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# Rate of torque development is the primary contributor to quadriceps avoidance gait following total knee arthroplasty☆

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ABSTRACT

*Background:* Following rehabilitation for total knee arthroplasty, "quadriceps avoidance gait", defined by limited knee flexion angle excursion during walking, persists and contributes to poor long-term outcomes. Given the presence of several post-surgical impairments, identifying the contribution of multiple factors to knee flexion angle excursion is important to developing targeted interventions to improve recovery after total knee arthroplasty.

*Research questions:* Which outcomes continue to improve following rehabilitation for total knee arthroplasty? What are the primary contributors to impaired knee flexion angle excursion during walking following total knee arthroplasty?

*Methods:* Peak muscle strength and rate of torque development of the quadriceps, hip abductors, and hip external rotators, five-time sit-to-stand test, Knee Injury & Osteoarthritis Outcome Score, and gait mechanics were assessed in 24 participants at three and six months post-surgery. Paired sample t-tests or Wilcoxon Signed-Rank tests were used to compare outcomes between assessments. Stepwise multiple linear regression were used to assess the contribution of each measure to knee flexion angle excursion.

*Results:* Significant improvements were noted in all outcomes except hip external rotation rate of torque development, gait speed, and knee flexion angle excursion. Quadriceps rate of torque development and knee pain significantly contributed to knee flexion angle excursion at three months (Adjusted $R^2 = 0.342$), while quadriceps rate of torque development and peak hip external rotation strength significantly contributed at six months (Adjusted $R^2 = 0.436$).

*Significance:* While higher pain levels at three months and greater peak hip external rotation muscle strength at six months contribute to impaired knee flexion angle excursion, quadriceps rate of torque development was the primary contributor to knee flexion angle excursion at both three and six months after surgery. Implementing strategies to maximize quadriceps rate of torque development during rehabilitation may help to reduce quadriceps avoidance gait after total knee arthroplasty.

## 1. Introduction

There is growing evidence that asymmetrical gait patterns manifest early, become chronic, and are linked with declined functional mobility after total knee arthroplasty (TKA) [1,2]. Specifically, reduced knee flexion excursion, defined as the total arc of knee flexion motion during the stance phase of gait, is a hallmark characteristic of "quadriceps avoidance gait." Limited knee flexion excursion persists despite the resolution of knee pain and is associated with suboptimal patient-reported quality of life after TKA [1,3]. Additionally, limited knee flexion excursion may lead to compensations from other muscle groups and result in persistent movement dysfunction [2,4–6].

While deficits in knee flexion excursion after TKA are well-documented, the factors contributing to aberrant gait patterns are less clear. To reduce post-operative pain, improve muscle strength, and maximize functional ability, rehabilitation is commonly recommended during the first three months following TKA [7] with continued improvement observed until progress stabilizes approximately six months after

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surgery [8,9]. Individual factors known to contribute to improved functional and gait outcomes after TKA include quadriceps strength and power (e.g., rate of torque development) [10–12], hip muscle strength [13], five-time sit-to-stand test performance [14], and knee pain [3]. However, given the presence of multiple impairments following TKA, there is a need to assess the combined contribution of these measures to knee flexion excursion in order to develop targeted intervention approaches.

Despite demonstrating value in identifying aberrant gait following TKA, three-dimensional gait analysis involves significant time, cost, and equipment burdens that precludes widespread clinical use [15]. As such, identifying the factors that contribute to knee flexion excursion at the conclusion of rehabilitation (~3 months post-TKA) and at the time progress typically stabilizes (~6 months post-TKA) may help overcome this limitation and lead to focused interventions to improve gait following TKA. Therefore, the aims of this study were to evaluate change in knee and hip muscle strength and power, functional performance, patient-reported knee pain and function, and knee flexion excursion outcomes at three and six months following TKA and determine the primary contributors to knee flexion excursion at each assessment point.

## 2. Methods

### 2.1. Participants

From July 2015–March 2017, patients with primary TKA for degenerative osteoarthritis were recruited consecutively for this longitudinal cohort study and enrolled within three months of surgery from the university orthopaedic clinic. Participants were screened using the following criteria: age 40–90 years, undergone unilateral TKA within the past three months, no prior surgery to the contralateral limb, no neurological/balance disorder requiring assistive device use, and able to walk ≥10 min without an assistive device. The study protocol was approved by the university Institutional Review Board. All participants read and signed an informed consent form prior to participation. Participants completed standard rehabilitation in community outpatient clinics with the total number of visits, visit frequency, and rehabilitation activities decided at the discretion of the surgeon and treating clinician.

### 2.2. Outcomes

#### 2.2.1. Muscle strength and power

Participants completed isometric strength testing of hip abduction, hip external rotation, and quadriceps muscle groups of the operative limb using a Biodex System 4 (Biodex Systems, Shirley, NY, USA) at three and six-month assessments. Hip abduction was assessed in sidelying with neutral hip alignment and dynamometer arm secured 5 cm proximal to the tibiofemoral joint. Participants were instructed to abduct their leg towards the ceiling. Hip external rotation and quadriceps assessments were each performed seated with 85° hip flexion, 0° hip rotation, 90° knee flexion, and the dynamometer arm secured 5 cm proximal from the malleoli with a cushioned pad. Participants were instructed to rotate their leg as if to look at the bottom of their shoe during hip external rotation and to extend their knee as if kicking forward during quadriceps testing. One practice and three experimental trials were performed for all testing. Visual and verbal feedback and encouragement was provided with patients asked to provide maximal effort for all trials. A minimum of 30 s rest were allowed between trials to minimize the influence of fatigue [16]. All strength testing was conducted by a single investigator.

Data were captured at 100 Hz with time and torque values exported using the native Biodex software. Peak torque values and rate of torque development determined for each trial and averaged for use in statistical analyses. All tests were normalized to body mass. Custom MATLAB code (MathWorks Inc, Natick, MA, USA) was used to determine peak torque and calculate rate of torque development. Peak torque was defined as the maximum torque value of each trial. Rate of torque development was defined as the mean slope of the torque-time curve over the first 200 ms of the linear portion between the onset of the trial and peak torque [17]. The linear portion was identified using visual inspection and occurred after the initial non-linear toe-in region during contraction onset.

#### 2.2.2. Five-time sit-to-stand test

Participants completed the five-time sit-to-stand test at each assessment [18]. Beginning seated in a 42.0 cm, armless chair, participants were asked to complete five consecutive sit-to-stands as quickly as possible without upper extremity assistance. All tests were conducted by a single investigator. Using a hand-held stopwatch, timing began upon initiation of the task from sitting and was stopped upon returning to sitting after the fifth sit-to-stand. An accommodation trial was allowed before completing the documented trial.

#### 2.2.3. Knee injury and osteoarthritis outcome score

All participants completed the Knee Injury & Osteoarthritis Outcome Score (KOOS) Pain and KOOS Activities of Daily Living subscales at each time point to quantify knee pain and perceived functional impairment. Each subscale is scored between zero to 100 with zero representing “worst” and 100 representing “best” and are reliable in patients after TKA [19].

#### 2.2.4. Gait analysis

All participants underwent three-dimensional motion analysis while walking at a self-selected speed on an instrumented treadmill (Bertec Corporation, Columbus, OH, USA) at each time point. An acclimation period for treadmill walking was allowed before data capture (~2–3 min). All participants were outfitted with 32 anatomical and 24 tracking markers as previously noted in the literature [17]. Markers were placed on the following locations: sternal notch, spinous process of the 7th cervical vertebra, bilateral superior acromial processes, posterior 5th lumbar/1st sacral intervertebral joint, bilateral iliac crests, bilateral greater trochanters, bilateral posterior superior and anterior superior iliac spines, bilateral medial and lateral distal femurs, bilateral medial and lateral proximal tibias, bilateral medial and lateral malleoli, bilateral first and fifth metatarsal heads, and bilateral distal feet. Rigid plates with 4 tracking markers each were secured to bilateral thigh and shank segments. On each rearfoot, a single marker was placed on the proximal, distal, and lateral heel to track the foot segment. All participants wore neutral athletic shoes (New Balance 662, New Balance Athletic Shoe Inc., Boston, MA, USA). A single investigator was responsible for marker placement and data capture for all gait analyses. Marker trajectories were recorded using a 10-camera motion analysis system (Motion Analysis Corp, Santa Ana, CA) with a sampling rate of 200 Hz. Marker position was filtered with a fourth-order, low-pass, zero-lag Butterworth filter at 8 Hz and calculations of joint kinematics performed using Visual 3D software (C-Motion, Germantown, MD, USA). Angles were calculated using Cardan XYZ angles referencing the distal segment to the proximal. Initial contact and toe off were determined using the vertical component of the ground reaction force data, sampled at 1200 Hz, with a threshold of 20 N. Custom MATLAB code was generated to extract sagittal plane knee kinematic data. Knee flexion excursion was calculated as the difference between the maximum and minimum knee flexion angle occurring between initial contact and midstance of the stance phase.

### 2.3. Statistics

Normality was inferred through Shapiro-Wilk tests. For normality distributed variables, paired sample t-tests were performed to compare between assessment time points. If not normally distributed, Wilcoxon

Signed-Rank tests were utilized. Statistical significance was defined as $P \leq 0.05$ for all tests. Forward stepwise multiple linear regression was used to explore potential factors contributing to knee flexion excursion in the operative leg. Sixteen predictor variables were assessed: peak strength of knee extensors, hip abductors, hip external rotators; rate of torque development of knee extensors, hip abductors, hip external rotators; five-time sit-to-stand time; KOOS-Pain and ADL scores; sex; height; body mass; body mass index; age; gait speed; and implant type. In each step, predictor variables remained included in the model if $P \leq 0.05$ or were excluded if $P > 0.10$ until the final model included only significant variables ($P \leq 0.05$). Multicollinearity was assessed using variance inflation factors with a value > 10 indicating the presence of multicollinearity. Data were analyzed with SPSS Statistics 24 (IBM, Armonk, NY, USA). Using previous correlation and regression analyses in patients with TKA [12,15], an effect size of 0.5 was assumed and an *a-priori* sample size calculation assuming $\alpha = 0.05$, 80% power, and the 16 predictor variables recommended a total sample of 23 participants (G-Power 3.1, Dusseldorf, Germany).

## 3. Results

A total of 24 participants completed the study. One hundred nineteen patients were screened (54 unable to contact/not interested (45%), 41 excluded (34%)). The most common reasons for exclusion were: planned contralateral TKA (18), use of assistive device for balance (9), and history of prior joint surgery (8). Participant demographics are described in Table 1. All participants completed formal rehabilitation prior to the three-month assessment. Comparisons between three and six-month assessments are detailed in Table 2. Significant improvements were noted in all outcomes except hip external rotation rate of torque development, gait speed, and knee flexion excursion. At three months post-surgery, the multiple linear regression found 34.2% of knee flexion excursion was explained by quadriceps rate of torque development and KOOS-Pain subscale score (Table 3). At six months post-surgery, the multiple linear regression shows 43.6% of knee flexion excursion was explained by quadriceps rate of torque development and hip external rotation peak torque (Table 4). Multicollinearity was not observed among the significant factors in either model (VIF = 1.074–2.496) (Tables 3 and 4). Sex, age, height, body mass, body mass index, or implant type/model were not significant contributors to either model (Tables 3 and 4).

## 4. Discussion

Asymmetrical knee flexion excursion is well-established after TKA and contributes to impaired functional mobility and poor quality of life [1–3]. Quadriceps rate of torque development and KOOS-Pain scores were contributors to knee flexion excursion during walking at three months post-TKA while quadriceps rate of torque development and peak hip external rotation muscle strength were significant contributors at six months post-TKA. The results suggest that quadriceps rate of torque development is a primary contributor to knee flexion excursion during the first six months after TKA with higher pain levels and greater hip external rotation strength potentially contributing at three and six months post-surgery, respectively. The current results identify modifiable factors contributing to knee flexion excursion during walking that could be addressed in rehabilitation to limit gait compensation after TKA.

**Table 1**
Participant Demographics: Mean (SD).

| | |
|---|---|
| Male/Female (n) | 6/18 |
| Age (years) | 60 (8) |
| Body weight (kg) | 89.4 (20.2) |
| Height (m) | 1.67 (0.08) |
| BMI (kg/m$^2$) | 32.0 (7.1) |
| Implant Type | 15 cruciate-retaining, 6 posterior-stabilized, 3 bi-cruciate stabilized |

BMI = body mass index.

Quadriceps function is typically assessed through measures of peak muscle strength with significant deficits noted after TKA [20]. These strength deficits are associated with impaired physical function and greater asymmetry during gait [2,21]. Despite the ease of implementation, measures of peak muscle strength do not account for time-dependent characteristics of torque production. During functional tasks (e.g., walking), appropriate muscle torque is needed within certain time windows for successful task completion. As a one dimensional measure, peak muscle strength may not reflect function as accurately as time-constrained measures like rate of torque development. The results of the regression models from this study support this notion as quadriceps rate of torque development, but not peak strength, was included in both three and six-month models. It is possible that quadriceps rate of torque development and peak strength explain overlapping amounts of variance in knee flexion excursion. However, the regression results indicate more of the variance is explained by rate of torque development, thus quadriceps peak strength is excluded from each model. There is initial evidence to support this paradigm in a small randomized controlled trial which found high velocity quadriceps exercise resulted in improved six-minute walk test performance compared to slow velocity exercise in patients after TKA [22]. Additionally, eccentric exercise effectively improved lower extremity rate of torque development in young and older adults [23]. This prior evidence and the inclusion of quadriceps rate of torque development in both regression models suggest that maximizing improvement in rate of torque development as a means of improving gait following TKA may be worthy of further investigation.

We also found that increased knee pain contributed to reduced knee flexion excursion at three months post-surgery. Individuals after TKA demonstrate reduced peak knee flexion angle and knee flexion excursion during walking, a pattern that has been termed quadriceps avoidance gait [1]. This gait pattern may also limit the pain experienced by patients when enduring load through a larger range of motion. Individuals who experience more knee pain undergo less knee flexion excursion at three months post-TKA suggesting knee pain may contribute to reductions in knee joint motion during walking. However, at the six-month assessment, patient-reported pain was not a significant contributor to knee flexion excursion at six months, indicating that the improvement in pain observed at six months post-TKA had a negligible contribution to knee flexion excursion. Based on these findings, deficits in knee flexion excursion do not resolve with improvement in knee pain from three to six months after TKA. Previous studies report minimal contribution of pain to physical performance measures and note consistent improvement in self-reported pain with increasing time from TKA [8]. Thus, interventions to address post-operative knee joint pain are most likely to influence gait mechanics at earlier time points in recovery but may not be necessary after three months post-TKA. Further investigation is needed to identify specific pain characteristics (e.g. intensity, duration, location) that may limit restoration of knee joint mechanics during walking within the first three months following TKA.

Interestingly, peak hip external rotation strength was also a significant contributor to knee flexion excursion, demonstrating a negative coefficient in the six-month regression model. This finding suggests that stronger hip external rotation musculature contributed to less knee flexion excursion at six months post-surgery. The gluteus maximus primarily contributes to hip external rotation muscle strength when assessed in sitting [24]. Previous studies report improvement in functional performance measures in individuals with greater hip abduction strength after TKA [13,25,26]. Additionally, patients after TKA commonly shift demand from the knee to the hip during walking and stair tasks [4–6]. To the author's knowledge, no previous studies specifically investigate the contribution of hip muscle performance to gait mechanics after TKA. These results indicate that better gluteal function

**Table 2**
Three & Six Month Comparisons: Mean (SD).

| Variable | 3-month | 6-month | *P* | Effect Size (*d*) |
|---|---|---|---|---|
| FTSTS (s) | 11.7 (3.0) | 10.1 (3.0) | 0.000* | 0.829 |
| KOOS-Pain | 78.0 (10.5) | 84.6 (10.1) | 0.016* | 0.530 |
| KOOS-ADL | 83.9 (8.5) | 88.7 (7.5) | 0.002* | 0.711 |
| ABD RTD (Nm/kg*s) | 1.88 (1.12) | 2.23 (1.19) | 0.038* | 0.471 |
| ABD Peak Torque (Nm/kg) | 0.57 (0.28) | 0.68 (0.33) | 0.003*,# | 0.772 |
| ER RTD (Nm/kg*s) | 0.72 (0.41) | 0.78 (0.42) | 0.219# | 0.210 |
| ER Peak Torque (Nm/kg) | 0.30 (0.11) | 0.32 (0.12) | 0.025* | 0.412 |
| Quadriceps RTD (Nm/kg*s) | 2.33 (1.12) | 2.87 (1.55) | 0.011*,# | 0.708 |
| Quadriceps Peak Torque (Nm/kg) | 0.82 (0.31) | 0.98 (0.47) | 0.002*,# | 0.883 |
| KFLEXC (°) | 9.2 (4.1) | 10.2 (4.0) | 0.112 | 0.342 |
| Gait Speed (m/s) | 0.76 (0.23) | 0.82 (0.19) | 0.113# | 0.334 |

FTSTS = five-time sit-to-stand test; KOOS-Pain = Knee Injury and Osteoarthritis Outcomes Score Pain subscale; KOOS-ADL = Knee Injury and Osteoarthritis Outcomes Score Activities of Daily Living subscale; ABD = Hip abduction; ER = Hip external rotation; RTD = rate of torque development; KFLEXC = knee flexion angle excursion during walking.
*d* = Cohen's *d* (Effect size).
* Significant ($P < 0.05$).
\# Wilcoxon Signed-Rank test utilized.

**Table 3**
Three Month Regression Analysis with KFLEXC as the Dependent Variable.

| Predictor Variable | B (95% CI) | *P* | VIF |
|---|---|---|---|
| Quadriceps RTD (Nm/kg*s) | 0.408 (0.120–2.76) | 0.034* | 1.074 |
| KOOS-Pain | 0.389 (0.006–0.281) | 0.042* | 1.074 |
| Non-significant Predictors | | | |
| Sex | 0.157 | 0.485 | 1.575 |
| Height (m) | −0.271 | 0.175 | 1.302 |
| Body weight (kg) | −0.029 | 0.880 | 1.140 |
| BMI (kg/m$^2$) | 0.064 | 0.749 | 1.249 |
| Age (years) | −0.123 | 0.515 | 1.114 |
| FTSTS (s) | −0.268 | 0.137 | 1.069 |
| KOOS-ADL | −0.221 | 0.401 | 2.182 |
| ABD RTD (Nm/kg*s) | −0.511 | 0.052 | 2.372 |
| ABD Peak Torque (Nm/kg) | −0.241 | 0.264 | 1.484 |
| ER RTD (Nm/kg*s) | −0.367 | 0.273 | 3.581 |
| ER Peak Torque (Nm/kg) | −0.357 | 0.229 | 2.832 |
| Quadriceps Peak Torque (Nm/kg) | −0.321 | 0.346 | 3.684 |
| Implant Type | 0.231 | 0.196 | 1.038 |
| Gait Speed (m/s) | 0.340 | 0.056 | 1.077 |

Adjusted $R^2$ of model including significant predictors = 0.342.
β = standardized coefficient; VIF = Variance Inflation Factor; KFLEXC = knee flexion angle excursion during walking; RTD = rate of torque development; KOOS-Pain = Knee Injury and Osteoarthritis Outcomes Score Pain subscale; BMI = body mass index; FTSTS = five-time sit-to-stand test; KOOS-ADL = Knee Injury and Osteoarthritis Outcomes Score Activities of Daily Living subscale; ABD = Hip abduction; ER = Hip external rotation.
* Significant ($P < 0.05$).

**Table 4**
Six Month Regression Analysis with KFLEXC as the Dependent Variable.

| Predictor Variable | B (95% CI) | *P* | VIF |
|---|---|---|---|
| Quadriceps RTD (Nm/kg*s) | 1.099 (1.45–4.13) | 0.000* | 2.496 |
| ER Peak Torque (Nm/kg) | −0.795 (−43.89 to −8.87) | 0.005* | 2.496 |
| Non-significant Predictors | | | |
| Sex | 0.047 | 0.828 | 1.657 |
| Height (m) | −0.254 | 0.151 | 1.193 |
| Body weight (kg) | −0.170 | 0.369 | 1.325 |
| BMI (kg/m$^2$) | −0.061 | 0.766 | 1.498 |
| Age (years) | 0.082 | 0.651 | 1.203 |
| FTSTS (s) | −0.109 | 0.557 | 1.248 |
| KOOS-ADL | 0.162 | 0.366 | 1.181 |
| KOOS-Pain | 0.061 | 0.733 | 1.178 |
| ABD RTD (Nm/kg*s) | −0.138 | 0.568 | 2.130 |
| ABD Peak Torque (Nm/kg) | −0.084 | 0.761 | 2.754 |
| ER RTD (Nm/kg*s) | −0.082 | 0.790 | 3.452 |
| Quadriceps Peak Torque (Nm/kg) | 0.508 | 0.245 | 7.176 |
| Implant Type | 0.069 | 0.677 | 1.006 |
| Gait Speed (m/s) | 0.071 | 0.691 | 1.153 |

Adjusted $R^2$ of model including significant predictors = 0.436.
β = standardized coefficient; VIF = Variance Inflation Factor; KFLEXC = knee flexion angle excursion during walking; RTD = rate of torque development; ER = Hip external rotation; BMI = body mass index; FTSTS = five-time sit-to-stand test; KOOS-ADL = Knee Injury and Osteoarthritis Outcomes Score Activities of Daily Living subscale; KOOS-Pain = Knee Injury and Osteoarthritis Outcomes Score Pain subscale; ABD = Hip abduction.
* Significant ($P < 0.05$).

may not ameliorate impaired quadriceps function or improve quadriceps avoidance gait. Rather, better gluteal function may reinforce hip compensatory patterns at the expense of restoring normal knee mechanics as those with greater hip strength may be more capable hip compensation strategies and transfer muscle demand from the knee to the hip. As a result, these individuals may decrease quadriceps utilization and limit increased knee flexion excursion during walking.

Despite statistically significant improvements in most measures, the magnitude of these improvements is not clinically meaningful. A mean improvement of 1.6 s in the five-time sit-to-stand test is within the minimal detectable change of 2.5 s, suggesting this improvement is within the measurement error native to the test [18]. Although a minimal detectable change is not available for the KOOS, mean improvements of 6.6 and 4.8 points for KOOS-Pain and KOOS-Activities of Daily Living scores are less than the 8–10 point improvement typically observed with concurrent functional improvement [19]. A meaningful threshold for improvement in strength or rate of torque development is lacking. However, despite the significant improvement in quadriceps peak strength and rate of torque development, these values remain impaired compared to similar-aged controls [27,28]. The lack of significant improvement in knee flexion excursion is confirmatory with previous reports of gait impairment following TKA as knee flexion excursion in our sample did not significantly change between three to six months post-TKA and remained less than previously reported values in similar-aged healthy participants (10.6 vs 14.1°) [1,2]. In aggregate, these findings are consistent with evidence that recovery of muscle strength, functional performance, and gait mechanics is incomplete following rehabilitation and modest gains are observed by six months [8,29]. Previous studies discuss the importance of maximizing recovery during the first six months following TKA as improvement begins to plateau after this time point [8,9]. These findings point to the importance of identifying appropriate targets and maximizing recovery during rehabilitation after TKA.

There are limitations to this study that should be noted. For example, there are other potential contributors that were not included in the regression analyses that may influence knee flexion excursion.

Preoperative measures including muscle strength, functional performance, gait mechanics, pain level, duration of symptoms, and physical activity level were not assessed. Additionally, post-operative rehabilitation was not controlled nor monitored. Variability in preoperative measures and dosage, duration, mode, intensity, and patient compliance of rehabilitation may have influenced the observed outcomes. Furthermore, there is potential for sampling bias that may have prevented enrollment of lower functioning patients following TKA. Lastly, rate of torque development measures were collected at 100 Hz, less than the minimum 1000 Hz typically recommended, which may have influenced identification of contraction onset [30].

Future investigations are needed to validate these results and determine the potential thresholds for quadriceps rate of torque development required for optimal long-term outcomes. Additionally, investigation of interventions to improve quadriceps rate of torque development or knee flexion excursion would further explore the potential mechanism between quadriceps rate of torque development and knee flexion excursion. Moreover, investigations of hip compensatory patterns after TKA would be beneficial to determine if and how reliance on hip musculature disrupts recovery of quadriceps muscle performance and knee joint mechanics during walking.

## 5. Conclusions

In conclusion, while higher knee pain levels at three months and greater peak hip external rotation muscle strength at six months contribute to impaired knee flexion excursion, the ability of the operative limb to rapidly generate quadriceps torque was the primary contributor to knee flexion excursion at both three and six months after TKA. Implementing strategies to maximize quadriceps rate of torque development during postoperative rehabilitation may improve gait and early functional outcomes after TKA.

## Conflict of interest statement

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One author (SD) is a paid consultant for Smith & Nephew and Zimmer Biomet. Two authors serve on the editorial/governing boards of medical journals (*Journal of Sports Rehabilitation* [CJ]) and *Journal of Arthroplasty* [SD]). Two authors also have appointments to society committees (CJ: Orthopaedic Research Society, International Cartilage Repair Society; SD: Kentucky Orthopaedics Society).

## CRediT authorship contribution statement

**Paul W. Kline:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Cale A. Jacobs:** Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing - review & editing. **Stephen T. Duncan:** Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing - review & editing. **Brian Noehren:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing.

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