Gait & Posture 70 (2019) 179–184

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

The contralateral knee may not be a valid control for biomechanical outcomes after unilateral total knee arthroplasty

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ARTICLE INFO

Keywords:
Joint replacement
Kinetics
Kinematics
Osteoarthritis
Gait
Symmetry

ABSTRACT

Background: Although unilateral symptoms and unilateral total knee arthroplasty (TKA) are common, many patients have bilateral radiographic osteoarthritis (OA). Because the contralateral (non-operated) limb is often used as a comparison for clinical and biomechanical outcomes, it is important to know if the presence of OA influences movement patterns in either limb.

Research question: The purpose of this study was to compare bilateral sagittal plane biomechanics between subjects with and without contralateral knee OA after unilateral TKA.

Methods: Fifty-three subjects who underwent unilateral TKA underwent three-dimensional gait analysis 6–24 months after surgery participated in this cross-sectional study. Kellgren-Lawrence (KL) OA severity in the contralateral limb was measured, and subjects were classified into either a non-OA (KL 0 or 1) or OA (KL 2–4) group. Mixed-model ANOVA tests with factors of group and limb were used to compare biomechanical measures. In the presence of a significant interaction effect, post-hoc comparisons were performed.

Results: The OA group had more knee flexion at initial contact, less knee flexion and extension excursions, and less knee extension in the contralateral limb compared to the non-OA group. The non-OA group had significant differences between limbs, with more knee flexion at initial contact, less knee joint excursion, and less peak knee extension on the operated limb compared to the contralateral limb, whereas there were no limb differences for the OA group. Kinetic variables were not different in the ANOVA models.

Significance and interpretation: Subjects with contralateral knee OA have more symmetrical gait, although they adopt a more abnormal and stiff-legged gait pattern bilaterally. Researchers and clinicians should consider radiographic disease severity, not just symptoms, in the contralateral limb when identifying appropriate subject samples for unilateral biomechanical studies. Symmetrical movement patterns between limbs after surgery should not be the sole factor upon which movement recovery is based.

1. Introduction

Total knee arthroplasty (TKA) is routinely used to reduce pain and improve function for patients with end-stage knee osteoarthritis (OA) [1]. Although most patients report substantial improvement in functional mobility, studies using three-dimensional motion analysis have revealed persistent abnormalities in gait kinetics and kinematics after surgery compared to age-matched controls [2]. A systematic review found that patients after TKA ambulate with residual deficits in the sagittal plane, exemplified by less knee joint excursion, less knee flexion during loading response, and lower joint moments in the operated limb [3]. These studies have led to clinical interventions designed to normalize movement patterns and improve sagittal plane biomechanics after surgery [4,5].

In biomechanical studies of patients after TKA, the contralateral (non-operated) limb, is often used as a control limb for comparative analysis [6,7]. While this may be appropriate for patients with unilateral OA, most individuals who report unilateral pain, actually have structural changes in both knees. In individuals who have primarily unilateral knee OA symptoms, 87.4% had radiographic evidence of

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https://doi.org/10.1016/j.gaitpost.2019.01.030
Received 9 May 2018; Received in revised form 3 December 2018; Accepted 18 January 2019

bilateral OA [8]. It is likely that many of these patients will elect to undergo unilateral TKA because their symptoms are not severe enough to warrant simultaneous or staged TKA. For these individuals, it is important to determine if the contralateral OA influences movement patterns. If so, the contralateral limb may not serve as a true control comparator for clinical outcomes or biomechanical studies.

Patients with increasing severity of radiographic knee OA have progressively abnormal biomechanics [9]. Patients with more severe OA often have less knee flexion excursion and adopt a stiffer gait pattern in the lower extremity [9,10]. This gait pattern is similar to post-operative gait impairments in which patients after TKA walk with a characteristically stiff gait pattern on the operated side [11]. However, most previous work has evaluated the effect of progressive knee OA in a population of patients who have substantial joint symptoms. It is not known if patients who undergo TKA with unilateral symptoms, but who have bilateral radiographic OA, exhibit abnormal movement patterns on either limb. This is important for two reasons; 1) abnormal movement patterns in the presence of contralateral knee OA may lead to an under-reporting of gait abnormalities after TKA when that limb is used as a control comparator and 2) residual abnormal movement patterns, particularly reduced joint excursion, may result in larger forces over a smaller cartilage area [12]. This may perpetuate OA progression in the contralateral limb and, in part, explain the large prevalence of contralateral TKA after unilateral surgery [13,14].

The purpose of this study was to compare the sagittal plane biomechanics in the contralateral limb between subjects with and without contralateral knee OA after unilateral TKA. In this study, we specifically wanted to evaluate the effect of structural differences in the contralateral knee on movement patterns, as none of the patients had substantial symptoms on the contralateral side or were planning a contralateral TKA. We hypothesized that subjects who underwent unilateral TKA with primarily unilateral symptoms, but who had contralateral knee OA as measured by radiographs would have less sagittal plane joint excursion and lower sagittal plane knee moments in the contralateral limb compared to subjects without contralateral knee OA. We also hypothesized that subjects after TKA with OA in the contralateral knee would have more symmetrical gait mechanics than those without contralateral knee OA. The findings from this study could have important implications for future research that uses the contralateral knee as a control comparator when measuring biomechanical outcomes.

2. Methods

2.1. Subjects

Subjects who underwent unilateral TKA for end-stage knee OA underwent three-dimensional gait analysis 6 to 24 months after surgery as part of a larger cross-sectional study [15]. In order to identify a symptomatically unilateral cohort of patients, subjects were excluded from this study if they reported maximal pain greater than or equal to 4 out of 10 in the contralateral knee at the time of the surgery, or were considering staged TKA for the contralateral knee. Hence, the subjects included as part of this study were intentionally largely asymptomatic on the contralateral at the time of the primary TKA. Subjects signed a written informed consent form approved by the Human Subjects Review Board at the University of Delaware before participating in the study.

2.2. Pain and KL grade

Age, BMI, sex, and knee pain were recorded at the time of biomechanical testing. Knee pain was assessed using a single pain question from the Knee Outcome Survey Activities of Daily Living Scale (KOS-ADLS) [16]. This pain was scored on a 0 to 5 scale, where is 0 indicates that the pain prevents all daily activities and 5 indicates no pain [16,17].

Pre-operative bilateral knee radiographs were obtained from patient records. Radiographic images were obtained using a posterior to anterior view with the knee flexed to 30 °. The Kellgren-Lawrence (KL) scale was used to quantify OA severity according to the following grades: no arthritis (0), doubtful (1), minimal (2), moderate (3), and severe (4) [18,19] in the contralateral knee. The radiographs were graded by a single examiner who underwent a structured training program and demonstrated intersession reliability in scoring. The examiner had excellent intersession reliability (ICC = 0.956) with a narrow confidence interval (95% CI = 0.921 – 0.975). The radiographic examiner was blinded to the biomechanical outcomes of subjects at the time of grading. Subjects were grouped according to their pre-operative KL grades in the contralateral knee. The “non-OA group” was defined as those with KL grade 0 or 1, while the “OA Group” had KL grades 2, 3, or 4 in the contralateral limb.

2.3. Biomechanical measurements

Subjects underwent a three-dimensional biomechanical analysis during shod gait at self-selected speed 6–24 months after TKA. Subjects were instructed to wear their regular athletic footwear (no sandals or high heel were allowed to use). Several biomechanics variables in the sagittal plane during the stance phase of gait were measured in both operative and non-operative limbs using an 8-camera motion analysis system (VICON, Oxford Metrics, London, England) and two embedded force plates (Bertec Corp., Worthington, OH, USA). Sagittal plane kinematic variables included 1) knee angle at initial contact, 2) knee flexion excursion, 3) knee extension excursion, 4) peak knee flexion, and 5) peak knee extension. Kinetic variables included peak external knee flexion and extension moments. Variables were determined during the stance phase of the gait cycle (0 level on the figure means heel strike and 100% means toe off). Additionally, spatiotemporal parameters were computed.

Details of this testing have been published previously [15], but briefly, a total of 14 spherical retro-reflective anatomical markers (16 mm) were placed bilaterally on the head of the 5th metatarsal, two markers on the heel, lateral malleolus, lateral femoral condyle, greater trochanter, and iliac crest. Four rigid thermoplastic shells with four non-anatomical markers were applied on subjects' thigh and lower leg bilaterally. A rigid thermoplastic shell with 3 non-anatomical markers was used to track the pelvic motion. To minimize movement artifact, the rigid thermoplastic shells were secured with elastic wraps (Fabrifoam SuperWrap; Isokinetics Inc, De Queen, AR). Marker data were collected at 120 Hz sampling rate, while the force data were sampled at 1080 Hz.

Standing calibration was collected before walking trials to identify joint centers to create each segment's coordinate system. Then, subjects practiced walking while self-selected speeds were identified during a pre-session walking assessment. Five valid gait trials were recorded and used in the analysis. A valid trial was defined as a trial in which walking speed was between 95% and 105% of the average pre-determined self-selected speed, and the subject contacted each force platform without obvious targeting.

The marker trajectories were filtered with a 6 Hz low pass filter and force data were low-pass filtered at 40 Hz using a second order phase-corrected butterworth filter. Knee joint kinematics were calculated using the Euler sequence (flexion/extension, abduction/adduction, rotation sequences). Kinetics were calculated based on three-dimensional inverse dynamics that were expressed as net external moments normalized body weight and height (kg × m). Data analysis and calculations were performed in Visual3D Software (C-Motion, Germantown, MD, USA).

2.4. Statistical analysis

Independent t-tests or Chi-Square tests were used to compare patient demographics. For the biomechanical comparisons, a 2 × 2 analysis of variance (ANOVA) was used to identify differences between groups (OA vs non-OA) and within groups (surgical vs contralateral limb). In the presence of a significant interaction effect, post-hoc Least Squares Difference (LSD) tests were used to compare the biomechanical variables within and between groups. The assumptions of the ANOVA and t-tests were examined and deemed to be appropriate for use. All statistical analyses were performed using SPSS 24. The alpha level was set at $p < 0.05$ for all analyses.

3. Results

Fifty-nine subjects had pre-operative X-rays available and were enrolled in the study. Of these, six subjects did not have valid biomechanical data and were excluded from the analysis. Eight of the remaining 53 subjects did not have pain data (non-OA group: 5, and OA group: 3), but were included for all biomechanical analyses. Therefore, 53 subjects were divided into OA (n = 35; 66%) and non-OA (n = 18; 34%) groups based on their KL grades of the contralateral knee at the time of surgery. There were no significant differences between OA and non-OA groups in age, BMI, height, sex, walking speed, or pain (Table 1).

There were significant interaction effects for knee angle at initial contact, knee flexion excursion, knee extension excursion, and peak knee extension (Table 2). There were no significant interaction effects for peak knee flexion and peak knee flexion/extension moments. Post-hoc tests revealed significant differences in the contralateral knee between the OA and non-OA groups. The OA group had 4.5 more degrees of knee flexion at initial contact ($p = 0.008$), 3 fewer degrees of knee flexion excursion ($p = 0.010$), 3.8 less degrees of knee extension excursion ($p = 0.012$), and 5.5 ° less peak knee extension ($p = 0.009$) compared to the non-OA group in the non-operated knee (Table 2). No significant differences were found between OA and non-OA groups for peak knee flexion or kinetic variables (Table 2; Fig. 2). Visual inspection of the knee flexion curves supported findings from the discrete data points indicating less knee motion throughout the stance phase in the contralateral knee of the OA group (Fig. 1).

Post-hoc comparisons between limbs revealed that the non-OA group had significantly more knee flexion at initial contact ($p = 0.002$), less knee flexion excursion ($p = 0.002$), less knee extension excursion ($p = 0.001$), and less peak knee extension ($p < 0.001$) on the operated limb compared to the contralateral limb (Fig. 3). There were no differences between limbs for the OA group.

Table 1
Participant demographics (N = 53).

	Non-OA Group n = 18 (34%)	OA Group n = 35 (66%)	*p*-value
Age (years)	66.0 (5.8)	68.4 (7.4)	0.253
BMI	30.7 (3.8)	31.6 (5.1)	0.501
Height (m)	1.7 (0.1)	1.7 (0.1)	0.215
Time Since Surgery (months)	12.9 (7.1)	16.3 (10.3)	0.142
Gender			
Female n (%)	10 (55%)	21 (60%)	0.756
Male n (%)	8 (45%)	14 (40%)	
Walking Speed (m/sec)	1.31 (0.2)	1.30 (0.1)	0.872
Contralateral Knee Pain	0.5 (1.0)	1.0 (1.0)	0.112
Operated Knee Pain	0.7 (0.8)	0.5 (0.7)	0.214

Data are presented as "Means (Standard Deviations)".
Knee pain was measured using a Likert scale, where is 0 indicates that the pain prevents all daily activities and 5 indicates no pain.

Table 2
Kinematic variables for each group.

	Non-OA Group	OA Group	*ANOVA p*-value
Knee Angle at Initial Contact **			
Contralateral	1.0° (5.5)	5.5° (5.7)	**0.009***
Operated	5.7° (5.4)	6.1° (4.7)	
Knee Flexion Excursion			
Contralateral	16.3° (3.3)	13.3° (4.0)	**0.011***
Operated	12.7° (2.7)	12.9° (4.1)	
Peak Knee Flexion			
Contralateral	17.2° (6.0)	18.8° (6.6)	0.567
Operated	18.4° (6.0)	19.0° (4.6)	
Knee Extension Excursion			
Contralateral	14.8° (5.1)	11.0° (5.1)	**0.003***
Operated	10.2° (4.9)	10.6° (4.8)	
Peak Knee Extension **			
Contralateral	2.5° (4.9)	8.0° (7.7)	**0.009***
Operated	8. 2° (5.4)	8.4° (5.1)	
Kinetics (peak external knee moments)			
Peak Knee Flexion Moment ***			
Contralateral	0.38° (0.15)	0.35° (0.16)	0.499
Operated	0.38° (0.13)	0.38° (0.15)	
Peak Knee Extension Moment ***			
Contralateral	−0.08° (0.10)	−0.05° (0.15)	0.099
Operated	−0.02° (0.11)	−0.06° (0.11)	

Data are presented as "Means (Standard Deviations)".
* Significant ($p < 0.05$).
** Positive values indicate knee flexion (lack of full extension).
*** Negative values indicate external knee extension moment.

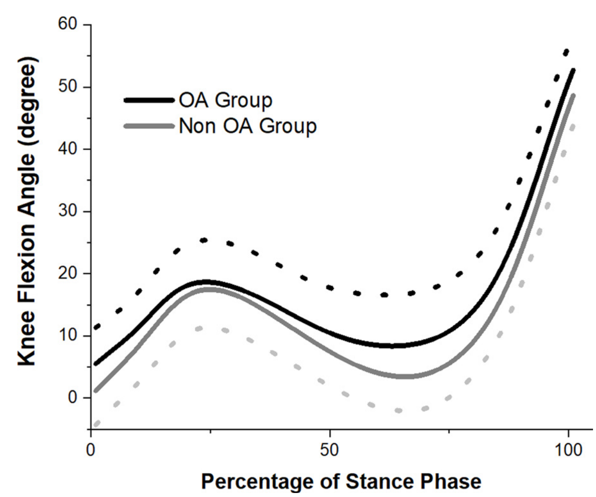

Fig. 1. Knee flexion angles in the contralateral limb during stance phase of gait for the OA and non-OA groups. The dashed lines represent standard deviations (SD).

4. Discussion

The goal of this study was to compare the sagittal plane biomechanics in subjects with and without contralateral knee OA after unilateral TKA. We focused on sagittal plane biomechanics as these metrics have been the target of movement retraining programs after TKA [20] and represent common abnormalities that persist in the operated limb after TKA [3]. If clinicians and researchers are to use the contralateral limb as a control comparator, it is important to understand if structural changes in that knee, even without substantial joint pain, are related to abnormal movement patterns. We found that despite no difference in pain between groups, individuals who had

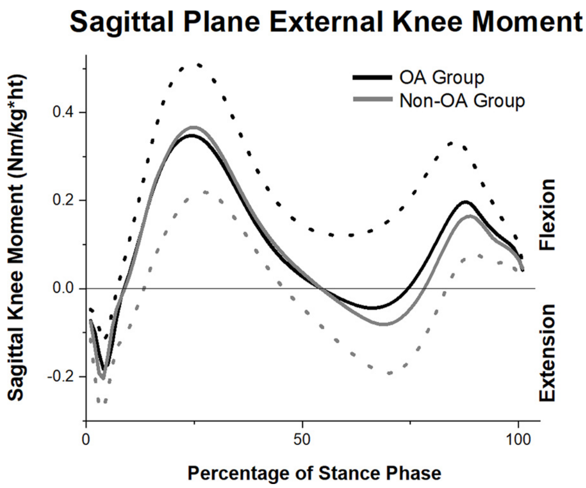

Fig. 2. Sagittal plane knee moments in the contralateral limb during stance phase of gait for the OA and non-OA groups. The dashed lines represent standard deviations (SD).

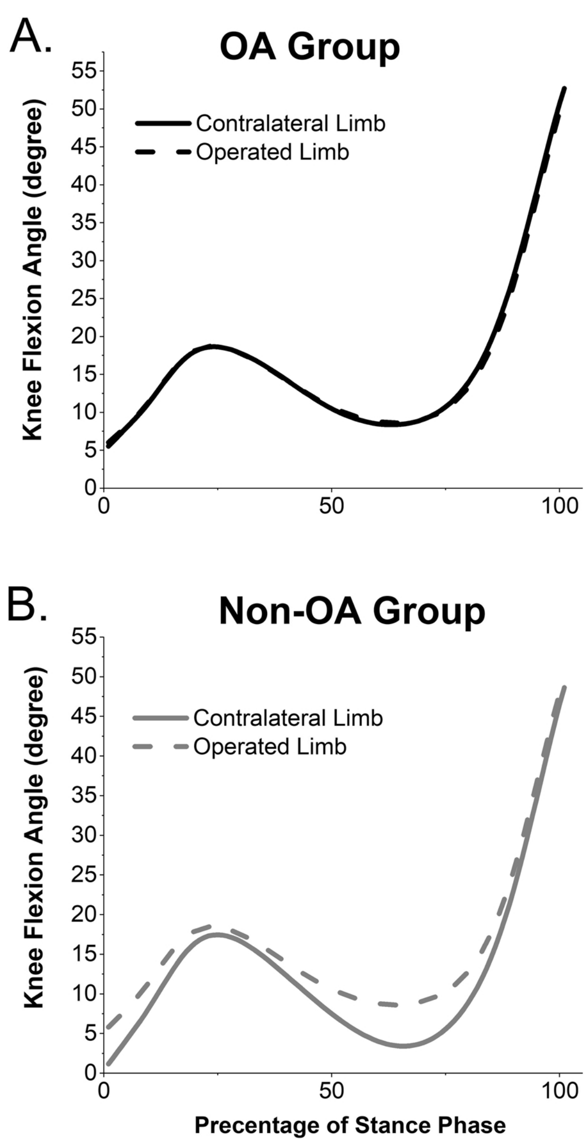

Fig. 3. Curves demonstrating inter-limb symmetry for sagittal plane knee angles during stance phase of gait for the OA (A) and non-OA (B) groups.

structural OA in the contralateral limb moved more symmetrically, albeit more abnormal than individuals without contralateral knee OA.

Although all subjects in this study had no plans for contralateral TKA and all had pain less than 4 out of 10 in the contralateral limb, two-thirds (66%) of subjects had radiographic evidence of OA in the contralateral knee at the time of index surgery (primary TKA). This is concerning, as subjects with contralateral knee OA also had abnormal knee motion that was characterized by less knee flexion excursion and a sustained knee flexion throughout stance (Fig. 1). These biomechanical differences existed between groups, even though there was no difference in contralateral knee pain (Table 1). This suggests that structural changes in the knee can affect knee biomechanics, even without substantial symptomatic changes. However, because we do not have preoperative biomechanical data, we cannot assume that the structural changes preceded changes in knee biomechanics. It is possible that the structural changes and/or the biomechanical abnormalities were present in the contralateral knee prior to the incidence or progression of contralateral knee OA.

Visual inspection of the ensemble curves (Fig. 3) supported the findings of the discrete measures of difference (Table 2), showing that subjects in the OA group had more symmetrical movement patterns than the non-OA group throughout the stance phase. Movement symmetry has been suggested to be an optimal biomechanical outcome after TKA and rehabilitation treatment protocols have been designed to reduce inter-limb asymmetries [15,21–24]. This is a concept that is applied to many therapeutic areas, including patients with neurological conditions and other musculoskeletal pathologies, such as anterior cruciate ligament reconstruction [25]. While training biomechanical symmetry may be an ideal treatment approach for patients who have true unilateral pathology, our results suggest that biomechanical symmetry should not be the only factor upon which movement patterns are assessed after TKA. In our study, gait mechanics in the OA group could be considered bilaterally abnormal, even though they had surprisingly symmetrical movement patterns in the sagittal plane (Fig. 3) and a lack of differences between limbs (Table 2). Normative values for knee excursion during weight acceptance in age-matched individuals is 15.5° [26]. This value is higher than that found in the operated (12.9°) and contralateral (13.3°) knees of our OA group. To date, there is no clear evidence on how large a difference between limbs or between groups is clinically important. Differences in knee excursion between healthy older adults without OA and those with symptomatic knee OA was found to be 3.8° [27]. Although our differences were smaller, the interaction effects from our ANOVA models suggest a significant difference in bilateral movement patterns in the OA and non-OA group. Future prospective and longitudinal studies that determine the effect of joint excursion on OA progression or functional decline are needed.

Previous studies have found that gait patterns become more symmetrical two and three years after TKA [2]. By several years after TKA, it is also known that many patients experience a predictable decline and strength and function of the contralateral knee [28]. It is conceivable that the improved symmetry several years after TKA is the result of the persistent decline in the status of the contralateral limb, not an improvement in the operated side [23]. This hypothesis is supported by the findings of this study. Structural changes associated with greater OA severity in the contralateral knee seem to be the primary driver of limb symmetry. Subjects who did not have OA in the contralateral knee presented in the typical post-operative fashion of asymmetrical movement in which only the operated limb deviated from normal values.

Even though sagittal plane knee excursions were different between groups, there was no difference in peak knee flexion. Clinically, there has been an emphasis on restoring normal peak knee flexion so that the quadriceps can act to absorb the force of the body with each step. Our findings suggest that therapists attempting to normalize knee biomechanics after TKA should attempt to increase knee extension at initial contact and increase knee extension at midstance (Fig. 1). Most subjects walked with a stiff and flexed knee joint throughout the majority of the stance phase and failed to come to full extension at midstance in the operated limb. Future work should determine whether these differences in knee extension during gait are related to loss of active knee extension range of motion, or due to residual abnormalities in limb coordination strategies. Although slower walking speeds are related to less joint excursion during gait [9,29], this does not appear to be a factor in our sample since both groups had similar walking speeds.

Although this study identified distinct differences in movement patterns between those with and without contralateral knee OA, there are some limitations to our methods. Future research should determine whether other measures of OA severity, including joint space width or magnetic resonance imaging features, are more beneficial in determining how early OA may influence biomechanics. Due to the nature of testing, subjects with substantial health comorbidities were excluded from this analysis. The results from this study may not be generalizable to all patients after the TKA. We also did not evaluate the association between many clinical measures and movement patterns. Although we found that the OA group did not have significantly greater pain, it is possible that other factors such as weakness, poor proprioception, or feelings of instability were related to reduced joint excursions. Future studies should consider including other clinical measures when determining the underlying cause for abnormal movement patterns in both limbs after TKA.

There were also limitations related to sample size and statistical approach in this analysis. Given that this was a preliminary research into the effect of the presence of contralateral knee OA and movement patterns, we intended to identify all variables that may be included for future longitudinal studies. It is also possible that given our smaller sample size, we did not have enough power to detect a statistical difference, should a true difference exist, for all of the outcomes. Therefore, we cannot assume that a true difference does not exist for all of the biomechanical metrics. Future work should seek to replicate our study using a larger sample size powered for biomechanical variables that may be inherently more variable. To address some of these limitations, we reported the effect size and provided confidence intervals (Table 2) to better quantify the magnitude of differences between groups.

5. Conclusions

The majority of subjects with primarily unilateral symptoms have bilateral radiographic OA at the time of primary TKA even though they were considered as unilateral TKA patients at the time of surgery. Subjects with contralateral knee OA do not have more contralateral knee pain, but do have gait that is more symmetrical, albeit more abnormal, than those without contralateral knee OA. Symmetrical movement patterns should not be the sole factor upon which movement recovery is based. The contralateral knee cannot be used as a valid control limb after unilateral TKA in the presence of radiographic knee OA. Researchers and clinicians should consider radiographic disease severity in the contralateral limb when developing research protocols, screening patients, or creating treatment plans.

Conflict of interest

The authors have no conflict of interest with the material to be published in the paper.

Acknowledgements

This work was supported by the National Institutes of Health [R56 AG048943 and P20 RR016458]; and a scholarship from Umm Al-Qura University (Makkah, Saudi Arabia) to Moiyad Aljehani through Saudi Arabian Cultural Mission (SACM).

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