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Gait Mechanics are Influenced by Quadriceps Strength, Age, and Sex after Total Knee Arthroplasty

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Abstract

Although most patients are satisfied with outcomes after total knee arthroplasty (TKA), many retain preoperative altered gait mechanics. Identifying patient characteristics associated with gait mechanics will improve rehabilitation strategies and enhance our understanding of movement disorders. Therefore, the purpose of this study was to identify which patient characteristics are related to gait mechanics in the surgical limb during walking post-TKA. Patient characteristics included age, body mass, sex, quadriceps strength, self-reported function, and knee pain. General linear regression was used to compare patient characteristics associated with gait mechanics, after controlling for gait speed, functional capacity and time from surgery. We tested 191 patients cross-sectionally at 6–24 months after primary, unilateral TKA. Quadriceps weakness in the surgical limb was associated with less peak vertical ground reaction force (PvGRF) ($\beta = .245$, $p = .044$), knee extension moment ($\beta = .283$, $p = .049$), and knee extension excursion ($\beta = .298$, $p = .038$). Older age ($\beta = .168$, $p = .050$) was associated with less PvGRF. Quadriceps strength in the nonsurgical limb ($\beta = -.357$, $p = .021$) was associated with greater knee extension excursion in the surgical limb. Females with TKA ($\beta = -.276$, $p = .007$) had less knee flexion excursion compared to males. Faster gait speed was also associated with greater PvGRF ($\beta = .585$, $p < .001$), knee extensor moment ($\beta = .481$, $p < .001$), and knee flexion excursion ($\beta = .318$, $p < .001$). Statement of Clinical Significance: This study showed quadriceps weakness, slower gait speed, older age and being female were related to altered gait mechanics post-TKA. These findings will help clinicians better educate patients and develop targeted interventions for improving care in patients post-TKA.

1 INTRODUCTION

Over 700,000 total knee arthroplasty (TKA) procedures are performed each year in the United States.[1] The number of TKA procedures performed annually is projected to be 1.26 million by 2030 and 2.60 million by 2060.[2] A successful outcome is traditionally based on radiographic alignment of the artificial joint,[3] pain resolution,[4] and self-reported physical function[5] after surgery. Restoring the ability to walk is also a primary goal post-TKA.[6] However, patients with TKA continue to demonstrate altered gait mechanics including reduced vertical ground reaction force, knee internal moments, and knee excursion between limbs, despite proper kinematic alignment and improved self-report outcomes.[7-9] Patients with TKA also walk more slowly and with reduced sagittal plane knee moments, less knee flexion excursion during initial contact, and less knee extension excursion during mid stance compared to healthy-matched peers.[6, 8] Altered gait mechanics are associated with poorer functional performance,[10] lower satisfaction,[11] and increased knee osteoarthritis progression of the contralateral limb.[12, 13] Identifying risk factors for altered mechanics or identifying patients who may benefit from targeted interventions are key areas for improving TKA rehabilitation. Currently, it is unclear why altered gait mechanics persist, despite patients reporting low residual knee pain[4] and high satisfaction[5] scores post-TKA.

Analyzing gait mechanics is typically quantified in movement science laboratories with camera-based motion capture systems with fixed force platforms, allowing for precise biomechanical measure in the surgical limb. Most clinicians, however, do not have access to these resources; thus, direct translation to clinical practice is limited. Evaluating the effect of various patient characteristics that clinicians can readily assess may provide new insight on improving gait mechanics recovery post-TKA. Patient characteristics such as older age,[14] greater body mass,[15] knee pain,[16] and muscle weakness[17] predict poorer gait mechanics in patients 6 months post-TKA. Men also retain altered gait mechanics after surgery, while women demonstrate improved movement patterns 6 months post-TKA.[18] Self-reported outcomes of function improve during the first 6–12 months post-TKA; however, altered gait mechanics persist despite improved perceived function.[19] Altered gait mechanics also appear to continue beyond the first 6 months and persist 24 months post-TKA.[8] However, it is unknown how these patient characteristics influence gait mechanics beyond the first 6 months following surgery. Given limited patient-provider follow-up is provided beyond 6 months post-TKA,[20-22] it is important to study how patient characteristics influence gait mechanics at later time points.

Therefore, the purpose of this study was to cross-sectionally identify the relationships between patient characteristics and gait mechanics in the surgical limb during walking at 6–24 months following TKA. Patient characteristics were selected a priori based on demographic, self-reported, and functional performance metrics that influence postoperative recovery. We specifically targeted factors that may influence patient's volitional movement pattern (age, sex, body mass index, and knee pain) and common physical impairments known to persist post-TKA (quadriceps weakness and self-reported physical limitations). Our first hypothesis was that, after controlling for relevant confounders, age, body mass index, sex, quadriceps strength, self-reported function, and knee pain would predict peak vertical ground reaction force and knee moment kinetics in the surgical limb at 6–24 months following TKA. Our second hypothesis was that these patient characteristics would predict knee flexion and extension excursion in the surgical limb at 6–24 months following TKA. Identifying how patient characteristics influence gait mechanics may provide valuable information to improve functional performance and reduce risk of knee osteoarthritis progression of the contralateral limb. Providers can then identify those at risk and thereby allocate necessary education and develop targeted interventions focused on normalizing altered gait mechanics.

2 METHODS

2.1 Level of evidence

Cross-sectional study, level of evidence: 3.

2.2 Participants

This was a cross-sectional correlational analysis of a large cohort study of patients who underwent unilateral TKA. Participants who underwent TKA at the Center for Advanced Joint Replacement were sent a letter informing them about the study. Interested participants contacted the research coordinators for more information and an initial telephone screening. Individuals who were interested in participating and met the eligibility criteria were scheduled for a functional testing, followed by a gait analysis on a separate day within the same week. Individuals who had (1) previous hip replacement; (2) planned to undergo a simultaneous, staged or future contralateral TKA; (3) contralateral knee pain of 5/10 or greater on the verbal analog pain rating scale[10, 23, 24]; (4) any neurological condition that impaired movement; (5) musculoskeletal conditions that affected walking ability; (6) decreased sensation in the feet; (7) the inability to ambulate unassisted >5 ft; or (8) a body mass index >50 kg/m^2 were excluded. All participants underwent tricompartmental cemented TKA using a medial parapatellar approach by one of six orthopedic surgeons between 2003 and 2013 at a single medical center (Newark, DE, USA). All participants completed a comprehensive clinical and gait analysis 6–24 months after unilateral TKA. All procedures were approved by the University of Delaware Institutional Review Board and all participants provided written, informed consent before participating in the study. A sample size calculation was conducted with an expected medium size effect and a two-sided alpha level of $p \leq .05$; approximately $n = 141$ patients (Cohen's $f^2 = 0.15$, medium effect) were needed to achieve 90% statistical power (G*Power).[25] This estimated sample size exceeds the recommended 10 events per predictor variable in a regression model to avoid statistical overfitting, which implies risk of unreliable correlations due to having too many predictor variables for the available sample size.[26,27] The obtained sample size ($n = 191$) was therefore acceptable for the analyses.

2.3 Procedures

All participants completed gait analysis testing of over-ground walking between 6 and 24 months after primary TKA, as described previously.[24] Pooling data from 6 to 24 months post-TKA was conducted because gait mechanics plateau around 3 months and the adopted movement strategy developed at that time remains consistent when compared to 12 and 36 months following surgery.[9] Before gait analysis, retroreflective markers were affixed to bony landmarks throughout the pelvis and bilateral lower limbs, including the iliac crests, greater trochanters, lateral femoral condyles, lateral malleoli, head of the 5th metatarsals, and upper and lower aspects of the heels. Rigid, thermoplastic shells with retroreflective markers were secured to the participants' posterior pelvis, thighs, and lower legs.

Following marker placement, participants walked at a self-selected pace across a 10-m walkway that included two embedded force platforms (Bertec Corp.) that captured force data at a sampling rate of 1080 Hz. Marker trajectories were captured at 120 Hz using an eight-camera motion capture system (Vicon, Oxford Metris). Participants practiced walking in the lab at a self-selected speed before gait analysis collection. The average speed of the practice trials was recorded as the participants' self-selected speed. Subsequently, the participant completed five trials of walking that were deemed successful if the participant maintained a speed between 95% and 105% of the previously determined self-selected speed and cleanly struck the force platforms with each limb without targeting the force platform.

2.4 Data processing and analysis

Kinematic and kinetic variables were calculated using commercial software (Visual3D, C-Motion). Kinematic data were low-pass filtered at 6 Hz, while kinetic variables were low-pass filtered at 40 Hz using a second-order, phase-corrected Butterworth filter. Data were normalized to the stance phase of gait with 0% representing initial contact and 100% representing the “toe-off” event of gait. The gait mechanic variables of interest included peak vertical ground reaction force, peak internal knee extension moment, peak internal knee abduction moment, knee flexion excursion, and knee extension excursion. Knee flexion excursion was defined as sagittal plane knee motion from initial contact to peak knee flexion angle. Knee extension excursion was defined as the total sagittal plane knee motion from peak knee flexion angle to peak knee extension angle. Peak vertical ground reaction force, peak knee extension moment, and peak knee abduction moment were normalized to body mass (kg). The peak values of five walking trials were averaged for each participant during the stance phase of gait and used in the analysis.

2.5 Demographics, clinical, and functional performance measures

Patient characteristics were obtained at the time of gait analysis testing.

2.5.1 Demographics

Participants' age (years), sex, and time since TKA were collected on data entry forms. Body mass index was calculated based on mass (kg) and height (m) metrics.

2.5.2 Clinical

The Knee Outcome Survey-Activities of Daily Living Scale (KOS-ADL) is a reliable, valid, and responsive patient-reported outcome measure that captures knee symptoms and functional limitations during activities of daily living, such as walking, rising from a chair, and climbing stairs.[28,29] Scores range from 0% to 100%; higher scores indicate better function and fewer symptoms. Participants in the present study completed the KOS-ADL separately for each limb (e.g., surgical and nonsurgical limb). Participants also reported their average knee pain at rest using a visual analog scale with 0 representing “no pain” and 10 representing “worst pain imaginable.” Separate assessments were completed for each limb. The visual analog pain scale has shown high test–retest reliability in patients with arthritis ($r = .96$)[30] and is commonly used for patients with TKA.[31]

2.5.3 Functional performance

Isometric quadriceps strength was assessed using a KinCom isokinetic dynamometer (Chattecx Corp.). Participants completed testing first on the nonsurgical limb followed by the surgical limb. Participants were seated with their knees secured at 75° of knee flexion and their hips flexed to approximately 90°. Two submaximal (50% and 75%) and one maximal (100%) contractions were performed before collecting three maximal isometric contractions for analysis. The three maximal trials were averaged and computed as maximal force output (N) for each limb. Maximum isometric strength testing has shown good to excellent reliability ($r = .81–.98$).[32] Self-selected gait speed was collected for all trials using an electronic timing system (FarmTek, Inc.) on a 5-m walkway. The 6-min walk test, which measures the distance a person walks without assistance over a 6-min interval, was also completed.[33] Participants were instructed to cover as much distance as possible during the 6-min test while not running. The test was completed on a 157-m course in a 3.05-m wide hallway.[34] The 6-min walk test is reliable in patients after TKA.[35]

2.6 Statistical analysis

Descriptive statistics were used to provide demographic characteristics of the participants in this study. All kinetic and kinematic outcome data were screened for univariate outliers using scatterplots, *k*-density plots, boxplots, and *z*-scores (using a ±2.0 *z*-score cut-point). Sensitivity analyses were employed omitting potential outliers (>2.0 *z*-scores) and results were compared to the original data. If the parameter estimates did not significantly change between the two statistical models, the values were kept in the subsequent analysis. General linear regression models were computed using all patient characteristics (i.e., age, sex, body mass index, surgical limb quadriceps strength, nonsurgical limb quadriceps strength, surgical limb KOS-ADL, nonsurgical limb KOS-ADL, surgical limb knee pain, and nonsurgical limb knee pain), controlling for gait speed, functional capacity (6-min walk test), and time from surgery. Separate models were regressed onto each outcome variable. Alpha level to test for statistical significance was set at $p \leq .05$ and post hoc correction was conducted using the Tukey–Ciminera–Heyse procedure to minimize the risk of multiplicity.[36] Effect sizes (ES) for the general linear regression models were calculated based on partial correlations (Cohen's f^2).[37] Cohen's f^2 values ≥.02 represent a small effect, ≥.15 represent a medium effect, and ≥.35 represent a large effect.[37] Analyses were performed using STATA v14.0 statistical software package.

3 RESULTS

One hundred and ninety-one participants from a cohort study of individuals after the primary, unilateral TKA were included in this study (Table **1**). Our cross-sectional correlational analysis compared patients between 6 and 24 months post-TKA (6 months, *n* = 65 [34%]; 12 months, *n* = 61 [32%], 24 months, *n* = 65 [34%]). For hypothesis one, the patient characteristics (age, body mass index, sex, quadriceps strength, self-reported function, and knee pain) collectively explained 47% of the variance of peak vertical ground reaction force ($F(12, 167) = 12.16$; $p < .001$) and 26% of the variance of peak knee extension moment ($F(12, 163) = 4.85$; $p < .001$) in the surgical limb during walking. Quadriceps weakness in the surgical limb ($\beta = .245, ES = .04$, $p = .044$; Figure **1**) and older age ($\beta = .168, ES = .04$, $p = .050$) were associated with less peak vertical ground reaction force in the surgical limb during walking (Table **2**). Quadriceps weakness in the surgical limb ($\beta = .283, ES = .04$, $p = .049$; Figure **1**) was also associated with less peak knee extension moment in the surgical limb during walking (Table **2**). The covariate gait speed was also associated with peak vertical ground reaction force ($\beta = .585, ES = .40$, $p < .001$; Table **2**) and peak knee extensor moment

($\beta = .481, ES = .19, p < .001$; Table 2). No significant relationships were observed for peak knee abductor moment in the surgical limb (Table 2).

Table 1. Participant characteristics

Variable	**TKA cohort (*n* = 191)**
Age (years)	67.8 (7.7)
Sex, male (%)	91.0 (47.6)
Mass (kg)	89.4 (20.0)
Height (m)	1.7 (0.1)
BMI (kg/m^2)	31.2 (5.3)
Surg KOS-ADL (%)	83.0 (1.0)
NonSurg KOS-ADL (%)	90.0 (1.0)
Surg VAS, no	0.9 (0.1)
NonSurg VAS, no	0.8 (1.0)
Surg MVIC (N/kg)	17.7 (6.7)
NonSurg MVIC (N/kg)	20.8 (7.6)
Gait speed (m/s)	1.3 (0.2)
6MWT (m)	165.6 (25.5)
Time from surgery (months)	15.0 (9.3)

Note: Values represented as mean (*SD*), unless otherwise stated.
Abbreviations: 6MWT, 6-minute walk test; BMI, body mass index; KOS-ADL, Knee Outcome Survey-Activities of Daily Living; MVIC, maximum voluntary isometric contraction; NonSurg, nonsurgical; Surg, surgical; TKA, total knee arthroplasty; VAS, visual analog pain scale.

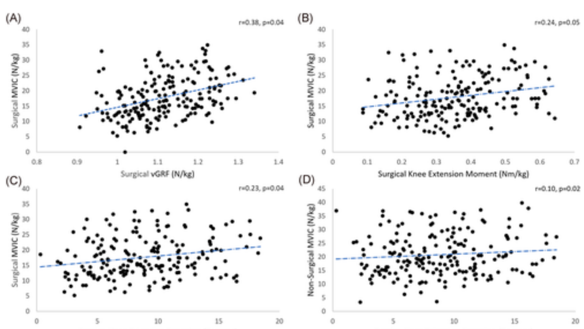

Figure 1 The relationship between quadriceps strengths and gait mechanic variables. (A) Surgical quadriceps maximum voluntary isometric contraction (MVIC) and surgical peak vertical ground reaction force (vGRF); (B) surgical quadriceps MVIC and surgical peak sagittal plane knee extension moment; (C) surgical quadriceps MVIC and surgical knee extension excursion; (D) nonsurgical quadriceps MVIC and surgical knee extension excursion

Table 2. General linear regression model of patient characteristics on kinetic loading mechanics in the surgical limb from 6 to 24 months postoperatively

Variable	**Predictor**	***B*** [a]	***SE***	***β*** [b]	**Effect size, f^2** [c]	***p* value**[d]	**95% CI**
PvGRF (N/kg)							
	Age	.002	.001	.168	.04	**.050** *	.001, .004
	BMI	−.001	.001	−.041	.00	.907	−.003, .001
	Sex	−.009	.001	−.053	.00	.859	−.035, .016
	Surg KOS-ADL	−.003	.070	−.004	.00	1.000	−.141, .136
	NonSurg KOS-ADL	−.017	.068	−.025	.00	.992	−.152, .118
	Surg MVIC	.003	.001	.245	.04	**.044** *	.001, .006

	NonSurg MVIC	−.001	.001	−.087	.00	.788	−.003, .001
	Surg VAS	−.003	.009	−.034	.00	.979	−.021, .015
	NonSurg VAS	−.002	.007	−.023	.00	.991	−.016, .0123
	Gait speed	.330	.041	.585	.40	**.000** *	.250, .410
	6MWT	.000	.000	.022	.00	.996	−.000, .000
	Time	.001	.001	.139	.03	.064	−.000, .002
PKEM (Nm/kg)							
	Age	.002	.001	.144	.02	.248	−.000, .005
	BMI	−.001	.002	−.063	.00	.869	−.005, .002
	Sex	.017	.023	.064	.00	.889	−.029, .063
	Surg KOS-ADL	−.007	.125	−.008	.00	1.000	−.256, .240
	NonSurg KOS-ADL	−.039	.122	−.039	.00	.991	−.280, .202
	Surg MVIC	.005	.002	.283	.04	**.049** *	.001, .009
	NonSurg MVIC	−.003	.002	−.190	.01	.392	−.007, .001
	Surg VAS	.002	.016	.018	.00	.999	−.029, .035
	NonSurg VAS	−.011	.013	−.088	.00	.831	−.037, .015
	Gait speed	.387	.069	.481	.19	**.000** *	.250, .524
	6MWT	.001	.001	−.027	.00	.996	−.000, .000
	Time	−.245	.236	.043	.03	.934	−.001, .002
PKAM (Nm/kg)							
	Age	−.002	.001	−.151	.02	.287	−.004, .000
	BMI	−.002	.002	−.112	.01	.564	−.005, .001
	Sex	−.006	.019	−.027	.00	.994	−.044, .033
	Surg KOS-ADL	−.096	.105	−.129	.00	.790	−.305, .112
	NonSurg KOS-ADL	−.005	.102	.008	.00	1.000	−.209, .197
	Surg MVIC	−.003	.002	−.210	.02	.308	−.006, .001
	NonSurg MVIC	.002	.002	.203	.01	.409	−.001, .006
	Surg VAS	−.013	.013	−.131	.01	.730	−.040, .013
	NonSurg VAS	−.003	.011	−.034	.00	.993	−.025, .018
	Gait speed	−.116	.058	−.186	.02	.160	−.231, .001
	6MWT	−.000	.000	−.088	.00	.871	−.000, .000
	Time	−.000	.001	−.044	.00	.946	−.002, .001

Note: The final model was adjusted for gait speed, 6MWT, and time from surgery (continuous). The bold values are signify statistical significance.

Abbreviations: 6MWT, 6-minute walk test; BMI, body mass index; PKAM, peak knee abduction moment; PKEM, peak knee extension moment; PvGRF, peak vertical ground reaction force; Surg, surgical; NonSurg, nonsurgical; KOS-ADL, Knee Outcome Survey-Activities of Daily Living; MVIC, maximum voluntary isometric contraction; VAS, visual analog pain scale.

[a] Unstandardized regression coefficient.

[b] Standardized regression coefficient.

[c] Effect size categories (.02 small, .15 medium, .35 large).

[d] Adustment using Tukey–Ciminera–Heyse procedure.

* $p \leq .05$

For hypothesis two, the patient characteristics (age, body mass index, sex, quadriceps strength, self-reported function, and knee pain) collectively explained 27% of the variance of knee extension excursion ($F(12, 163) = 5.09$; $p < .001$) and 31% of the variance of knee flexion excursion ($F(12, 162) = 6.01$; $p < .001$) in the surgical limb during walking. Quadriceps weakness in the surgical limb ($\beta = .298, ES = .04$, $p = .038$;

Figure 1) was associated with less knee extension excursion in the surgical limb during walking (Table 3). Conversely, greater quadriceps strength in the nonsurgical limb ($\beta = -.357, ES = .05,\ p = .021$; Figure 1) was associated with less knee extension excursion in the surgical limb during walking. Females ($\beta = -.276, ES = .06,\ p = .007$; Figure 2) had less knee flexion excursion in the surgical limb compared to males (Table 3). The covariate gait speed was also associated with knee flexion excursion ($\beta = .318, ES = .09,\ p < .001$; Table 3).

Table 3. General linear regression model of patient characteristics on knee kinematic mechanics in the surgical limb from 6 to 24 months postoperatively

Variable	**Predictor**	***B*** [a]	***SE***	***β*** [b]	**Effect size, f^2** [c]	***p* value**[d]	**95% CI**
Knee extension excursion (degrees)							
	Age	.041	.042	.079	.01	.749	−.042, .126
	BMI	−.071	.059	−.097	.01	.603	−.188, .046
	Sex	−.787	.704	−.098	.01	.656	−2.178, .603
	Surg KOS-ADL	.973	3.716	.033	.00	.996	−6.365, 8.313
	NonSurg KOS-ADL	−4.255	3.602	−.140	.01	.612	−11.368, 2.856
	Surg MVIC	.176	.068	.298	.04	**.038** *	.040, .311
	NonSurg MVIC	−.184	.065	−.357	.05	**.021** *	−.314, −.054
	Surg VAS	−.305	.482	−.074	.00	.925	−1.258, .646
	NonSurg VAS	−.071	.395	−.018	.00	.999	−.851, .708
	Gait speed	11.238	2.103	.453	.18	**.000** *	7.085, 15.392
	6MWT	.002	.005	.059	.00	.946	−.007, .012
	Time	.017	.029	.041	.00	.939	−.045, .075
Knee flexion excursion (degrees)							
	Age	.016	.035	.036	.00	.976	−.053, .086
	BMI	.020	.049	.033	.00	.982	−.077, .118
	Sex	−1.870	.592	−.276	.06	**.007** *	−3.047, -.706
	Surg KOS-ADL	−.626	3.068	−.025	.00	.999	−6.686, 5.433
	NonSurg KOS-ADL	−.811	2.998	.031	.00	.996	−6.733, 5.109
	Surg MVIC	.084	.057	.168	.01	.417	−.027, .197
	NonSurg MVIC	−.019	.055	−.043	.00	.991	−.128, .089
	Surg VAS	−.657	.402	−.186	.02	.330	−1.453, .138
	NonSurg VAS	.174	.326	.053	.00	.961	−.470, .819
	Gait speed	6.581	1.724	.318	.09	**.000** *	3.175, 9.987
	6MWT	.001	.004	.031	.00	.994	−.007, .009
	Time	.065	.025	.178	.04	**.036** *	.015, .115

Note: The final model was adjusted for gait speed, 6MWT, and time from surgery (continuous). The bold values are signify statistical significance.

Abbreviations: 6MWT, 6-minute walk test; BMI, body mass index; KOS-ADL, Knee Outcome Survey-Activities of Daily Living; MVIC, maximum voluntary isometric contraction; NonSurg, nonsurgical; Surg, surgical; VAS, visual analog scale for knee pain.

[a] Unstandardized regression coefficient.

[b] Standardized regression coefficient.
[c] Effect size categories (.02 small, .15 medium, .35 large).
[d] Adjustment using Tukey–Ciminera–Heyse procedure.
* $p \leq .05$.

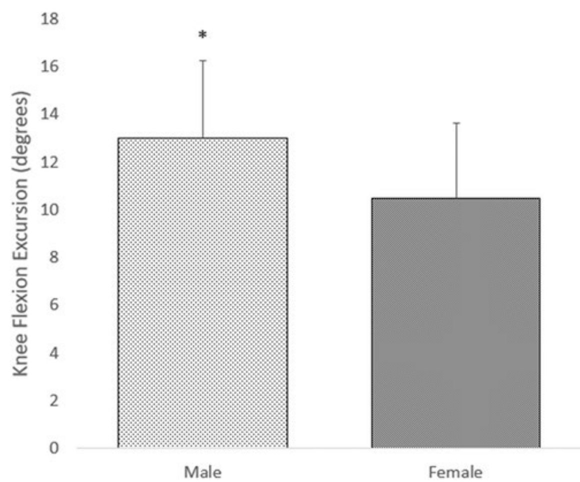

Figure 2 The relationship between sex and knee flexion excursion; *$p < .05$

4 DISCUSSION

The purpose of this study was to identify the relationship between patient characteristics and gait mechanics in the surgical limb post-TKA. Our primary findings of this study were (1) quadriceps weakness in the surgical limb and older age were related to less peak vertical ground reaction force loading; (2) quadriceps weakness in the surgical limb was related to less peak knee extension moment loading; (3) quadriceps weakness in the surgical limb was related to less knee extension excursion, while greater quadriceps strength in the nonsurgical limb resulted in less knee extension excursion in the surgical limb; (4) females showed significantly less knee flexion excursion during walking compared to males; and (5) gait speed was moderately to strongly associated with most gait mechanic outcomes. These findings provide new insight on how demographics and common physical impairments known to persist post-TKA associate with altered gait mechanics following surgery, which places patients at greater risk for future disability[10, 11] and progressive knee osteoarthritis in the contralateral limb.[12, 13]

To our knowledge, this is the largest study to investigate whether patient characteristics are related to gait mechanics during walking following TKA. This study is important given that prior work indicates patients with TKA continue to demonstrate altered gait mechanics 12–36 months following surgery,[6, 8] despite self-reported improvements in knee pain and physical function.[38] Our data indicate quadriceps weakness in the surgical limb, after controlling for relevant confounders, was the most consistent patient characteristic associated with altered gait mechanics including less peak vertical ground reaction force, peak knee extension moment, and knee extension excursion outcomes. These findings are consistent with prior studies showing quadriceps weakness in the surgical limb was associated with greater reliance on the nonsurgical limb during stair negotiation,[39] slope walking,[40] and sit–stand tasks[41] within the first 12 months post-TKA. Targeted quadriceps strength training is common in rehabilitation programs post-TKA,[42] however, patients with TKA continue to demonstrate 20%–30% strength loss, compared to the nonsurgical limb, 12–36 months following surgery.[43, 44] Objectively measuring quadriceps strength in the clinical setting and using this metric as a surrogate of physical recovery should be an important consideration post-TKA. Developing more effective interventions to address chronic quadriceps weakness is necessary not only to reduce physical limitations, but also to improve the quality of the patient's movement. Clinicians should educate patients on the impact quadriceps weakness has on postoperative outcomes and provide guidance on continual quadriceps strength development beyond supervised interventions.

Our analysis revealed that greater quadriceps strength in the nonsurgical limb was associated with a more stiff-legged gait pattern in the surgical limb. It is possible that decreased excursions and forces on the surgical limb lead to compensatory use of the nonsurgical limb, which may increase the strength of the knee extensors on the nonsurgical side. However, it is also possible that patients with greater strength and capacity on their nonsurgical side are those who can compensate and reduce the forces on the surgical limb when walking. Greater quadriceps weakness on the surgical limb was also related to worse gait mechanics. Despite therapeutic efforts to improve quadriceps strength in the surgical limb, patients continue to receive inadequate therapeutic dosing and volume of loading.[45] Clinicians should consider adopting strategies to more effectively increase dose and volume response to quadriceps weakness (e.g., neuromuscular electrical stimulation, movement pattern retraining, blood flow restriction therapies, etc.). However, further prospective longitudinal studies are needed to determine long-term effects of improved quadriceps strength and how these strategies influence gait mechanics.

Gait speed was the strongest predictor of altered gait mechanics, although identified a priori as a confounding variable due its known relationship with the proposed variables.[46] Faster walking speed was associated with greater vertical ground reaction force, peak knee extension moment, and knee flexion excursion in the surgical limb, which is consistent with existing literature in older adults.[47-49] Quadriceps strength has shown to be the strongest predictor for gait speed post-TKA.[50] However, quadriceps weakness demonstrates moderate association with altered gait mechanics at 6 months post-TKA, but found to be less influential at 12 months.[19] Based on our findings, instructing patients to walk faster with appropriate motor retraining may be one strategy to address commonly observed altered gait mechanics, including lower sagittal plane kinetics and truncated knee excursions, post-TKA. Restoring proper gait mechanics is an important biomarker for future disability. This is particularly true for reduced knee flexion excursion. For every degree less of knee flexion excursion, the risk of a secondary contralateral TKA increases by nearly 10%.[24] This is true despite reduction in knee pain and improved physical function following the primary surgery.[38] Future, prospective research is needed to determine how intervening on gait speed affects gait mechanics, with a particular emphasis on physical impairments associated with reduced knee flexion excursion.

Demographic patient characteristics of age, sex, and body mass index were not consistent predictors of gait mechanics across the gait mechanic variables. Older age was associated with reduced peak vertical ground reaction force loading in patients after TKA, which is consistent with previous findings showing healthy older adults inherently demonstrate less joint kinetic and kinematic output of the knee compared to younger peers.[46] It is unclear, however, if the observed lower limb underloading in the surgical limb is related to surgery or secondary neuromuscular adaptions related to aging or both. Additionally, females with TKA showed less knee flexion excursion compared to their male counterparts. Data pertaining to sex-specific gait mechanics are limited and conflicting. Females with TKA have shown greater gait mechanic deficits in the surgical limb compared to males with TKA.[51] Conversely, females with TKA have also shown biomechanical variables more similar to matched-peers compared to males with TKA.[52] Finally, evidence evaluating the influence obesity has on altered gait mechanics is limited. Obese patients with TKA demonstrate similar gait kinematics and clinical outcomes as nonobese patients 12 months post-TKA.[53] Conversely, higher body mass index is also associated with poorer quadriceps strength,[54] gait speed,[54] and knee pain[55] up to 3 years postoperatively. Other studies have found no association between body mass index and pain,[56] physical function,[57] or satisfaction[57] 24 months post-TKA. Our study is the first to compare body mass index and gait kinetics, indicating obesity may not be as significant of a factor on altered gait mechanics as it is on other health-related outcomes. While our study is among the largest gait mechanic investigations of people post-TKA, our study is unable to determine cause and effect relationships.

Although most studies use self-reported knee pain and physical function as primary metrics for a successful recovery, little is known about how these measures influence gait mechanics. Our data showed no relationship of residual knee pain or KOS-ADL scores on the gait mechanic variables. Self-reported outcomes show only modest relationship to actual performance-based outcomes,[58] indicating perceived metrics measure different constructs than more objective testing. The findings contribute to growing evidence that although TKA may provide relief of knee pain and improve quality of life,[4, 38] gait mechanics remain impaired and largely unaffected by pain or perceived function. Self-reported measures and gait mechanics appear to measure different constructs of postoperative recovery, indicating both are important in determining functional recovery after TKA.

Finally, our findings showed time from surgery (6–24 months) did not significantly influence the gait mechanic variables other than a small effect on knee flexion excursion. These data indicate that patients' gait mechanics at 6 months are approximately the same as 24 months post-TKA. These findings strengthen the existing evidence showing the adopted movement strategy developed within the first 3–6 months following surgery remains consistent when compared to gait mechanics up to 36 months following surgery.[6, 8] Our data also provide new insight on how both self-report and timing of surgery influence functional ability related to gait mechanics.

This study has limitations that need to be considered when interpreting the data. First, several surgeons and implants were utilized in this study, which could have influenced the results. However, all TKAs were performed using a tricompartmental cemented implant from a medial parapatellar approach at a single surgical center. Second, we did not track duration, type, or quality of rehabilitation provided, which could have influenced our findings. However, all participants participated in the same medical regimen and all were instructed to participate in outpatient physical therapy after TKA. Third, our study used a cross-sectional design, which limited our ability to differentiate cause and effect. Fourth, participants were tested between 6 and 24 months after surgery and although we did include time from surgery as a covariate, this could have influenced our results.

5 CONCLUSION

Quadriceps weakness, slower gait speed, older age, and being female were related to altered gait mechanics during walking at 6–24 months following TKA. None of the other patient characteristics (body mass index, self-reported function, and knee pain) had a direct relationship on gait mechanics post-TKA. It is possible the relationship of patient characteristics on gait mechanics in the surgical limb could have implications for physical performance and progression of contralateral knee osteoarthritis. Future prospective longitudinal research is needed to further elucidate how modifiable and non-modifiable patient characteristics influence gait mechanics.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

All authors contributed to the development of this manuscript in the following manner: study conception and design (Jesse C. Christensen, Jacob J. Capin, Lauren A. Hinrichs, Moiyad Aljehani, Jennifer E. Stevens-Lapsley, Joseph A. Zeni); acquisition of data (Moiyad Aljehani, Joseph A. Zeni); analysis and interpretation of data (Jesse C. Christensen, Jacob J. Capin, Moiyad Aljehani, Joseph A. Zeni); drafting of manuscript (Jesse C. Christensen, Jacob J. Capin, Lauren A. Hinrichs); and assisted with critical revisions (Jesse C. Christensen, Jacob J. Capin, Lauren A. Hinrichs, Moiyad Aljehani, Jennifer E. Stevens-Lapsley, Joseph A. Zeni).

ETHICS STATEMENT

The University of Delaware Institutional Review Board (Newark, DE, USA) approved this study.

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