lower peak loading-response KEM in the replaced limb of TKR patients compared to the matched limb of healthy controls in 7° downhill walking. Previous studies have also reported similar apparent deficits in knee loading-response KEM in replaced limb of TKR patients compared with healthy controls in level walking.[5,6,25,26] Levinger et al.[5] showed that TKR patients had 60.9% lower peak KEM in their replaced limb at 12 months post-surgery and walked 17.5% slower compared with healthy controls. However, in our study no group differences were detected in walking speed as well as peak VGRF and knee flexion ROM across all comparisons between 0° and 15°. Therefore, lower KEM in TKR patients may be due to the quadriceps strength deficit compared to healthy controls. Some studies have reported a quadriceps strength loss after TKR surgery[27–30] and have also revealed that TKR patients had less quadricep electromyographic activity than healthy controls during level walking,[31] providing support for the findings of reduced KEM in TKR compared to healthy controls in level, 5°, and 10° downhill walking.

Both peak loading-response and push-off KAbM were similar in the replaced limb and matched limb of healthy controls across all comparisons between 0° and 15° of decline angle, which supports our hypothesis. The loading-response KAbM, along with KEM, is commonly used to estimate medial

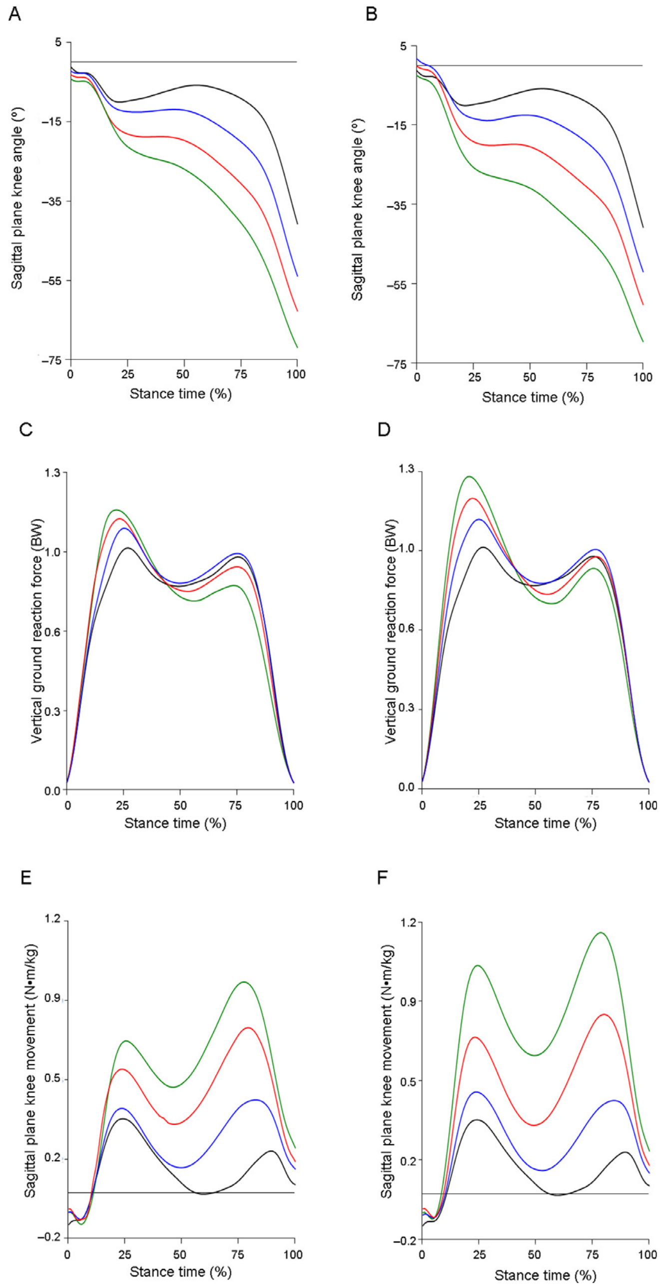

Fig. 2. Ensemble curves of (A) sagittal plane knee angle in the replaced limb, (B) sagittal plane knee angle in the non-replaced limb, (C) vertical ground reaction force in the replaced limb, (D) vertical ground reaction force in the non-replaced limb, (E) sagittal plane knee moment in the replaced limb, and (F) sagittal plane knee moment in the non-replaced limb. The black line is 0° downhill walking; the blue line is 5° downhill walking; the red line is 10° downhill walking; and the green line is 15° downhill walking. BW = body weight.

compartment knee joint loading for knee OA patients in gait.[32] Increased medial knee joint loading may increase wear and tear on the joint replacement.[33] Similar peak loading-response KAbMs between replaced and matched limb of healthy controls in both level and downhill walking indicated that TKR surgeries may have successfully restored medial knee joint loading to the healthy level in not only level but also downhill walking.

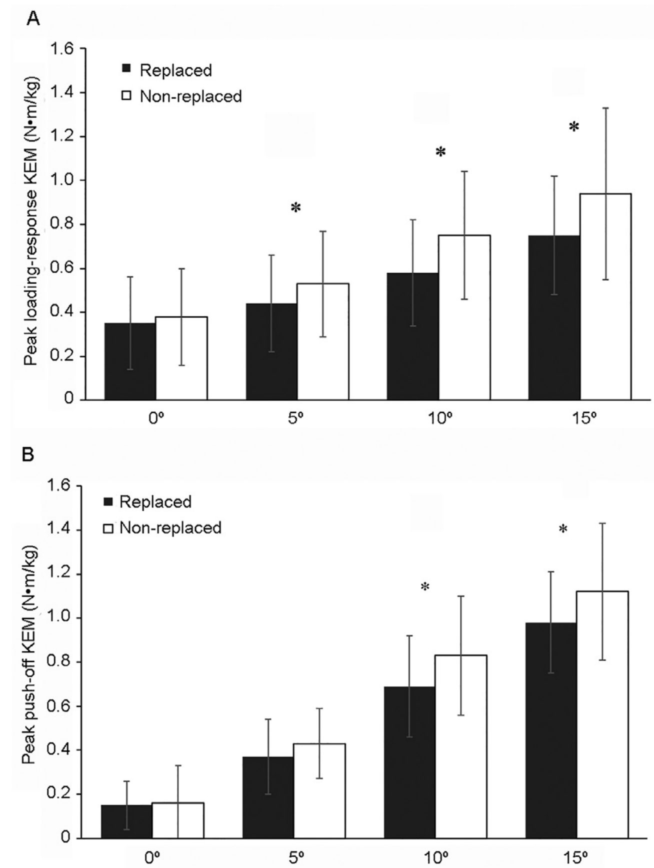

Fig. 3. (A) The peak loading-response KEM and (B) the peak push-off KEM in TKR patients during level and downhill walking. *Significant difference between replaced and non-replaced limbs ($p < 0.04$ for all comparisons). The error bar indicates the standard deviation. KEM = knee extension moment; TKR = total knee replacement.

Our second hypothesis was that the replaced limb in TKR patients would have lower peak KEM and similar peak KAbM compared to the non-replaced limb. The results supported the hypothesis. Compared to the non-replaced limb, the replaced limb had lower peak loading-response KEM across all comparisons between 5° and 15° of decline angle and lower peak push-off KEM in 10° and 15° downhill walking. In addition, interactions and *post hoc* comparisons did not exhibit any differences between replaced and non-replaced limbs for both peak loading-responses and push-off KAbM. The peak loading-response KEM was 17.0%, 22.7%, and 20.0% lower in the replaced limb compared to the non-replaced limb across all comparisons between 5° and 15° decline angle, respectively. The peak push-off KEM was 16.9% and 12.5% lower in the replaced limb compared to the non-replaced limb in 10° and 15° downhill walking, respectively. Reynolds[22] reported that the replaced limb was 22.7% and 22.4% lower in peak loading-response and push-off KEM, respectively, in 7° downhill walking.

The replaced limb had lower peak loading-response VGRF than the non-replaced limb in 10° and 15° downhill walking. Findings for VGRF provide partial support for the differences in peak KEMs between replaced and non-replaced limbs.

These findings indicate that patients displayed unloading of the replaced limb and shifting of the load to the non-replaced limb when performing downhill walking. The increased dependence on the non-replaced limb may be to compensate for the quadricep strength deficits and/or residual pain in the replaced limb. However, greater knee joint loading in the non-replaced limb may accelerate development of knee OA in non-replaced limb. A previous study[34] reported that 40% of patients had to replace their contralateral knee within 10 years after primary unilateral TKR surgery. Monitoring symmetry of patients during their recovery from primary unilateral TKR surgery may help to avoid or postpone contralateral TKR surgery in the future. However, we found no differences in peak KEM and VGRF between the replaced limb and the non-replaced limb in level walking.[35,36] Downhill walking is more demanding than level walking; thus, it may intensify the quadricep strength deficit in the replaced limb compared to non-replaced limb.

In our study, peak loading-response and push-off KAbM were not different between the replaced limb and non-replaced limb during level and downhill walking. However, Alnahdi et al.[37] have reported that the non-replaced limb had a greater knee adduction angle and KAbM compared with the replaced limb during level walking. In our study, we excluded patients who had severe OA on the contralateral knee, whereas Alnahdi et al.[37] did not specify whether the patients with unilateral TKR had OA on the contralateral knee. The KAbM is related to the severity of OA and may predict OA progression.[38] Greater KAbM in the non-replaced limb may subsequently expedite knee OA progression.

Our third hypothesis was that the peak KEM (Fig. 2E and 2F) and the knee flexion ROM (Fig. 2A and 2B) would increase across all slope comparisons between 0° and 15° in both the replaced and non-replaced limb of TKR patients. The findings in our study supported this hypothesis. Increased KEMs across all the decline conditions should be a concern in using downhill walking in rehabilitation exercises after the surgery. Increased KEM is associated with high knee joint force[39] and may be directly linked to wear and damage to the polyethylene component of knee implants in the replaced limb.[40] TKR patients are less capable of handling higher demands on quadriceps at an early stage of rehabilitation because their quadriceps are still weak. It has been demonstrated that the quadriceps are more than 60% weaker in the early rehabilitation stage (3−4 weeks) after TKR surgery compared to pre-surgery quadriceps strength.[28] Thus, downhill walking may not be appropriate to include in early-stage rehabilitation protocols following TKR surgery. In addition, TKR patients should avoid downhill terrain during hiking. If downhill terrain cannot be avoided, the use of hiking poles would help to reduce the loading on the knee joint.[12]

In our study the slope effect was significant in both peak loading-response and push-off vertical GRFs. Peak loading-response VGRF increased significantly across all slope comparisons. The peak push-off VGRF was greater during level walking compared to downhill walking conditions for TKR patients. Previous studies have also reported similar findings for VGRF in young healthy populations.[11,16,17] In these studies, as the decline angle increased during downhill walking, shock absorption increased in weight acceptance and propulsion decreased before toe-off. Greater peak loading-response VGRF may increase knee joint loading, and therefore downhill walking may not be appropriate to include in early-stage rehabilitation protocols following TKR surgery. However, it might be added to progressive rehabilitation schemes.

In our study, there was a significant slope effect for all kinetic variables except for peak loading-response KAbM. Our finding demonstrated good agreement with previous studies on downhill walking.[11,16,17,21] Since the center of gravity of the body is continuously lowered during downhill walking, the knees have to maintain a more flexed position through the stance phase, and therefore the knee sagittal-plane joint loading increases accordingly. No differences were present in peak loading-response KAbM across all slopes between 0° and 15° in the replaced, and non-replaced, indicating that medial joint loading remained unchanged, even with increased sagittal-plane loading.

Certain limitations in this study should be noted. First, 3 TKR patients could not perform 15° downhill walking. We excluded their data for 15° downhill walking from the statistical analyses. Second, 7 of the 25 TKR patients used the handrail of the ramp system for balance purposes, which may have influenced their knee biomechanical results. We performed a 2 × 2 × 4 (limb (replaced *vs*. non-replaced) × group (handrail user and non-handrail user) × decline slope (0°, 5°, 10°, and 15°)) ANOVA on peak loading-response and push-off VGRFs and KEM, and no group effects or interactions were detected in these key variables. Third, the spread of post-surgery times of our TKR participants was relatively large (7−46 months). The presence of muscle co-contraction during walking after TKR is common,[30] which may have affected the interpretations of the joint moments. Finally, the TKR patient group had 15 more participants than the healthy control group. However, the assumption of equal variances was satisfied for all dependent variables and the unequal sample size did not influence the ANOVA results.

5. Conclusion

The replaced limb of TKR patients had lower peak loading-response and push-off KEM than the matched limb of healthy controls and non-replaced limb. No differences were found in loading-response and push-off KAbMs between the replaced and non-replaced limb of TKR patients or between the replaced limb of TKR patients and the matched limb of healthy controls. The knee flexion ROM, loading-response VGRF, and peak KEM increased across all slope comparisons between 0° and 15° in TKR patients. These results indicate that downhill walking may not be appropriate to include in early-stage rehabilitation protocols following TKR surgery.

Authors' contributions

CW completed data collection and drafting of the manuscript; CW, SZ, and HEC contributed to the study conception and design; CW and SZ were involved in the data analysis.

JTW and SEC were involved in revising the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

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