Individual Gait Features Are Associated with Clinical Improvement After Total Knee Arthroplasty

Kathryn L. Young-Shand, MASc, Michael J. Dunbar, MD, PhD, FRCSC, and Janie L. Astephen Wilson, PhD

Investigation performed at Dalhousie University, Halifax, Nova Scotia, Canada

**Background:** Over 20% of patients do not report clinically relevant pain relief or functional improvements after total knee arthroplasty (TKA). The aim of this study was to investigate the effect of demographics, pre-TKA knee-joint biomechanics, and postoperative changes in knee biomechanics on meaningful improvements in self-reported pain and function after TKA.

**Methods:** Forty-six patients underwent 3-dimensional gait analysis and completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) questionnaire before and 1 year after TKA. Response to treatment in terms of pain relief and functional improvement (“pain and function responders”) was defined as improvements in WOMAC scores that met minimal clinically important difference thresholds in the pain and function domains. Differences between responder and non-responder demographics, severity of the osteoarthritis as seen radiographically, and knee kinematics and kinetics before TKA were explored using the t test and Mann-Whitney U test. Correlations and regression models were used to examine demographics, baseline knee kinematics and kinetics, and post-TKA kinematic and kinetic improvements associated with being a pain responder and a function responder separately. Analyses were conducted using a hypothesis-driving approach.

**Results:** Of the 46 patients, 34 were pain responders and 36 were function responders. Preoperatively, both responder groups had a higher radiographic severity (Kellgren-Lawrence) grade (p = 0.03) and pain responders were more symptomatic according to their WOMAC score (p < 0.04). Less preoperative stance-phase flexion-extension angle range (p ≤ 0.03), lower preoperative stance-phase adduction (varus) angle magnitude (p = 0.01), and less postoperative reduction in the adduction angle magnitude (p ≤ 0.009) were independently associated with more self-reported improvement in pain and function.

**Conclusions:** Patients with a higher radiographic severity grade, with specific frontal and sagittal knee kinematic patterns during gait before TKA, and who demonstrated less reduction in frontal plane angles during gait after TKA had greater self-reported pain and function score improvements after standard TKA. Gait analysis may aid preoperative identification of kinematic subgroups associated with self-reported improvements after TKA, and provide evidence that may inform triaging, surgical planning, and expectation management strategies.

**Level of Evidence:** Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

More than 20% of patients with knee osteoarthritis do not report clinically meaningful improvements in pain and function or satisfaction after total knee arthroplasty (TKA), raising concerns over the potential overuse of TKA. Appropriate patient selection thus requires an understanding of the symptom state most associated with meaningful improvements after arthroplasty, previously termed the “sweet spot.” While patients with worse self-reported pain and function preoperatively experience greater improvements in patient-reported outcome measures (PROMs) after TKA, common PROM tools lack the ability to predict optimal candidates preoperatively. Used in isolation, PROMs also provide limited insights into potential underlying biomechanical mechanisms associated with whether patients fare well or poorly.

**Disclosure:** This study was supported by the government of Nova Scotia, the Nova Scotia Health Research Foundation, the Canadian Institutes for Health Research, and Mitacs Canada in collaboration with T4G Limited. Funding did not play a role in the study design, collection, analysis, result interpretation, or submission decision. The Disclosure of Potential Conflicts of Interest forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A151).

Copyright © 2020 The Authors. Published by The Journal of Bone and Joint Surgery, Incorporated. All rights reserved. This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.
PROM improvements after arthroplasty have been associated with baseline gait mechanics. TKA is inherently a mechanical surgery, and gait mechanics worsen with osteoarthritis progression, severity seen on radiographs, and pain. Objective assessment of the severity of gait features at baseline may aid in identifying functional features most associated with PROM improvements after TKA, providing important information for preoperative candidate selection and expectation management. Another aim of TKA is to improve knee function, in part by improving patient gait. It remains unknown if patients who report poor outcomes actually demonstrate objective improvements in gait function and, furthermore, what gait function improvements are associated with PROM improvements. Exploring this could motivate investigations of the efficacy of surgically targeting specific functional deficits.

We performed this explorative study to compare pre-TKA demographic and knee-joint gait mechanics (kinematic and kinetic) between patients who reported clinically meaningful improvements in pain and function after TKA (responders) and those who did not (non-responders), and to model preoperative demographics and gait features descriptive of responders. The secondary aim was to compare pre-TKA to post-TKA changes in knee-joint gait mechanics among pain and function responders and non-responders, and to examine correlations between gait changes and self-reported improvements.

**Materials and Methods**

**Patients and Surgery**

Patients with end-stage knee osteoarthritis scheduled to receive a primary TKA at a high-volume academic orthopaedic clinic from 2003 to 2016 underwent gait assessment 1 week prior to (n = 135) and 1 year after (n = 109) TKA (Fig. 1). Patients were included in the study if they were able to walk 6 m unassisted, and they were excluded if they screened positive for neurological disease or other conditions affecting their gait or ability to safely participate. The TKAs followed a standard medial parapatellar approach, with distal femoral cuts set to 5° of valgus and tibial cuts targeting neutral mechanical alignment. The measured resection technique was used to obtain a balanced flexion-extension gap. The patients received standard postoperative inpatient physiotherapy, with immediate weight-bearing. The median hospital stay was 3 days, and outpatient physiotherapy was not standardized and was optional. Informed consent was obtained from the participants according to the institution ethics board.

**Gait Biomechanics**

Data on age, sex, weight, height, and osteoarthritis severity graded by an orthopaedic surgeon using Kellgren-Lawrence (KL) global radiographic scores were collected as part of the preoperative assessment. To perform the gait studies, infrared light-emitting markers were placed on participants according to a standardized protocol, which included 4 triads of markers attached to the pelvis, thigh, shank, and foot to establish limb-segment rigid body coordinate systems. To define local anatomical joint axes, the locations of 12 anatomical landmarks were digitized during a static calibration trial and calculated relative to the triads during motion trials. Participants walked along a 5-m walkway wearing comfortable shoes at a self-selected speed. Three-dimensional external ground reaction forces were recorded at 2,000 Hz with an AMTI Biomechanics...
Platform System (Advanced Medical Technology) embedded in the walkway. This was synchronized to an Optotrak optoelectronic motion capture system (NDI) sampling marker positions at 100 Hz. Knee-joint angles were calculated according to the joint coordinate system, and net resultant knee-joint moments were measured by inverse dynamics, amplitude normalized to body mass (Nm/kg). Following this protocol, a minimum of 4 walking trials were averaged and normalized for each participant to 1 gait cycle (0% to 100%) for flexion/extension angles and to stance phase (0% to 100%) for moments and adduction angles.

Principal component analysis (PCA) was used to capture major features of participant variability in knee angle and moments waveforms because it has demonstrated better sensitivity than discrete gait parameters. A large sample of patient waveforms before (n = 135) and 1 year after (n = 109) TKA were used to create robust principal component (PC) models using a standardized protocol. Three knee adduction moment, adduction angle, and flexion moment PCs and 4 knee flexion-extension angle PCs were retained (see Appendix). These features have been previously shown to describe the major modes of variability in the gait of individuals who underwent TKA and those with osteoarthritis, or were features typically applied to functional assessment after TKA.

Individual patient data were projected onto each PC, providing individual subject PC scores used in hypothesis testing.

**TABLE I Baseline Demographics and Self-Reported WOMAC Scores of Pain and Function Responders and Non-Responders**

|                          | Total | Responders | Non-Responders | P Value* | Responders | Non-Responders | P Value* |
|--------------------------|-------|------------|----------------|----------|------------|----------------|----------|
| No. of subjects          | 46    | 34         | 12             | 36       | 10         |                 |          |
| Sex                      |       |            |                |          |            |                 |          |
| Male                     | 17    | 12         | 5              |          | 13         | 4               |          |
| Female                   | 29    | 22         | 7              | 23       | 6          |                 |          |
| Age† (yr)                | 64.1 (6.6) | 63.6 (7.0) | 65.7 (5.4) | 0.354    | 63.5 (6.8) | 66.4 (5.7) | 0.223    |
| BMI† (kg/m²)             | 32.6 (5.7) | 32.7 (6.2) | 32.5 (4.0) | 0.926    | 32.4 (6.1) | 33.3 (4.1) | 0.687    |
| KL grade‡§ (no. of subjects) | 4.0 (3, 4) | 4.0 (3, 4) | 3.0 (3, 3) | **0.030** | 4.0 (3, 4) | 3.0 (3, 3) | **0.030** |
| 0                        | 0     | 0          | 0              | 0        | 0          |                 |          |
| 1                        | 0     | 0          | 0              | 0        | 0          |                 |          |
| 2                        | 0     | 0          | 0              | 0        | 0          |                 |          |
| 3                        | 13    | 9          | 4              | 9        | 4          |                 |          |
| 4                        | 14    | 14         | 0              | 14       | 0          |                 |          |
| Gait speed† (m/s)        |       |            |                |          |            |                 |          |
| Pre-TKA                  | 0.9 (0.2) | 0.9 (0.2) | 0.8 (0.2) | **0.038** | 0.9 (0.2) | 0.9 (0.2) | 0.536    |
| Post-TKA                 | 1.0 (0.2) | 1.1 (0.2) | 1.0 (0.2) | 0.232    | 1.1 (0.2) | 1.0 (0.2) | 0.153    |
| WOMAC score‡            |       |            |                |          |            |                 |          |
| Total                    | 47.9 (21.3, 75.6) | 45.5 (19.1, 71.0) | 54.7 (38.2, 75.0) | **0.037** | 46.1 (19.3, 70.7) | 56.9 (38.3, 75.1) | 0.101    |
| Pain                     | 50.0 (26.3, 75.0) | 45.0 (24.1, 70.9) | 62.5 (37.8, 78.6) | **0.007** | 47.5 (24.3, 75.0) | 60.0 (37.2, 77.8) | 0.074    |
| Joint stiffness           | 50.0 (12.5, 75.0) | 50.0 (10.3, 75.0) | 50.0 (19.4, 75.0) | 0.082    | 50.0 (10.9, 75.0) | 43.8 (15.3, 75.0) | 0.529    |
| Physical function        | 47.1 (25.6, 80.1) | 44.1 (22.9, 82.4) | 47.8 (35.2, 73.1) | 0.197    | 46.9 (23.6, 74.5) | 58.1 (34.7, 86.0) | 0.068    |

*Significant (p < 0.05) values are in bold. †The values are given as the mean and standard deviation. ‡The values are given as the median and 95% CI. §Grades were available for 27 of the 46 participants, reasonably distributed between groups—i.e., they were available for 23 of the 34 pain responders, 4 of the 12 pain non-responders, 23 of the 36 function responders, and 4 of the 10 function non-responders.

**PROMs**

A portion of the participants who underwent gait analysis completed the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) PROM questionnaire (scale, 0 [worst] to 100 [best]) 1 week before (n = 59) and 1 year after (n = 46) TKA, meeting international PROM collection timing standards. Patients with both pre-TKA and post-TKA WOMAC scores (n = 46) were included in the analysis (Fig. 1). Pre-TKA to post-TKA improvements of ≥23 points in the WOMAC pain score and ≥19 points in the WOMAC function score were used to categorize patients, independently, as “pain responders” and “function responders,” following WOMAC minimal clinically important difference (MCID) criteria. Non-responder follow-up scores were assessed for ceiling effects (a postoperative score of 100), ensuring that the WOMAC boundaries did not contribute to non-responder classification.
**Statistical Analysis**

**Baseline Analysis (Primary Aim)**
Baseline variable (sex, age, body mass index [BMI], KL grade, WOMAC scores, and gait speed) and PC score differences between pain and function responders and non-responders were assessed with use of chi-square tests, unpaired t tests, and Mann-Whitney U tests. Correlations of baseline demographics and gait PC scores with changes in WOMAC pain and function scores (post-operative minus pre-operative) were examined using Pearson correlation coefficients. Variables showing significant correlations with changes in WOMAC pain and function scores were retained for multiple regression analyses. Binomial generalized linear models were used to examine baseline demographics and baseline gait features associated with pain and function responder classification independently, assessed using the Akaike information criterion. Final models were presented using modified Poisson regression for improved clinical interpretation, representing coefficients as relative risk ratios (RRs) and 95% confidence intervals (CIs) derived from standard errors using the robust sandwich estimator. Features were scaled (0 to 10), with a 1-point increase in RR associated with a 10% change in PC score. All analyses were conducted in an exploratory fashion with p values of <0.05 considered significant.

**Pre-TKA to Post-TKA Changes (Secondary Aim)**
Differences between pre-TKA and post-TKA gait features within the pain and function responder and non-responders were compared using paired t tests. Correlations between changes in PC scores (post-TKA minus pre-TKA) and changes in WOMAC pain and function scores were examined using Pearson correlation coefficients.

**Results**

**Baseline Analysis**

**Pain**
Seventy-four percent (34) of the 46 patients met the WOMAC pain domain MCID improvement criterion and were classified as pain responders; the remaining 26% (12) were classified as pain non-responders. Preoperatively, pain responders (compared with non-responders) had more severe osteoarthritis as classified radiographically ($p = 0.03$), were more symptomatic (median total WOMAC pain score, 45.5 [95% CI = 19.1 to 71.0] versus 54.7 [95% CI = 38.2 to 75.0], $p = 0.04$), and walked at faster gait speeds (mean [and standard deviation], 0.93 ± 0.19 m/s versus 0.80 ± 0.18 m/s, $p = 0.04$) (Table I). Pain responders also walked with a lower stance-phase adduction angle magnitude (PC1)
relative to pain non-responders preoperatively (p = 0.03), indicating lower overall knee adduction angle magnitudes (less consistently varus) throughout the stance phase of gait (Fig. 2, Table II).

Patients who had less stance-phase flexion-extension angle range (PC4: r = −0.32, p = 0.03) and a lower stance-phase varus (adduction angle) magnitude (PC1: r = −0.37, p = 0.01) preoperatively had more improvement in WOMAC pain scores (Figs. 3-A and 3-B). In multivariate modeling, lower stance-phase varus (adduction angle) magnitude was the only preoperative feature predictive of being a pain responder (PC1: RR = 0.92, p < 0.05) (Table III).

Function
Seventy-eight percent (36) of the 46 patients met the WOMAC function domain MCID improvement criterion and were classified as function responders; the remaining 22% (10) were classified as function non-responders. Preoperatively, function responders had more severe osteoarthritis as classified radiographically (p = 0.03) than function non-responders (Table I). Function responders also had a lower stance-phase varus (adduction angle) magnitude (PC1: p < 0.05) and less stance-phase flexion-extension angle range than non-responders (PC4: p = 0.01) preoperatively (Fig. 4, Table IV).

Patients who were younger (r = −0.41, p = 0.005), had less stance-phase flexion-extension angle range (PC4: r = −0.38, p = 0.009), and had a lower stance-phase varus (adduction angle) magnitude (PC1: r = −0.34, p = 0.01) preoperatively had more improvement in WOMAC function scores (Figs. 3-D, 3-E, and 3-F). In multivariate modeling, the likelihood of being a function responder increased only if the patient walked with less stance-phase flexion-extension angle range preoperatively (PC4: RR = 0.90, p = 0.01) (Table III).
Fig. 3

**Figs. 3-A through 3-H** Associations of demographic and gait features with pre-TKA to post-TKA changes in WOMAC pain and function scores.

**Figs. 3-C and 3-G** Positive (+ive) changes in stance-phase varus (adduction angle) magnitude (PC1) represent an increase in varus alignment during stance while negative changes represent more varus magnitude reduction (varus-to-valgus change). Lower stance-phase varus magnitudes at baseline and less pre-TKA to post-TKA reduction in stance-phase varus magnitude after TKA were each independently associated with more self-reported improvements in pain and function. **Fig. 3-H** Positive changes in the adduction moment range (PC2) represent a larger medial compartment loading/unloading range during stance. Larger increases in the dynamic loading range were associated with more improvement in self-reported function.
Pre-TKA to Post-TKA Changes

Pain and function responders demonstrated typically reported pre-TKA to post-TKA gait improvements (toward being asymptomatic) in terms of the magnitude and pattern of adduction moment, flexion moment, and flexion angle features (Tables II and IV). The only gait change captured in both the pain and function non-responder groups was a reduction in the stance-phase varus (adduction angle) magnitude after TKA relative to preoperatively (PC1: $p < 0.005$; Figs. 2 and 4 and Tables II and IV).

Pain non-responders alone also showed more stance-phase flexion moment range after TKA relative to preoperatively (PC2: $p = 0.03$, Table II).

Patients who experienced less pre-TKA to post-TKA reduction in the stance-phase varus (adduction angle) magnitude ($\Delta$PC1: $r = 0.47$, $p = 0.001$) had more improvement in WOMAC pain scores (Fig. 3-C). Patients who experienced less reduction in the stance-phase varus (adduction angle) magnitude after the TKA ($\Delta$PC1: $r = 0.38$, $p = 0.009$) and showed a

**TABLE III Baseline and Change in Gait Features Contributing to Clinically Meaningful Improvements in Self-Reported Pain and Function***

| RR     | 95% CI        | Estimate | Std. Error | P Value† |
|--------|---------------|----------|------------|----------|
| Pain domain ($r^2 = 0.14$‡) |             |          |            |          |
| Adduction angle PC1: pre-TKA magnitude of stance-phase varus alignment | 0.915 | 0.838, 0.998 | −0.089 | 0.045 | 0.046 |
| Function domain ($r^2 = 0.15$‡) |             |          |            |          |
| Flexion angle PC4: pre-TKA flexion angle range of motion during stance | 0.898 | 0.827, 0.976 | −0.107 | 0.042 | 0.011 |

*From multivariate modified Poisson regression analysis. Items were scaled (0 to 10), with a 1-point increase in RR associated with a 10% change in PC score. †Significant ($p < 0.05$) values are in bold. ‡Linear models were applied using the magnitude of WOMAC domain improvement as the independent variable to provide estimates of $r^2$. 

---

**Fig. 4**

Mean gait-study waveforms collected 1 week before TKA and 1 year after TKA in the function responder ($n = 36$) and non-responder ($n = 10$) groups. Light shaded regions represent 1 standard deviation around the mean gait waveforms of 209 asymptomatic adults.
larger increase in the early to mid-stance adduction moment range (ΔPC2: r = 0.32, p = 0.03) had more improvement in WOMAC function scores (Figs. 3-G and 3-H).

**Discussion**

Patients who responded to TKA in terms of improvement in function (function responders) were characterized biomechanically by less stance-phase flexion-extension angle range and lower adduction angle magnitude preoperatively (Fig. 4, Table IV). In multivariate modeling, less stance-phase flexion-extension angle range was the only feature predictive of being a function responder (Table III). This finding is in agreement with a similar study by Niali et al. (n = 28), who reported less sagittal-plane knee-angle range before TKA in patients who met the minimal detectable change criterion for improvement in knee-related quality-of-life scores postoperatively compared with those who did not (stance to swing, 45° ± 6° versus 52° ± 5°)15. Less sagittal range is typically associated with “more severe,” or stiffer, sagittal plane kinematics, resembling more severe osteoarthritis pattern norms16,30 (Fig. 4). Younger age was also associated with more improvement in WOMAC function scores in our univariate analysis (r = −0.41, p = 0.005) (Fig. 3). Although younger patients typically report less satisfaction after TKA17, they have been found to have more self-reported improvements18, attributing to improved functional abilities captured within activities of daily living scores. Of the 5 function responders who were ⩾55 years old in this study, 4 demonstrated stance-phase flexion-extension angle ranges (PC4) below the norm preoperatively, potentially representing a subset of young patients with stiff sagittal kinematics. Stiff kinematics, coupled with radiographic evidence of more severe osteoarthritis (p = 0.03), and trends toward greater symptom severity (Table I) align with previous

---

**TABLE IV Principal Component Scores of Function Responders and Non-Responders Before and After TKA**

| Gait Feature                           | Variance Explained (%) | Pre-TKA (N = 36) | Post-TKA (N = 36) | P Value* | P Value* for Within-Responder and Non-Responder Group Difference | P Value* | Responders | Non-Responders |
|----------------------------------------|------------------------|------------------|------------------|----------|-----------------------------------------------------------------|----------|-------------|---------------|
| Flexion angle                          |                        |                  |                  |          |                                                                 |          |             |               |
| PC1: gait cycle flexion angle magnitude| 65.09                  | −14.90 (56.42)   | −5.59 (33.33)    | 0.655    | 20.43 (58.94)                                                  | 0.231    | 0.011       | 0.233         |
| PC2: stance-to-swing angle range       | 15.79                  | −0.33 (40.32)    | −14.92 (28.65)   | 0.291    | 7.06 (28.97)                                                   | 0.039    | 0.375       | 0.162         |
| PC3: phase shift: timing of stance and peaks | 11.91                  | −8.81 (30.64)    | 6.86 (32.91)     | 0.163    | 3.89 (24.13)                                                   | 0.752    | 0.053       | 0.593         |
| PC4: stance-phase range of motion      | 2.60                   | −4.99 (11.58)    | 6.78 (12.84)     | **0.008** | 0.95 (10.85)                                                   | 0.155    | **0.028**   | 0.374         |
| Adduction angle                        |                        |                  |                  |          |                                                                 |          |             |               |
| PC1: stance-phase adduction angle magnitude | 57.40                  | 3.75 (20.31)     | 18.07 (16.15)    | **0.046** | −6.79 (19.81)                                                  | **0.001** | 0.029       | 0.005         |
| PC2: midstance-to-terminal stance range | 24.04                  | 0.02 (16.64)     | −1.18 (10.03)    | 0.829    | −2.24 (12.82)                                                  | 0.811    | 0.521       | 0.985         |
| PC3: heel strike-to-midstance range    | 8.60                   | 1.21 (9.91)      | −2.79 (8.69)     | 0.254    | 0.49 (5.95)                                                    | 0.173    | 0.710       | 0.142         |
| Flexion moment                         |                        |                  |                  |          |                                                                 |          |             |               |
| PC1: gait cycle flexion moment magnitude | 72.59                  | −0.03 (1.99)     | 0.18 (1.68)      | 0.762    | −0.39 (1.23)                                                   | 0.234    | 0.355       | 0.627         |
| PC2: stance-phase flexion moment range | 16.53                  | −0.29 (0.56)     | −0.07 (0.66)     | 0.303    | 0.24 (0.57)                                                    | 0.151    | <0.001      | 0.764         |
| PC3: phase shift: timing of flexion peaks | 3.90                   | 0.00 (0.43)      | 0.01 (0.45)      | 0.951    | 0.01 (0.29)                                                   | 0.994    | 0.919       | 0.625         |
| Adduction moment                       |                        |                  |                  |          |                                                                 |          |             |               |
| PC1: stance-phase adduction moment magnitude | 83.17                  | 0.06 (1.64)      | 0.04 (1.73)      | 0.962    | −0.10 (0.85)                                                   | 0.726    | 0.593       | 0.890         |
| PC2: first-peak and midstance range   | 8.40                   | −0.19 (0.38)     | −0.12 (0.27)     | 0.598    | 0.10 (0.35)                                                   | 0.069    | **0.001**   | 0.944         |
| PC3: midstance and second-peak range  | 3.20                   | −0.08 (0.26)     | −0.04 (0.36)     | 0.640    | 0.15 (0.24)                                                   | 0.068    | <0.001      | 0.290         |

*Significant (p < 0.05) values are in bold.
inferences that patients with more severe preoperative problems (typically measured by PROMs) tend to have better arthroplasty outcomes\textsuperscript{4,7,8,13}. Our study suggests that severity could be captured objectively by measuring knee kinematics during gait. Furthermore, these kinematic features could be detectable in clinical settings through simple wearable or markerless motion capture.

The only biomechanical gait feature descriptive of pain responders before TKA was a lower stance-phase varus (adduction angle) magnitude, suggested by comparative tests and in multivariate modeling (Tables II and III). Conversely, pain non-responders appeared more varus during stance preoperatively. While static and dynamic varus alignment have both been associated with more severe medial compartment osteoarthritis\textsuperscript{4,8,41,42}, less severe osteoarthritis seen on radiographs and less symptom severity in pain non-responders (Table I) suggest a potential kinematic subgroup of individuals with constitutional varus alignment\textsuperscript{43} or kinematic varus\textsuperscript{44}. Although interesting, these results should be interpreted with caution. Our exploratory approach did not account for multiple comparisons. This, coupled with small non-responder group sizes, increased the possibility of type-I errors and resulted in large CIs around our estimates. However, visualizations of kinematic data did suggest that 10 of 12 pain responders and 9 of 10 function non-responders had preoperative varus angle magnitudes above the norm. If the soft tissue and muscle surrounding the joint have adapted to native varus kinematics\textsuperscript{45}, mechanics after standard arthroplasty might be perceived by the patient as unnatural, potentially contributing to less self-reported improvements in pain and function. It has been suggested that standardized alignment may not be optimal for all patients\textsuperscript{46-48}. Vanlommel et al.\textsuperscript{49} reported significantly better function and knee scores in individuals with preoperative varus when postoperative alignment remained in mild varus. Under these assumptions, native varus magnitudes might be a false signal during selection of patients for arthroplasty, or this presentation with an absence of other severe osteoarthritic features might characterize clinical candidate subgroups for whom neutral corrections are not “clinically relevant.”\textsuperscript{72} Investigating patient biomechanical variability with respect to outcomes in larger studies is an important area for further research. These groups might benefit from altered clinical or surgical approaches (such as individualized alignment or a high tibial osteotomy), relative to standard-of-care arthroplasty.

Patients who report less pain and function improvement postoperatively appear to demonstrate less objective functional improvements during gait. Non-responders showed significantly reduced stance-phase varus angles after TKA, yet lagged in terms of sagittal kinematic and kinetic loading pattern corrections typically reported in population-average studies (Tables II and IV)\textsuperscript{42,43,52,53,11,12}. Naili et al. proposed that poor patient-reported outcomes might be partially explained by a lack of dynamic kinematic and kinetic corrections, despite alignment corrections in the frontal plane, a feature that surgery may be most able to address biomechanically\textsuperscript{53}. Although our results suggested less 3-dimensional corrections in non-responders overall (Tables II and IV), we did find frontal plane changes to be associated with self-reported improvement in pain and function. Specifically, less reduction in stance-phase varus (adduction angle) magnitude was independently associated with more improvement in PROM scores (in both the pain and function domains), as were larger increases in dynamic frontal plane loading (PC2) (in the function domain alone) (Fig. 3). This was a unique finding, supporting our interpretation that standard arthroplasty might not be optimal for a subset of patients. Post-hoc tests also showed no difference among the 5 surgeons in terms of the magnitude of varus reduction that they imposed (p ≥ 0.8).

Despite including a relatively large 3-dimensional gait analysis sample, our study had fewer non-responders than responders, making it difficult to generalize our results to the TKA population. We instead aimed to provide insights through the linkage of comprehensive biomechanical and clinical data sets and to share valuable information to guide targeted research. Our exploratory approach did not correct for multiple comparisons, and results should be interpreted as preliminary evidence of patient subgroups that may benefit from altered treatment approaches. Furthermore, the power of our ability to detect pre-TKA to post-TKA gait changes among non-responders was low (9% to 32%). However, small permutations between pain and function non-responder groups (non-responder overlap of 8 of 12 and 8 of 10, respectively) operated as a natural sensitivity analysis, improving confidence in the findings reported in both domains. Radiographs to determine the KL grade were not available for all individuals, nor were whole-leg standing radiographs, limiting our ability to translate stance-phase findings to the static alignment that is traditionally considered surgically. Using MCID thresholds to dichotomize outcomes was also not without limitations. MCID thresholds are not applicable for measuring individual change for all patients, nor do they translate well to global metrics such as satisfaction\textsuperscript{82}. Furthermore, MCIDs can be influenced by pre-operative symptom severity\textsuperscript{80}, and questionnaire ceiling effects may restrict rates of patients meeting MCID thresholds, despite their still having improvement. Still, PROM responsiveness scores have been recommended by the International Society of Arthroplasty Registries Working Group\textsuperscript{51} and others\textsuperscript{83}, due to their ability to improve interpretation of within and between-patient score changes from interventions. Pain and function domains were selected as they tend to be key outcomes assessed after TKA and they are the domains most associated with satisfaction\textsuperscript{84}. Seventy-four percent and 78% of patients met MCID thresholds for pain and function response, respectively, which is greater than in a previous Canadian study\textsuperscript{9} but aligns closely with other studies\textsuperscript{2,3,9} and with the 20% dissatisfaction rate typically reported after TKA\textsuperscript{6}. WOMAC pain and function domains also tend to be less susceptible to floor and ceiling effects than joint stiffness\textsuperscript{84}; none of the non-responders in our study reached ceilings postoperatively.
This study contributes to the growing body of evidence that suggests variability in patient-reported outcomes may be partially explained by a combination of clinical and objectively measured knee-joint biomechanical factors. Specifically, more “severe” objective gait features preoperatively tended to be associated with a larger potential for both objective and self-reported functional improvements. Unique findings in this study included preliminary evidence of a varus kinematic subgroup that may be susceptible to less pain and function improvements from standard arthroplasty, and that larger reductions in stance-phase varus alignment may be unfavorable to some patients. These trends warrant further investigation. Objective functional assessment preoperatively may aid in identifying the optimal functional state (the “sweet spot”) associated with patient-reported improvements and help identify those who may benefit from an individualized approach, informing triaging, surgical planning, and expectation management strategies. Our findings support the notion that TKA innovation depends on a better understanding of 3-dimensional knee mechanics at an individual level to provide expected improvements for all patients.

**Appendix**

Supporting material provided by the authors is posted with the online version of this article as a data supplement at jbjs.org (http://links.lww.com/JBJSA/A152).

Kathryn L. Young-Shand, MASc
Michael J. Dunbar, MD, PhD, FRSC
Janie L. Astephen Wilson, PhD

1Department of Surgery (M.J.D. and J.L.A.W.) and School of Biomedical Engineering (K.L.Y.-S., M.J.D., and J.L.A.W.), Dalhousie University, Halifax, Nova Scotia, Canada
2Department of Surgery, McMaster University, Hamilton, Ontario, Canada

Email address for K.L. Young-Shand: kathryn.young@dal.ca

**ORCID iD for K.L. Young-Shand:** 0000-0002-4450-5890

**ORCID iD for M.J. Dunbar:** 0000-0003-3629-498X

**ORCID iD for J.L. Astephen Wilson:** 0000-0002-5998-7677

---

**References**

1. Quintana JM, Escobar A, Arostegui I, Bilbao A, Azkarate J, Goenaga JI, Arenaza JC. Health-related quality of life and appropriateness of knee or hip joint replacement. Arch Intern Med. 2006 Jun 26;166(2):220-6.

2. Escobar A, Quintana JM, Bilbao A, Arostegui I, Lafuente I, Vidaurreta I. Responsiveness and clinically important differences for the WOMAC and SF-36 after total knee replacement. Osteoarthrits Cartilage. 2007 Mar;15(3):273-80. Epub 2006 Oct 17.

3. Hawker GA, Badley EM, Borkhoff CM, Croxford R, Davis AM, Dunn S, Gignac MA, Jaglal SB, Kreder HJ, Sale JE. Which patients are most likely to benefit from total joint arthroplasty? Arthritis. 2013 May;65(5):1243-52.

4. Robertson S, Dunbar M, Pehrsson T, Knutsen K, Lidgren L. Patient satisfaction after knee arthroplasty: a report on 27,372 knees operated on between 1981 and 1995 in Sweden. Acta Orthop Scand. 2000 Jun;71(3):262-7.

5. Clavel N, De Coster C, Pomey MP, Samann C, Bohn E, Dunbar MJ, Frank CY, Hawker G, Noseworthy T. Appropriateness for total joint replacement: perspectives of decision-makers. Healthc Policy. 2016 Feb;11(3):80-92.

6. Losina E, Katz JN. Total joint replacement outcomes in patients with concomitant comorbidities: a glass half empty or half full? Arthritis Rheum. 2013 May;65(5):1157-9.

7. Jiang Y, Sanchez-Santos MT, Judge AD, Murray DW, Arden NK. Predictors of patient-reported pain and functional outcomes over 10 years after primary total knee arthroplasty: a prospective cohort study. J Arthroplasty. 2017 Jan;32(1):92-100.e2. Epub 2016 Jun 23.

8. Fortin PR, Clarke AE, Joseph L, Liang MH, Tanzer M, Feller DJ, Phillips C, Paradis J, Charlebois D, Lachance M, Dionne F. Patient satisfaction after total knee arthroplasty: an 8-year follow-up study. J Arthroplasty. 2018;33(7):2083-9.

9. Judge A, Arden NK, Price A, Gnajd-Jones S, Beard C, Dawson J, Fitzpatrick R, Judge AD, Murray DW, Arden NK. Assessing patients for joint replacement: can pre-operative Oxford hip and knee scores be use to predict patient satisfaction following joint replacement surgery and to guide patient selection? J Bone Joint Surg Br. 2011 Dec;93(12):1660-4.

10. Baker PN, Rushton S, Jameson SS, Reed M, Gregg P, Deehan DJ. Patient satisfaction with total knee replacement cannot be predicted from pre-operative variables alone: a cohort study from the National Joint Registry for England and Wales. Bone Joint J. 2013 Oct;95-B(10):1359-65.

11. Turcot K, Sagawa Y Jr, Fritschy D, Hoffmeyer P, Suva D, Armand S. How gait and clinical outcomes contribute to patients’ satisfaction three months following a total knee arthroplasty. J Arthroplasty. 2013 Sep;28(8):1297-300. Epub 2013 Mar 23.

12. Nairi JE, Wretenberg P, Lindgren V, Iversen MD, Hedström M, Broström EW. Improved knee biomechanics among patients reporting a good outcome in knee-related quality of life one year after total knee arthroplasty. BMC Musculoskelet Disord. 2017 Mar 21;18(1):122.

13. Smith AJ, Lloyd DG, Wood DJ. Pre-surgery knee joint loading patterns during walking predict the presence and severity of anterior knee pain after total knee arthroplasty. 2004;22:260-266.

14. Astephen JL, Deluzio KJ, Caldwell GE, Dunbar MJ. Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity. J Orthop Res. 2008 Mar;26(3):332-41.

15. Astephen Wilson JL, Deluzio KJ, Dunbar MJ, Caldwell GE, Hubley-Kozey CL. The association between knee joint biomechanics and neuromuscular control and moderate knee osteoarthritis radiographic and pain severity. Osteoarthrits Cartilage. 2011 Feb;19(2):186-93. Epub 2010 Nov 11.

16. Maly MR, Costigan PA, Oleny SJ. Mechanical factors relate to pain in knee osteoarthritis. Clin Biomech (Bristol, Avon). 2008 Jul 23(6):796-805. Epub 2008 Mar 17.

17. Henriksen M, Aaboje J, Bliddal H. The relationship between pain and dynamic knee joint loading in knee osteoarthritis varies with radiographic disease severity. A cross sectional study. Knee. 2012 Aug;19(4):392-8. Epub 2011 Aug 11.

18. Andreacci JP. Functional analysis of pre and post-knee surgery; total knee arthroplasty and ACL reconstruction. J Biomech Eng. 1993 Nov;115(4B):57S-81.

19. Noble PC, Gordon MJ, Weiss JM, Reddin RN, Conditt MA, Mathis KB. Does total knee replacement restore normal knee function? Clin Orthop Relat Res. 2005 Feb; 431:157-65.

20. Hatfield GL, Hubley-Kozey CL, Astephen Wilson JL, Dunbar MJ. The effect of total knee arthroplasty on knee joint kinematics and kinetics during gait. J Arthroplasty. 2011 Feb;26(2):309-18. Epub 2010 May 31.

21. Sosdian L, Dobson F, Wingley TV, Paterson K, Bennett K, Dowsey M, Chong P, Allison K, Hilman RS. Longitudinal changes in knee kinematics and moments following knee arthroplasty: a systematic review. Knee. 2014 Dec;21(6):994-2008. Epub 2014 Oct 12.

22. Keligren JH, Lawrence JS. Radiological assessment of osteoarthritis. Ann Rheum Dis. 1957 Dec;16(4):494-502.

23. Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ. Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed. J Biomech. 2007;40(8):1754-61. Epub 2006 Nov 7.

24. Grove ES, Sunyay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. J Biomech Eng. 1983 Mar; 105(2):136-44.

25. Costigan PA, UP Wyss, Deluzio KJ, Ll J. Semi-automated three-dimensional knee motion assessment system. Med Biol Eng Comput. 1992 May;30(3):343-50.
27. DeLuizy KJ, LP Wyss, Li J, Costigan PA. A procedure to validate three-dimensional motion assessment systems. J Biomech. 1993 Jun;26(6):753-9.
28. Li J, UP Wyss, Costigan PA, DeLuizy KJ. An integrated procedure to assess knee-joint kinematics and kinetics during gait using an optoelectric system and standardized X-rays. J Biomech Eng. 1993 Sep;115(5):392-400.
29. Deluizy KJ, Astephen JL. Biomechanical features of gait waveform data associated with knee osteoarthritis: an application of principal component analysis. Gait Posture. 2007 Jan;25(1):86-93. Epub 2006 Mar 29.
30. Astephen JL, Deluizy KJ, Caldwell GE, Dunbar MJ, Hubley-Kozej CL. Gait and neuromuscular pattern changes are associated with differences in knee osteoarthritis severity levels. J Biomech. 2004 Apr;37(4):868-76. Epub 2004 Feb 20.
31. McClelland JA, Webster KE, Feller JA, Menz HB. Knee kinematics during walking at different speeds in people who have undergone total knee replacement. Knee. 2011 Jun;18(3):151-5. Epub 2010 May 26.
32. Bonnefoy-Mazure A, Armand S, Sagawa Y Jr, Suva D, Miozzi H, Turcot K. Knee kinematic and clinical outcomes evolution before, 3 months, and 1 year after total knee arthroplasty. J Arthroplasty. 2017 Mar;32(3):793-800. Epub 2016 Apr 4.
33. Bellamy N, Buchanan WW, Goldsmith CH, Campbell J, Stitt LW. Validation study of WOMAC: a health status instrument for measuring clinically important patient relevant outcomes to antirheumatic drug therapy in patients with osteoarthritis of the hip or knee. J Rheumatol. 1988 Dec;15(12):1833-40.
34. International Consortium for Health Outcomes Measurement (ICHOM). Hip & knee osteoarthritis data collection reference guide. 2017 Apr 10. Accessed 2020 Feb 12. https://ichom.org/files/medical-conditions/hip-knee-osteoarthritis/hip-knee-osteoarthritis-reference-guide.pdf
35. Roos EM. 3 steps to improve reporting and interpretation of patient-reported outcome scores in orthopedic studies. Acta Orthop. 2018 Feb;89(1):1-2. Epub 2017 Nov 27.
36. Zou G. A modified Poisson regression approach to prospective studies with binary data. Am J Epidemiol. 2004 Apr 1;159(7):702-6.
37. Knol MJ, Le Cessie S, Algra A, Vandenbroucke JP, Groenwold RHH. Overestimation of risk ratios by odds ratios in trials and cohort studies: alternatives to logistic regression. CMAJ. 2012 May 15;184(8):895-9. Epub 2011 Dec 12.
38. Astephen Wilson JL, Dunbar MJ, Hubley-Kozej CL. Knee joint biomechanics and neuromuscular control during gait before and after total knee arthroplasty are sex-specific. J Arthroplasty. 2015 Jan;30(1):118-25. Epub 2014 Jul 25.
39. Williams DP, Price AJ, Beard DJ, Hadfield SG, Arden NK, Murray DW, Field RE. The effects of age on patient-reported outcome measures with total knee replacements. Bone Joint J. 2013 Jan;95-B(1):38-44.
40. Alzahrani K, Gandhi R, Debeer J, Petruccelli D, Mahomed N. Prevalence of clinically significant improvement following total knee replacement. J Rheumatol. 2011 Apr;38(4):753-9. Epub 2011 Jan 15.
41. Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shinada S. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. Ann Rheum Dis. 2002 Jul;61(7):617-22.
42. Orishimo KF, Kremenick LJ, Deshmukh AJ, Nicholas SJ, Rodriguez JA. Does total knee arthroplasty change frontal plane knee biomechanics during gait? Clin Orthop Relat Res. 2012 Apr;470(4):1171-6. Epub 2011 Nov 29.
43. Belemans J, Colyn W, Vandenneucker H, Victor J. The Chitrnanjan Ranawat Award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res. 2012 Jan;470(1):45-53.
44. Chang A, Hochberg M, Song J, Dunlop D, Chmiel JS, Nevitt M, Hayes K, Eaton C, Bathon J, Jackson R, Kwoh CK, Sharma L. Frequency of varus and valgus thrust and factors associated with thrust presence in persons with or at higher risk of developing knee osteoarthritis. Arthritis Rheum. 2010 May;62(5):1403-11.
45. Young KL, Dunbar MJ, Richardson G, Astephen Wilson JL. Intraoperative passive knee kinematics during total knee arthroplasty surgery. J Orthop Res. 2015 Nov;33(11):1611-9. Epub 2015 Jun 3.
46. Parratte S, Pagnano MW, Trousdale RT, Berry DJ. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. J Bone Joint Surg Am. 2010 Sep 15;92(12):2143-9.
47. Blakeney W, Clément J, Desmeules F, Hagemeister N, Rivière C, Vendittoli PA. Kinematic alignment in total knee arthroplasty better reproduces normal gait than mechanical alignment. Knee Surg Sports Traumatol Arthrosoc. 2019 May;27(5):1410-7. Epub 2018 Oct 1.
48. Vanommel L, Vanommel J, Ciaes S, Belemans J. Slight undercorrection following total knee arthroplasty results in superior clinical outcomes in varus knees. Knee Surg Sports Traumatol Arthrosoc. 2013 Oct;21(10):2325-30. Epub 2013 Apr 4.
49. Katz NP, Paillard FC, Ekman E. Determining the clinical importance of treatment benefits for interventions for painful orthopedic conditions. J Orthop Surg Res. 2015 Feb 3;10:24.
50. Escobar A, García Pérez L, Herrera-Espiñeira C, Alipuru F, Sarasqueta C, González Sáenz de Tejada M, Quintana JM, Bilbao A. Total knee replacement: minimal clinically important differences and responders. Osteoarthrits Cartilage. 2013 Dec;21(12):2006-12. Epub 2013 Oct 2.
51. Rolfson O, Eresian Chenok K, Bohn E, Lubebeke A, Denissen G, Dunn J, Lyman S, Franklin P, Dunbar M, Overgaard S, Garellick G, Dawson J. Patient-Reported Outcome Measures Working Group of the International Society of Arthroplasty Registries. Patient-reported outcome measures in arthroplasty registries. Acta Orthop. 2016 Jul;87(Suppl 1):3-8. Epub 2016 May 11.
52. Scott CE, Howie CR, MacDonald D, Blant LC. Predicting dissatisfaction following total knee replacement: a prospective study of 1217 patients. J Bone Joint Surg Br. 2010 Sep;92(9):1253-8.
53. Robertson O, Dunbar MJ. Patient satisfaction compared with general health and disease-specific questionnaires in knee arthroplasty patients. J Arthroplasty. 2001 Jun;16(4):476-82.
54. Dunbar MJ, Robertson O, Ryd L, Lidgren L. Appropriate questionnaires for knee arthroplasty. Results of a survey of 3600 patients from the Swedish Knee Arthroplasty Registry. J Bone Joint Surg Br. 2001 Apr;83(3):339-44.