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Is knee biomechanics different in uphill walking on different slopes for older adults with total knee replacement?

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ABSTRACT

The purpose of this study was to investigate knee biomechanics in uphill walking on slopes of 5°, 10° and 15° for total knee replacement (TKR) patients. Twenty-five post-TKR patients and ten healthy controls performed five walking trials on level ground and different slopes on an instrumented ramp system. A $2 \times 2 \times 4$ (limb × group × incline slope) mixed model ANOVA was used to examine selected variables. The peak knee extension moment (KEM) was greater in 15° uphill walking compared to level, 5° and 10° uphill walking. TKR patients had lower peak KEM and smaller knee extension range of motion than healthy controls in all walking conditions. The Replaced Limb showed lower peak KEM in 10° and 15° uphill walking than the Non-replaced Limb and smaller knee extension range of motion (ROM) in 10° uphill walking. Knee extension and abduction ROM increased with increased incline angles. The greater peak loading-response vertical ground reaction force was found in level walking compared to three levels of uphill walking. The peak loading-response knee abduction moment was greater in level walking compared to 10° and 15° uphill walking. However, the medial knee contact force was greater in non-replaced limb compared to replaced limb in 10° and 15° uphill walking. The results suggest 5° uphill walking may have the potential to become a safe exercise for unilateral TKR patients.

1. Introduction

Uphill walking is an inevitable part of daily living and has been integrated into rehabilitation protocols for patients undergoing total knee replacement (TKR) (Meier et al., 2008). However, knee biomechanics in TKR patients during uphill walking of different slopes have not been documented in the literature. Brisk walking is recommended for TKR patients as an optimal post-surgery exercise and the intensity should increase based on patients' progress (Pozzi et al., 2013). Ehlen et al. (2011) reported that the peak internal knee extension moment (KEM) was 19% smaller, while peak internal knee abduction moment (KAbM), which was widely used to estimate medial compartment knee joint loading, was 26% smaller when uphill walking at 6° and 0.75 m/s compared to level walking at 1.5 m/s in obese adults. Haight et al. (2014) also reported that walking relatively slowly up a moderate incline showed 35% smaller KEM compared to fast, level walking in non-obese individuals. Slow uphill walking may be an appropriate alternative exercise to fast walking for TKR patients to prevent high knee loading which may wears away the surface of the implant.

Previous studies demonstrated that during level walking TKR patients typically have slower walking speed, less knee flexion range of motion (ROM), and reduced KEM compared to healthy controls, which may be due to their quadriceps strength deficits (Benedetti et al., 2003; Levinger et al., 2013). Additionally, peak knee adduction angle (Mandeville et al., 2008; McClelland et al., 2011) and peak KAbM (McClelland et al., 2011) in TKR patients were similar or smaller to those in healthy controls which suggest that TKR surgery seems to successfully improve knee alignment and loading conditions in the frontal plane. However, it is unknown that whether these differences in knee biomechanics between TKR patients and healthy controls during level walking would still exist or become even more evident during uphill walking at greater slopes. Studies investigating the knee biomechanics differences between different incline angle during uphill walking in TKR patients may provide guidance for them to choose a proper incline to walk for rehabilitation.

Earlier uphill gait analyses have only focused on young healthy populations (Alexander and Schwameder, 2016b; Han et al., 2009; Hong et al., 2014a, 2014b; Kuster et al., 1995; Lay et al., 2006,

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2007; McIntosh et al., 2006; Redfern and DiPasquale, 1997). The Knee flexion ROM was smaller and the peak KEM was greater in uphill walking than those in level walking at the same walking speed (Alexander and Schwameder, 2016b; Han et al., 2009; Hong et al., 2014a, 2014b; Kuster et al., 1995; Lay et al., 2006, 2007; McIntosh et al., 2006; Redfern and DiPasquale, 1997). The peak knee flexion angle and the peak KEM were considerably increased with an increase in incline angle (Franz and Kram, 2014; Leroux et al., 2002; McIntosh et al., 2006). Haggerty et al. (2014) reported the peak KAbM during the stance phase of 10° uphill walking at 1.34 m/s was 22% less than that of level walking at the same speed. Furthermore, each 5.74° increment (10% gradient) of incline angle resulted in a 15–17% reduction in KAbM (Haggerty et al., 2014).

Currently, no studies have explored knee biomechanics during uphill walking at different slopes in TKR patients. There is a clear gap in the literature about the gait pattern adaption in TKR patients. Furthermore, uphill walking has been integrated into rehabilitation protocols after TKR surgery (Meier et al., 2008), therefore, a comprehensive biomechanical analysis of its benefit for this population is warranted. The information from such a study may help physical therapists creating appropriate post-surgery rehabilitation protocols. Thus, the purpose of this study was to investigate knee biomechanics in uphill walking on slopes of 5°, 10° and 15° for TKR patients. We hypothesized that during uphill walking, the peak KEM would be lower in the Replaced Limb of TKR patients compared to healthy controls, and peak loading-response KAbM in the Replaced Limb of TKR patients would be similar compared to healthy controls, and compared to the Non-replaced Limb, the Replaced Limb would have lower peak KEM and similar peak loading-response KAbM in ramp walking conditions. We further hypothesized that the peak KEM would increase and the knee flexion ROM would decrease with an increase in the incline angle in the Replaced and the Non-replaced Limbs of TKR patients.

2. Materials and methods

2.1. Participants

Twenty-five TKR patients were recruited from a local orthopedic clinic (Table 1). The inclusion criteria for TKR patients were having a unilateral total knee replacement conducted by a single surgeon between 6 months and 60 months and between the ages of 50 and 75 years. Potential participants were excluded if they had any additional lower extremity joint replacements, any additional diagnosed osteoarthritis (OA) of the hip, knee (contralateral side) or ankle, more than 75% radiographic joint space narrowing and chronic pain at the contralateral knee of the TKR side, body mass index (BMI) greater than 38, or neurological diseases. Ten older adults without any lower extremity pathology participated in the study as healthy controls (Table 1). All patients signed an informed consent document approved by the Institutional Review Boards. An *a priori* power analysis, using results of peak knee flexion angle (Reynolds, 2013), peak KEM (Haight et al., 2014), and peak KAbM (Haggerty et al., 2014), showed that a minimum of 10 participants were needed for each group in order to obtain an alpha of 0.05 and a beta of 0.80.

2.2. Instrumentation

A twelve-camera motion analysis system (240 Hz, Vicon Motion Analysis Inc., Oxford, UK) was used to acquire three-dimensional (3D) kinematics. Reflective anatomical markers were placed bilaterally on the 2nd toe, 1st and 5th metatarsal heads, medial and lateral malleoli, medial and lateral femoral epicondyles, greater trochanters, iliac crests, and acromion processes. A cluster of four reflective tracking markers 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 sides of heel counter of the shoe.

A customized instrumented ramp system was used in the study to measure ground reaction forces (GRF) and the moments of forces. The ramp consists of a walkway that is 1 m wide and 3 m long and with two separate surface structures (Fig. 1) bolted individually on to two force platforms (BP600600 and OR-6-7, 1200 Hz, American Mechanical Technology Inc., Watertown, MA, USA). The inclined angle of ramp surface can be adjusted to 5°, 10° and 15°, respectively. Gait speeds were monitored by two sets of photocells and two electronic timers (Lafayette Instrument Inc., IN, USA). TKR patients were asked to complete a questionnaire, Knee injury and Osteoarthritis Outcome Score (KOOS) (Roos et al., 1998). All participants were asked to walk at 0° (level), and at 5°, 10°, 15° (uphill) on the adjustable ramp. The three ramp incline conditions were performed in a randomized manner and followed by level walking (in order to reduce the setup and data collection time for TKR patients). The testing order of right and left leg was further randomized within each incline and level walking condition. Participants performed ramp and level walking trials at their self-selected speed range (mean ± 5%) obtained during the practice trials. 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 (VAS) was used to assess knee

Table 1
Descriptive statistics and survey data (mean ± stdv).

	TKR	Healthy	P value
Age (years)	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**
KOOS			
Symptom	78.7 ± 19.3	92.5 ± 13.1	**0.047**
Pain	82.6 ± 17.3	96.1 ± 4.0	**0.001**
Activity of daily life	85.1 ± 17.1	98.7 ± 1.8	**0.001**
Sport/recreation	50.0 ± 23.0	87.5 ± 14.2	**<0.001**
Quality of life	72 ± 24.3	90.6 ± 10.3	**0.003**

P values with a bold font indicates statistical significance.

Fig. 1. The setup of ramp at a 15° incline for experimental data collection.

pain level prior to the warm-up, and at the end of each test condition.

2.3. Data analyses

Visual3D biomechanical analysis software suite (version 2.5 C-Motion, Inc., Germantown, MD, USA) was used to compute 3D kinematic and kinetic variables. An X-Y′-Z″ (lateral-anterior-vertical) 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 and normalized to body mass (Nm/kg). 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 separately using a fourth-order low-pass Butterworth filter at a cut-off frequency of 50 Hz for the purpose of obtaining the peak values and were normalized to body weight (BW) (Bennett et al., 2017; Kristianslund et al., 2012; Paquette et al., 2014). Peak knee medical contact force (KMCF) were estimated based on a regression equation using peak KEM and peak KAbM (Walter et al., 2010).

2.4. 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 (healthy and TKR) × slope (0, 5, 10 and 15°)] ANOVA was used to examine the difference in walking speed between TKR patients and healthy controls in all walking conditions. A 2 × 2 × 4 [group (healthy and TKR) × limb (Replaced and Non-replaced) × incline slope (0, 5, 10 and 15°)] mixed model ANOVA was used to examine the interactions and main effects of GRF and knee kinematic and kinetic variables (24.0, IBM SPSS, Chicago, IL). The left and right limb of healthy controls were randomly selected to match with TKR Replaced and Non-replaced Limb, respectively. An a priori alpha level was set to 0.05. When the ANOVA results revealed a significant three-way interaction, two-way ANOVAs were followed. When two-way ANOVAs showed significant interaction or main effect, post-hoc comparisons with Bonferroni adjustments were used to detect differences between limbs and angles (adjusted $p < 0.025$ for differences detected between limbs and groups, $p < 0.0125$ for differences detected between incline angles, $p < 0.00625$ for slope × group and limb × slope interactions, and $p < 0.0125$ for limb × group interaction). In order to focus on effects on TKR patients and streamline result reporting, when there was a significant limb effect in 3-way or 2-way interaction, we only reported related TKR group results. The assumption of equal variance was examined and satisfied for all dependent variables.

3. Results

There were no differences of age, height, and mass between TKR patients and healthy controls (Table 1). TKR patients had greater BMI than healthy controls ($p = 0.014$). Sub-scales of symptom, pain, activity of daily life, sport/recreation, and quality of life of KOOS were significant lower in TKR patients compared to healthy controls ($p < 0.047$ for all comparisons).

There were no differences in walking speed between TKR patients and healthy controls (Table 2). Participants walked significantly faster on level ground than on 5°, 10° and 15° ramp, respectively ($p < 0.002$ for all comparisons), and faster on 5° and 10° ramp, respectively than on 15° ramp ($p < 0.007$ for all comparisons). TKR patients had higher VAS scores than healthy controls ($p < 0.012$ for all comparisons, Table 2).

A significant limb × slope × group interaction was detected in knee extension ROM ($p = 0.001$, Table 3 and Fig. 2A). In follow-up ANOVAs, a significant limb × slope interaction was found for TKR patients ($p = 0.003$) and a significant slope × group interaction was found in the Replaced Limb ($p = 0.003$). Post hoc comparisons showed that the Non-replaced knee had greater extension ROM than the Replaced knee in 10° uphill walking ($p = 0.024$). Knee extension ROM increased significantly as the incline angle increased in both the Replaced and the Non-replaced Limb of TKR patients and both limb of healthy controls ($p < 0.002$ for all comparisons). Both the Replaced and the Non-replaced Limbs of TKR patients had smaller knee extension ROM than their respective matched limb of healthy controls in all the uphill walking conditions ($p < 0.016$ for all comparisons). Knee flexion ROM decreased ($p < 0.001$ for all comparisons) and knee adduction ROM increased ($p < 0.011$ for all comparisons) as the incline angle increased in both limb of TKR patients, respectively. Mean ensemble curves of key variables for TKR patients can be found in Supplementary Fig. 1 (SF1).

The peak loading-response vertical GRF was greater in level walking compared to all three uphill conditions respectively ($p < 0.002$ for all comparisons, Table 4). It was also greater in 5° compared to 15° uphill walking ($p = 0.009$). The peak push-off vertical GRF was smaller in level walking compared to 5° ($p = 0.007$) and 10° ($p = 0.003$) uphill walking respectively.

Table 2
Walking speed and VAS data (mean ± stdv).

			0°	5°	10°	15°
Walking speed (m/s)$^{*,\alpha,\beta,\gamma,\varepsilon,\zeta}$	TKR		1.06 ± 0.15	1.00 ± 0.15	0.98 ± 0.16	0.94 ± 0.14
	Healthy		1.17 ± 0.20	1.05 ± 0.19	1.02 ± 0.17	0.96 ± 0.17
VAS (mm)$^{@}$	TKR	Replaced	4 ± 7	5.2 ± 10	6.8 ± 12	9.6 ± 16
		Non-replaced	4.4 ± 8	5.2 ± 9	6 ± 9	6 ± 9
	Healthy	Limb1	0 ± 0	0 ± 0	0 ± 0	0 ± 0
		Limb2	0 ± 0	0 ± 0	0 ± 0	0 ± 0

TKR: total knee replacement, VAS: visual analog pain scale.
Limb 1 of healthy controls matched with the replaced limb of TKR patients.
Limb 2 of healthy controls matched with the non-replaced limb of TKR patients.
@ Significant group main effect.
* Significant slope main effect.
$^{\alpha}$ Significantly different between 0° and 5°.
$^{\beta}$ Significantly different between 0° and 10°.
$^{\gamma}$ Significantly different between 0° and 15°.
$^{\varepsilon}$ Significantly different between 5° and 15°.
$^{\zeta}$ Significantly different between 10° and 15°.

Table 3
Mean knee kinematic variables (°) (mean ± stdv).

Variable	Group	Limb	0°	5°	10°	15°
Knee extension ROM[^,Y,Z]	TKR	Replaced	–	4.4 ± 6.6[&,δ,ε]	17.3 ± 7.8[&,ζ]	29.8 ± 6.8[&]
		Non-replaced	–	3.9 ± 6.1[&,δ,ε]	19.8 ± 8.0[&,$,ζ]	31.5 ± 7.6[&]
	Healthy	Limb 1	–	10.9 ± 6.8	28.4 ± 5.4	40.1 ± 7.5
		Limb 2	–	11.3 ± 6.0	26.5 ± 6.7	39.4 ± 6.9
Knee flexion ROM[*,α,β,γ,δ,ε,ζ]	TKR	Replaced	−40.8 ± 5.2	−34.5 ± 5.4	−31.1 ± 4.2	−28.9 ± 4.7
		Non-replaced	−43.1 ± 6.1	−36.8 ± 5.4	−33.6 ± 5.8	−28.6 ± 6.8
	Healthy	Limb 1	−43.4 ± 5.2	−41.3 ± 5.3	−38.2 ± 6.1	−35.7 ± 6.8
		Limb 2	−44.7 ± 7.2	−40.4 ± 5.9	−37.0 ± 5.5	−34.4 ± 5.9
Knee abduction ROM[*,β,γ,δ,ε,ζ]	TKR	Replaced	–	−3.5 ± 1.6	−5.1 ± 3.4	−8.1 ± 4.6
		Non-replaced	–	−3.6 ± 1.5	−5.5 ± 2.7	−8.1 ± 4.2
	Healthy	Limb 1	–	−4.3 ± 1.7	−7.4 ± 2.6	−9.6 ± 4.8
		Limb 2	–	−4.2 ± 1.6	−7.1 ± 4.1	−10.1 ± 5.6

Positive values indicate knee extension, adduction and internal rotation angles and ROM.
–No comparable values.
ROM: range of motion.
[*] Significant slope main effect.
[^] Significant limb × slope × group interaction.
[Y] Significant slope × group interaction.
[Z] Significant limb × slope interaction.
[$] Significantly different from replaced limb.
[&] Significantly different from healthy controls.
[α] Significantly different between 0° and 5°.
[β] Significantly different between 0° and 10°.
[γ] Significantly different between 0° and 15°.
[δ] Significantly different between 5° and 10°.
[ε] Significantly different between 5° and 15°.
[ζ] Significantly different between 10° and 15°.

Significant limb × slope interaction ($p = 0.006$), group ($p = 0.019$) and limb (0.008) main effects were found for peak KEM (Table 4 and Fig. 2B). In the Replaced Limb, the peak KEM was greater in 15° compared to level and 5° uphill walking ($p < 0.012$), and it was greater in 10° compared to 5° uphill walking ($p = 0.002$). In the Non-replaced Limb, the moment was greater in 15° uphill walking compared to level, 5°, and 10° uphill walking respectively ($p < 0.009$ for all comparisons). The moment was also greater in 10° compared to level and 5° uphill walking respectively ($p < 0.001$ for all comparisons). It was also smaller in the Replaced Limb compared to the Non-replaced Limb in 10° ($p = 0.002$) and 15° ($p < 0.001$) uphill walking, respectively. TKR patients had lower peak KEM than healthy controls in all walking conditions ($p < 0.021$ for all comparisons).

A significant limb × group interaction was found for peak knee flexion moment ($p = 0.003$, Table 4 and Fig. 2C). The moment was lower in the Replaced Limb compared to and the Non-replaced Limb ($p < 0.019$). TKR patients had lower peak knee flexion moment than healthy controls ($p < 0.012$). In addition, peak knee flexion moment significantly increased as incline angle increased ($p < 0.001$ for all comparisons).

A significant incline slope main effect was observed for peak loading-response KAbM ($p = 0.009$) and peak push-off KAbM ($p < 0.001$, Table 4 and Fig. 2D). The peak loading-response KAbM was greater in level walking compared to 10° ($p = 0.003$) and 15° ($p = 0.003$) uphill walking. The peak push-off KAbM was greater in level walking compared to all uphill walking conditions respectively ($p < 0.001$ for all comparisons). It was also greater in 5° compared to 10° and 15° uphill walking respectively ($p < 0.007$ for all comparisons).

A significant limb × slope interaction and slope main effect was found for peak loading-response KMCF (Table 4 and Fig. 2E). It was greater in Non-replaced Limb compared to Replaced Limb in 10° ($p = 0.015$) and 15° ($p = 0.008$). Non-replaced Limb showed smaller loading-response KMCF in 5° compared to 10° ($p = 0.012$) and 15° ($p = 0.019$). A significant limb × group interaction was also detected in peak push-off KMCF. Non-replaced Limb had smaller push-off KMCF than Replaced Limb in all slope conditions ($p \leq 0.015$ for all comparisons).

4. Discussion

4.1. Comparison between TKR patients and healthy controls

Our first hypothesis was supported as Replaced Limb of TKR patients showed lower peak KEM than healthy controls in all walking conditions. There were no differences in both peak loading-response and push-off KAbM between TKR and healthy participants.

Compared to healthy controls, peak KEM was 32.7%, 42.3%, 41.8% and 38.4% lower in Replaced Limb and 38.6%, 44.5%, 27.8% and 27.4% lower in Non-replaced Limb in level and three uphill walking conditions, respectively. These findings showed that deficits of both Replaced and the Non-replaced Limbs are apparent compared to healthy controls, even when walking speeds were similar between the groups. Previous studies have reported the deficits in peak KEM in Replaced and Non-replaced Limbs compared to healthy controls during level walking (Benedetti et al., 2003; Levinger et al., 2013; Mandeville et al., 2007; Ouellet and Moffet, 2002). TKR patients at two-year follow-up walked 21% slower and had 50% lower peak KEM in Replaced Limbs of TKR patients compared to healthy controls (Benedetti et al., 2003).

Reduced peak KEMs were found for TKR group while there were no differences in walking speed and peak vertical GRF between TKR and healthy participants across slopes. Reduced KEMs may be partially due to smaller knee extension ROM of TKR compared to healthy participants. Specifically, knee extension ROM was 59.6%, 39.1% and 25.7% smaller in Replaced Limb and 65.5%, 25.8% and 20.0% smaller in Non-replaced Limb in uphill conditions. Reduced knee extension ROM in TKR patients may be due to quadriceps strength deficit (Stevens-Lapsley et al., 2010) and knee joint stiffness (Su et al., 2010). In level walking, some studies reported smaller knee flexion ROM in Replaced Limbs compared

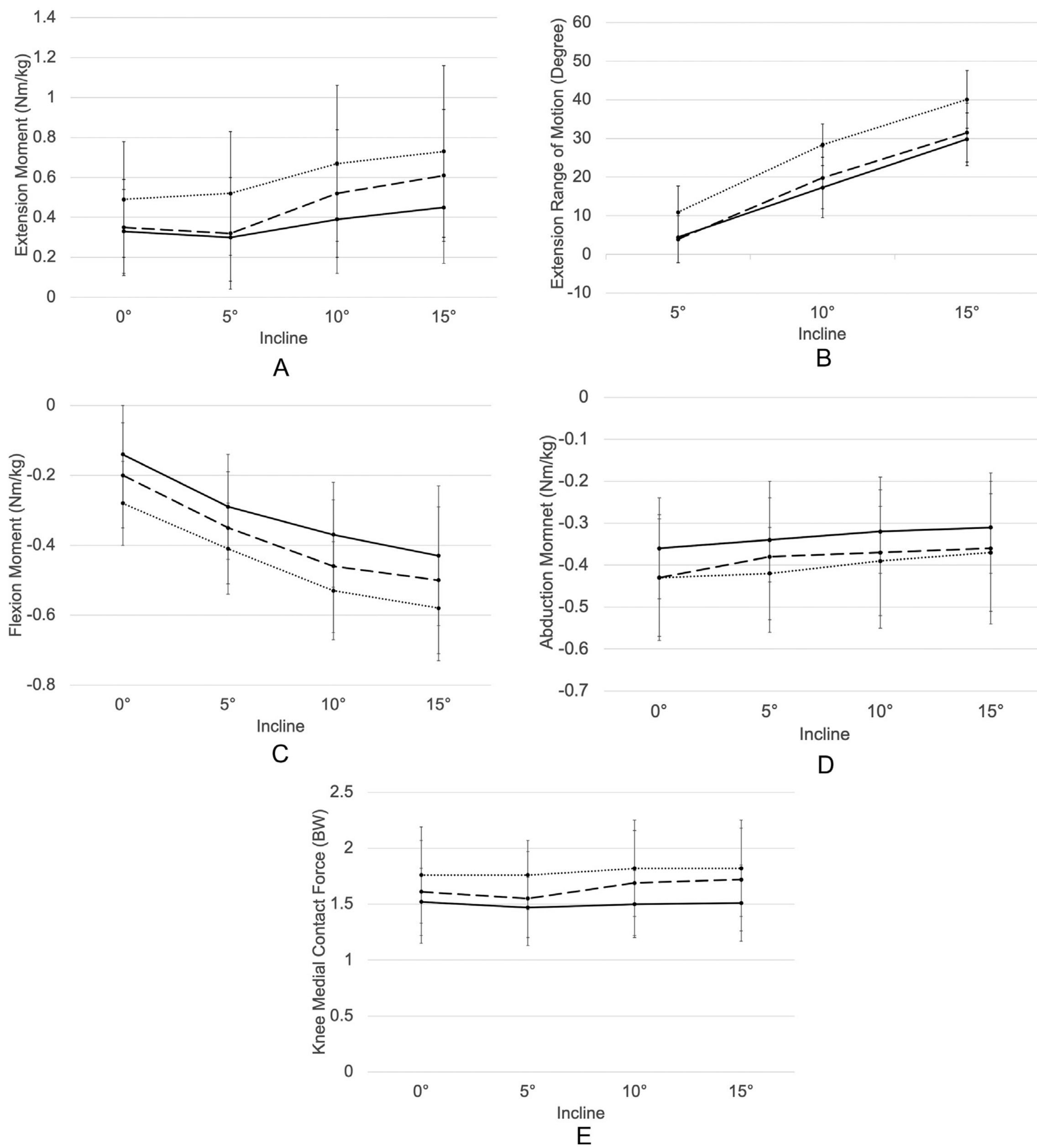

Fig. 2. The knee extension ROM, peak knee moments, and peak knee medial contact force. (A) Knee extension ROM, (B) peak KEM, (C) peak knee flexion moment, (D) peak loading-response KAbM, (E) peak loading-response KMCF. The solid line (—) is the Replaced Limb of TKR patients; the dashed line (– – – –) is for the non-replaced Limb of TKR patients; the dotted line (. . .) is for Healthy limb.

to healthy controls (Benedetti et al., 2003; Mandeville et al., 2007; Ouellet and Moffet, 2002). In this study, differences in knee flexion ROM between Replaced and matched limbs of healthy controls during level and uphill walking were small and not significant. This study provides novel data in knee biomechanics in uphill walking for TKR population.

Both limbs of TKR patients had similar peak loading-response KAbM and KMCF compared to healthy controls in all walking conditions. Increased medial knee joint loading may cause increased stress and accelerated wear on joint replacement (Halder et al., 2012). Before the surgery, TKR patients usually suffered severe medial compartment knee OA and had a greater peak loading-response KAbM than healthy controls in level walking (Zeni et al., 2010). Similar peak loading-response KAbM and KMCF in Replaced Limbs indicated that TKR surgery successfully reduced peak loading-response KAbM and medial knee loading.

4.2. Comparison between the replaced and the non-replaced Limb of TKR patients

Our second hypothesis was also supported by the results of this study. Peak KEM was lower in Replaced Limbs compared to Non-replaced Limbs in 10° and 15° uphill walking.

Compared to Non-replaced Limb ($SF1_F$), Replaced Limb ($SF1_E$) showed 25.0% and 26.2% lower peak KEM only in 10° and 15°. These differences were coupled with a reduced knee extension ROM (12.6%, $SF1_A$ and $SF1_B$) in 10°. Moreover, peak loading-response KMCF was 12.7% and 13.9% greater in Non-replaced Limb compared to Replaced Limb in these two inclinations. These results suggest that asymmetry in knee loading was exacerbated in the more demanding uphill walking conditions which was similar to the findings from previous studies in stair ascent (Standifird et al., 2016). During stair ascent, peak KEM of Replaced Limb was

Table 4
GRF (BW), knee moments (Nm/kg) and knee medial contact force (BW) (mean ± stdv).

Variables	Group	Limb	0°	5°	10°	15°
Peak loading-response vertical GRF[*,α,β,γ,ε]	TKR	Replaced	1.03 ± 0.09	1.00 ± 0.09	0.98 ± 0.08	0.97 ± 0.08
		Non-replaced	1.04 ± 0.09	1.00 ± 0.09	1.00 ± 0.08	0.99 ± 0.08
	Healthy	Limb 1	1.07 ± 0.07	1.05 ± 0.05	1.04 ± 0.06	1.03 ± 0.09
		Limb 2	1.09 ± 0.07	1.05 ± 0.05	1.04 ± 0.06	1.04 ± 0.08
Peak push-off vertical GRF[*,α,β]	TKR	Replaced	1.00 ± 0.08	1.03 ± 0.07	1.04 ± 0.07	1.02 ± 0.07
		Non-replaced	1.02 ± 0.07	1.04 ± 0.07	1.05 ± 0.09	1.04 ± 0.08
	Healthy	Limb 1	1.05 ± 0.05	1.07 ± 0.04	1.08 ± 0.07	1.08 ± 0.07
		Limb 2	1.06 ± 0.04	1.07 ± 0.04	1.08 ± 0.08	1.09 ± 0.11
Peak KEM[Z,*,@,#]	TKR	Replaced	0.33 ± 0.21[γ]	0.30 ± 0.22[δ,ε]	0.39 ± 0.27	0.45 ± 0.28
		Non-replaced	0.35 ± 0.24[β,γ]	0.32 ± 0.28[δ,ε]	0.52 ± 0.32[ζ]	0.61 ± 0.33
	Healthy	Limb 1	0.49 ± 0.29	0.52 ± 0.31	0.67 ± 0.39	0.73 ± 0.43
		Limb 2	0.57 ± 0.26	0.58 ± 0.30	0.72 ± 0.30	0.84 ± 0.34
Peak knee flexion moment[*,X,α,β,γ,δ,ε,ζ]	TKR[&]	Replaced	−0.14 ± 0.14	−0.29 ± 0.15	−0.37 ± 0.15	−0.43 ± 0.20
		Non-replaced[$]	−0.20 ± 0.15	−0.35 ± 0.16	−0.46 ± 0.19	−0.50 ± 0.21
	Healthy	Limb 1	−0.28 ± 0.12	−0.41 ± 0.13	−0.53 ± 0.14	−0.58 ± 0.15
		Limb 2	−0.21 ± 0.17	−0.35 ± 0.17	−0.43 ± 0.23	−0.51 ± 0.23
Peak loading-response KAbM[*,β,γ]	TKR	Replaced	−0.36 ± 0.12	−0.34 ± 0.10	−0.32 ± 0.10	−0.31 ± 0.11
		Non-replaced	−0.43 ± 0.15	−0.38 ± 0.18	−0.37 ± 0.18	−0.36 ± 0.18
	Healthy	Limb 1	−0.43 ± 0.14	−0.42 ± 0.11	−0.39 ± 0.13	−0.37 ± 0.14
		Limb 2	−0.43 ± 0.15	−0.38 ± 0.15	−0.38 ± 0.18	−0.36 ± 0.17
Peak push-off KAbM[*,α,β,γ,δ,ε]	TKR	Replaced	−0.28 ± 0.11	−0.24 ± 0.11	−0.23 ± 0.11	−0.20 ± 0.10
		Non-replaced	−0.32 ± 0.16	−0.28 ± 0.16	−0.27 ± 0.15	−0.27 ± 0.15
	Healthy	Limb 1	−0.25 ± 0.13	−0.24 ± 0.14	−0.19 ± 0.16	−0.21 ± 0.14
		Limb 2	−0.27 ± 0.18	−0.22 ± 0.16	−0.19 ± 0.18	−0.16 ± 0.29
Peak loading-response KMCF[Z,*]	TKR	Replaced	1.52 ± 0.30	1.47 ± 0.27	1.50 ± 0.30	1.51 ± 0.34
		Non-replaced	1.61 ± 0.46	1.55 ± 0.42[δ,ε]	1.69 ± 0.47[$]	1.72 ± 0.46[$]
	Healthy	Limb 1	1.76 ± 0.43	1.76 ± 0.31	1.82 ± 0.43	1.82 ± 0.43
		Limb 2	1.82 ± 0.40	1.71 ± 0.41	1.86 ± 0.53	1.87 ± 0.55
Peak push-off KMCF[X]	TKR	Replaced	1.24 ± 0.25	1.24 ± 0.22	1.26 ± 0.23	1.25 ± 0.24
		Non-replaced[$]	1.37 ± 0.34	1.45 ± 0.33	1.45 ± 0.34	1.40 ± 0.37
	Healthy	Limb 1	1.24 ± 0.29	1.31 ± 0.29	1.33 ± 0.31	1.37 ± 0.35
		Limb 2	1.22 ± 0.44	1.21 ± 0.35	1.24 ± 0.45	1.28 ± 0.43

Positive moment values indicate knee extension, adduction and internal rotation moments.
GRF: ground reaction force, KEM: knee extension moment, KAbM: Knee abduction moment, KMCF: Knee medial contact force.
[@] Significant group main effect.
[#] Significant limb main effect.
[*] Significant slope main effect.
[X] Significant limb × group interaction.
[Z] Significant limb × slope interaction.
[$] Significantly different from replaced limb.
[&] Significantly different from healthy controls.
[α] Significantly different between 0° and 5°.
[β] Significantly different between 0° and 10°.
[γ] Significantly different between 0° and 15°.
[δ] Significantly different between 5° and 10°.
[ε] Significantly different between 5° and 15°.
[ζ] Significantly different between 10° and 15°.

also shown to be 20% lower than Non-replaced Limb of TKR patients (Standifird et al., 2016). Uphill walking places more demand on knee joint and surrounding muscles, and therefore may exaggerate the strength deficit of knee muscles in Replaced Limbs. Asymmetrical loading to knee joint shown here indicate that Non-replaced Limb shared greater load in those high loading gait movements, which may expedite knee OA progression of Non-replaced Limb. After unilateral TKR, knee OA often progresses in the Non-replaced Limb and 40% of patients with unilateral TKR had to replace contralateral knees within 10 years of their TKR procedures (McMahon and Block, 2003). To slow down knee OA progression in Non-replaced knees, walking on a slope of 10° or steeper as rehabilitation exercises after TKR surgery should be avoided if possible. In addition, the peak knee flexion moment during late stance phase was 30%, 17%, 19.6% and 14% lower in Replaced Limb compared to Non-replaced Limb in level and uphill walking conditions, respectively. These finding indicate that TKR patients experienced a reduction in both KEM and knee flexion moment following surgery.

4.3. Comparison between different slopes

The results from this study also provided support for the third hypothesis. There was a significant slope effect for all knee kinetic variables. Peak KEM was greater in 15° compared to level, 5° and 10° uphill walking, and greater in 10° compared to level and 5° uphill walking $SF1_E$ and $SF1_F$). Knee extension ROM increased from 5° to 15°, and flexion ROM decreased significantly from 0° to 15° uphill walking ($SF1_A$ and $SF1_B$).

Peak loading-response vertical GRF was greater in level walking compared to all three uphill conditions, and greater in 5° compared to 15° uphill walking ($SF1_C$ and $SF1_D$). Participants walked faster on level ground than inclined surfaces, which may cause higher peak vertical GRF during loading-response phase in level walking compared to uphill conditions. However, although loading-response peak vertical GRF decreased, peak KEM actually increased as incline angle increased, similar to findings of previous studies of healthy participants (Franz and Kram, 2014; Hong et al., 2014a; Lay et al., 2006; McIntosh et al., 2006). During uphill walking, knees are more flexed at heel strike and have more extension ROM as the incline angle increased. These kinematic changes required the quadriceps to produce more power to raise lower limb for heel strike and then push the body up on inclined surface (Alexander and Schwameder, 2016a, 2016b).

There was a significant slope main effect for peak loading-response and push-off KAbM. The peak loading-response KAbM was 13.0% and 17.9% greater in level walking compared to 10° and 15° uphill walking, respectively ($SF1_G$ and $SF1_H$). Our findings were similar to the observation by Haggerty et al. in healthy young participants (Haggerty et al., 2014), showing peak KAbM in weight acceptance was 14.8%, 22.2% and 31.5% greater in level walking compared to that in 10% (5.7°), 15% (8.6°) and 20% (11.4°) uphill walking on treadmill, respectively. In addition, peak loading-response KAbM did not increase as the incline angle increased, even though 5° uphill walking did not cause a decrease of peak loading-response KAbM. Peak loading-response KMCF was 9.0% and 11.0% smaller in 5° compared to 10° and 15° in Non-replaced Limb, respectively. These results suggest that 5° uphill walking on increased inclines does not increase medial knee joint loading and therefore, may have the potential to become a safe rehabilitation exercise for unilateral TKR patients and knee OA patients. However, increased KEMs and peak loading-response KMCF observed during 10° and 15° uphill walking should be a concern in using uphill walking on a 10° or steeper slope in rehabilitation exercises after the surgery. Since increased KEM is associated with high tibiofemoral contact force (D'Lima et al., 2012) which may be directly linked to wear and damage to polyethylene component of knee implants in Replaced Limbs (D'Lima et al., 2001), increased loading-response KMCF may expedite knee OA progression in Non-replaced Limbs.

Certain limitations in this study should be noted. Six out of 25 TKR patients used of the handrail on our ramp system for balance purposes, which may have effects on their knee kinematic and kinetic results. However, a 2 × 2 × 4 ANOVA [limb × groups (handrail and non-handrail TRK patients) × slopes] (Supplementary Table 1) and another 2 × 2 × 4 ANOVA [limb × groups (non-handrail TKR patients and all TKR patients) × slopes] (Supplementary Table 2) were performed on peak loading-response and push-off vertical GRFs and peak KEM and the results showed no significant group effect or interactions involving group in neither ANOVA. The spread of post-surgery times of our TKR participants are relatively large and may have effects on generalizing our findings to all TKR patients.

5. Conclusion

TKR patients had lower peak KEM and smaller knee extension ROM than healthy controls. Replaced Limb also showed smaller knee extension ROM and peak KEM in uphill walking than the Non-replaced Limb. However, knee extension and abduction ROM increased as the incline angle increased. Our results also showed that peak KEM was greater in uphill walking compared level walking; however, peak loading-response vertical GRF was greater in level compared to uphill walking. Finally, peak loading-response KAbM was greater in level compared to uphill walking. Uphill walking may have the potential to become a safe rehabilitation exercise for unilateral TKR patients, but a slope of 10° or steeper slope should be avoided during rehabilitation after TKR procedure.

Conflict of interest

This study presents no conflicts of interest for all authors.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.006.

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