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Factors predicting weight-bearing asymmetry 1 month after unilateral total knee arthroplasty: a cross-sectional study

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Abstract

Factors predicting weight-bearing asymmetry (WBA) after unilateral total knee arthroplasty (TKA) are not known. However, identifying modifiable and non-modifiable predictors of WBA is needed to optimize rehabilitation, especially since WBA is negatively correlated to poor functional performance. The purpose of this study was to identify factors predictive of WBA during sit-stand transitions for people 1 month following unilateral TKA.

Methods—Fifty-nine people were tested preoperatively and 1 month following unilateral TKA for WBA using average vertical ground reaction force under each foot during the Five Times Sit to Stand Test. Candidate variables tested in the regression analysis represented physical impairments (strength, muscle activation, pain, and motion), demographics, anthropometrics, and movement compensations.

Results—WBA, measured as the ratio of surgical/non-surgical limb vertical ground reaction force, was 0.69 (0.18) (mean (SD)) 1 month after TKA. Regression analysis identified preoperative WBA ($\beta = 0.40$), quadriceps strength ratio ($\beta = 0.31$), and hamstrings strength ratio ($\beta = 0.19$) as factors predictive of WBA 1 month after TKA ($R^2 = 0.30$).

Conclusion—Greater amounts of WBA 1 month after TKA are predicted by modifiable factors including habitual movement pattern and asymmetry in quadriceps and hamstrings strength.

Keywords

Total Knee Arthroplasty; Movement Asymmetry; Rehabilitation

Identifying modifiable and non-modifiable predictors of WBA (WBA) following unilateral total knee arthroplasty (TKA) is needed to optimize rehabilitation, especially since WBA is negatively correlated to poor functional performance.¹ Previous investigations have demonstrated that patients move asymmetrically during functional task performance after unilateral TKA.^{2–6} For example, WBA during the sit-to-stand task has been reported at 3,^{2, 3}

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CONFLICT OF INTEREST

None of the authors have a conflict of interest.

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6,⁶ 12,^{4,6} and 16⁷ months after TKA. By identifying predictors of WBA within the first month after TKA during the rehabilitation phase, clinicians can develop targeted interventions to directly impact functional recovery of patients with TKA.

Lower extremity muscle weakness,² impaired quadriceps activation,⁸ pain,⁹ and knee joint motion⁵ are known impairments that potentially relate to WBA for people with unilateral TKA. These impairments are modifiable through targeted interventions. However, the relative strength of association these impairments have with WBA during the rehabilitation phase is not known. For example, pain is positively correlated to WBA for people with unilateral knee OA before TKA¹⁰, but at 16 months after surgery, Boonstra and colleagues⁷ found no association between pain and WBA. Identifying impairments that best predict WBA during the rehabilitation phase will allow for creation of targeted interventions to enhance functional recovery.

Demographics, anthropometrics and movement compensations are mediators beyond physical impairments that potentially predict WBA following TKA. Demographic and anthropometric variables such as female sex,^{11, 12} older age¹² and higher body mass^{12, 13} have each been negatively associated with physical function following TKA. Movement compensations that may mediate WBA following TKA include continuation of habitual movement patterns acquired prior to TKA.⁷ By identifying the best predictors of WBA, clinicians and researchers can develop optimal practices for promoting physical recovery after TKA.

The purpose of this study was to identify factors predictive of WBA during sit-stand transitions for people 1 month following unilateral TKA using regression analysis. Variables representing impairments, demographics, anthropometrics, and movement compensation were included in the regression model. It was hypothesized that quadriceps and hamstrings strength, quadriceps activation, surgical knee pain, active knee motion, age, sex, body mass index (BMI), preoperative WBA and upper extremity support during sit-stand transitions would be significant predictors of WBA for patients 1 month after unilateral TKA.

METHODS

Participants

Fifty-nine people with knee osteoarthritis (OA) (mean (SD), 65.1 (8.6) years) scheduled to undergo unilateral TKA were enrolled in the study. Participants for this analysis were control group subjects from 3 randomized controlled trials who participated in a standard of care rehabilitation protocol from July 2008 to October 2010. Eligible volunteers reported half the level of pain on their non-affected knee compared to their affected knee pre-operatively (numerical pain rating scale (NPRS) of 0–10). Volunteers were excluded if not within the age range of 50 to 85 years or had uncontrolled hypertension, uncontrolled diabetes, BMI > 35 kg/m², neurologic impairment, or other unstable lower-extremity orthopedic problems. Regression analyses were restricted to models small enough to be adequately supported by the existing sample. The (*name blinded*) Review Board approved the study, and written informed consent was obtained from all participants.

Intervention

Within 2 weeks following baseline testing, all participants received a unilateral TKA. Rehabilitation following TKA included acute (2–4 days), home-based (1–2 weeks) and outpatient (1.5–2.5 weeks) phases before a 1 month follow-up testing session. All treatment sessions were performed by licensed physical therapists who were trained to follow a standard rehabilitation protocol previously described.¹⁴

Weight-bearing Asymmetry

Vertical ground reaction force (vGRF) data was obtained from individual force platforms (PASCO Scientific, Roseville, CA) (sampling rate 500 Hz) positioned under each foot of the participant during performance of the Five Times Sit-to-Stand Test (FTSST).¹⁵ The FTSST is a timed test of 5 transitions between sitting and standing. Participants sat on a standard height chair (46 cm) with their feet on each force platform and chair placed according to the participant's selected position. Instructions were to perform the transitions naturally, as quickly and safely as possible. Participants performed one practice trial and two test trials, during which vGRF data were recorded.

Participants were encouraged to not use their hands for support during the test, neither on armrests of the chair or their lower extremities. However, to promote natural movement, participants unable to perform the test without use of hands were allowed use and this was documented. For the analysis, vGRF for each limb was averaged across the five sit-stand transitions and normalized to body mass. The FTSST was performed within 2 weeks prior to and 1 month after TKA. The 1 month time point was chosen because WBA during the FTSST intensifies in the first month following TKA¹ and identifying predictors during this early time period is critical to informing rehabilitation practice.

A weight-bearing ratio^{6, 10} was calculated using the average vGRF data, by dividing surgical limb values by non-surgical limb values to quantify WBA. A weight-bearing ratio equal to 1 represents perfect side-to-side symmetry (equation 1).

$$\text{weight-bearing ratio} = \text{vGRF}_S / \text{vGRF}_{NS} \quad (\text{equation 1})$$

where vGRF_S is the average vGRF under the surgical limb, and vGRF_{NS} is the average vGRF under the non-surgical limb.

Candidate Regressor Variables

Factors identified as candidate variables potentially predicting FTSST WBA 1 month after surgery were peak isometric quadriceps and hamstrings strength, quadriceps and hamstrings strength ratios (surgical/non-surgical), volitional quadriceps activation deficit, self-report surgical knee pain, knee extension motion, knee flexion motion, preoperative WBA, upper extremity support during the FTSST, sex, age, and BMI. (Table 1)

Quadriceps and hamstring strength are known to be impaired following TKA.^{16, 17} Quadriceps weakness following TKA has also been previously related to WBA after TKA. For example, Mizner and Snyder-Mackler² have shown that quadriceps strength 3 months after unilateral TKA is positively correlated with WBA during sit-to-stand task performance. Hamstrings strength was a candidate variable based on the idea that control of the sit-to-stand motion requires co-activation of the knee extensor and flexor muscles as a potential mechanism for stability control after TKA.¹⁸ Additionally, the hamstrings can serve as primary movers for hip extension during sit-stand transitions.

Based on WBA being a comparison between lower limbs, ratios of strength were included as candidate regressor variables in addition to strength deficits on the surgical limb. It has been shown previously that symmetry in quadriceps strength is linked to WBA measures before and after TKA.^{1, 10} While strength and strength symmetry were expected to be similar in ability to predict WBA, the regression analysis would indicate the influence of relative strength between limbs versus absolute strength.

Maximal isometric quadriceps and hamstrings strength was measured with an electromechanical dynamometer (CSMi, Stoughton, MA) with participants seated and stabilized in a position of 85° hip flexion and 60° knee flexion.¹⁷ Each participant performed two warm-up trials of 50–75% maximal effort prior to three maximal effort test trials. Maximal test trial torque normalized to body mass represented quadriceps and hamstrings strength in the analysis. A quadriceps and hamstrings strength limb-to-limb ratio was calculated using the same equation as weight-bearing ratio (equation 1) with the exception of maximal knee extension and flexion torque replacing vGRF.

Quadriceps muscle activation is also a known impairment following TKA.^{8, 16} With direct association to strength, muscle activation was a logical choice as a candidate variable for predicting WBA. Volitional quadriceps activation of the surgical limb was measured during the maximal knee extension torque testing using a doublet-twitch interpolation technique as previously described.¹⁹ A Grass S48 stimulator and Model SIU8T stimulus isolation unit (Grass Instruments, West Warwick, RI) were used to deliver electrical stimuli at rest and during maximal voluntary knee extension through two self-adherent electrodes placed on the proximal and distal quadriceps muscle. A quadriceps activation value of 100% represents full voluntary quadriceps activation with anything less than 100% representing incomplete motor unit recruitment.

Pain and knee motion were selected as candidate variables as they have been linked to physical function for patients with knee OA, before and after TKA.^{5, 9} Self-reported surgical knee pain was quantified by the patients reporting level of pain directly after the FTSST on a verbal numerical pain rating scale (NPRS) (0= no pain, 10= worst possible pain). Maximal knee active extension and flexion motion were measured by a trained tester using a universal manual goniometer while the participant was in supine on an examination table. Details of the goniometric measurement methods have been presented previously.^{1, 10}

Upper extremity support was included in the model because people can compensate to influence lower extremity WBA by loading their upper extremities such as with chair armrests use during sit-stand transitions.²⁰ For example, Houck and colleagues²¹ found compensatory hand use was related to unilateral lower limb unloading during the sit-to-stand task for people after unilateral hip fracture.

The remaining candidate variables considered as potential predictors of WBA were sex, age, and body mass index (BMI). These variables have all been previously identified as predictors of functional limitation following TKA.^{11–13} Sex, age, and BMI were all examined in relation to physical function for patients 2 and 5 years after primary TKA by Singh and colleagues.¹² Those authors found higher BMI, older age, and female sex all had significant negative impact on patient reports of functional performance ability.

The order of tests for the candidate regressor variables is summarized in Table 2.

Statistical Analysis

To identify predictors of WBA 1 month after TKA, a regression analysis was performed. The first step was to individually pre-screen all measured impairment, demographic, anthropometric, and movement compensation candidate variables using correlation coefficients. Only variables significantly correlated with WBA at the 1 month post-operative time point ($\alpha < 0.2$) were included as regressor variables. Models containing all possible subset of the remaining variables were compared based on R^2_{adj} value. The most parsimonious model of the 10 best models was then compared, using partial F-tests, to those of the other 9 models in which the smaller model was nested within the larger. Non-significant tests were interpreted as evidence in favor of the smaller model.

RESULTS

Average WBA during the FTSST was 0.87 (0.15) prior to TKA and 0.69 (0.18) 1 month after surgery, indicating that participants place 13% (preoperatively) and 31% (1 month postoperatively) less weight on the surgical limb than the non-surgical limb. Average vGRF values for the surgical and non-surgical limbs were 190.5 (50.4) N and 224.0 (62.1) N prior to TKA; 164.3 (47.2) N and 245.0 (66.0) N 1 month after TKA, respectively (values are mean (SD)). Outcome data for all candidate regressor variables are listed in Table 1.

The 10 models with highest R^2_{adj} values are listed in Table 3. The resulting “best” model from regression analysis identified preoperative WBA ($\beta = 0.40$), quadriceps strength ratio ($\beta = 0.31$) and hamstrings strength ratio ($\beta = 0.19$) as factors predictive of WBA 1 month after TKA ($R^2_{Adj} = 0.30$).

DISCUSSION

This study found that the best predictor of WBA during the rehabilitation phase after TKA was preoperative WBA. This finding suggests that WBA after TKA is largely due to a habitual compensatory movement pattern carried over from before surgery. In addition, ratios of quadriceps and hamstrings strength between limbs were better predictors of WBA than unilateral strength measures. The implication of this finding is that surgical limb quadriceps and hamstrings strength measures alone are not as important, in terms of WBA, as the degree of disparity of strength between the surgical and non-surgical limbs.

It has been previously suggested that WBA during sit-stand transitions can become chronic (lasting > 1 year post-TKA) due to a subconscious habitual movement compensation resulting from years of volitional unloading of the injured limb prior to TKA intervention.⁷ In the present study, pre-operative WBA was chosen as a candidate regressor variable representing a measure of pre-operative movement compensation. The identification of preoperative WBA as a significant predictor of WBA 1 month after TKA supports the idea that targeted re-training of functional movement symmetry should be considered during physical rehabilitation.

While strength and functional performance training are common components of rehabilitation programs, re-training functional movement symmetry is rarely included as a component of rehabilitation following TKA. However, a few studies have shown movement symmetry re-training to be successful at improving functional outcomes after joint arthroplasty.^{22–24} For example, White and Lifeso²³ demonstrated that biofeedback training with a force plate imbedded treadmill resulted in an equalization of loading impulse between limbs during treadmill walking for people following total hip arthroplasty. In addition, a recent case-report by McClelland and colleagues²² described the effectiveness of a movement retraining protocol used for a patient after unilateral TKA for improving movement symmetry and functional outcomes.

Another unique finding is that the ratios of both quadriceps and hamstring muscle strength were stronger predictors of WBA than unilateral measures. While this finding supports the well accepted practice of targeting strengthening during rehabilitation following TKA,¹⁷ it also suggests that focusing on gaining symmetry while remediating quadriceps and hamstring weakness could enhance current rehabilitation practices for optimizing functional outcomes.

In addition, deficits in voluntary activation of the quadriceps muscle were not predictive of WBA. While impaired voluntary activation after TKA is known to influence quadriceps strength in the surgical limb, it appears to have no influence on WBA during sit-stand

transitions. While not significant as a predictor of sit-stand WBA, activation deficits may play a larger role in activities requiring more dynamic postural control such as transitioning from sitting to walking, pivoting and turning. For example, quadriceps activation has been correlated with performance of dynamic functions such as the Get Up and Go test and tasks reported on the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC).²⁵

Surgical knee pain, knee extension motion, knee flexion motion, age, sex, BMI and upper extremity support during the FTSST were not significant predictors, indicating low or no ability to predict WBA 1 month post-TKA. In terms of pain symptoms, TKA surgery results in significant improvements for several years following surgery.²⁶ While pain has been shown to correlate fairly with WBA in people with unilateral knee OA prior to surgery,¹⁰ studies suggest a weak or absent relationship following surgery.^{1, 7} The current results confirm that pain is not a strong predictor of WBA during sit-stand transitions 1 month after TKA.

The results also demonstrate that maximal knee motion is not a predictor of WBA 1 month after TKA. Lack of knee extension following TKA may be associated with WBA for tasks requiring full extension such as standing.⁵ In the FTSST, the standing phase did not necessitate full knee extension. Likewise, there was no need for maximal knee flexion during the FTSST. Required knee flexion for sitting is approximately 80°³ and in this study, most participants (92%) had greater than 80° of active flexion 1 month after TKA. However, the influence of knee motion on WBA during other functional tasks may be significant. Additionally, constraining foot position during the FTSST may affect the influence knee motion has on WBA. Constraining foot placement limits potential movement compensations and has been shown to result in increased levels of movement asymmetry.³

The final group of candidate regressor variables included demographic (age and sex), anthropometric (BMI), and movement compensation with hand use. It has been shown that age, sex, and body mass are related to physical function after TKA.^{11, 13, 27} The hypothesis that BMI would predict WBA was also based on evidence that BMI is negatively related to knee extensor strength after TKA.²⁸ The lack of finding BMI as a significant predictor of WBA at 1 month may be partially related to the exclusion of BMIs > 35 kg/m². Results could differ for people with BMIs above 35 kg/m². In terms of compensatory upper extremity support during the FTSST, although it was prevalent 1 month after TKA, it was not predictive of WBA. This finding indicates that upper extremity support was not used to decrease WBA as a means of improving sit-stand performance.

Study Limitations

This study examined WBA only during sit-stand transitions. Examining predictors of WBA during activities requiring different levels of lower limb loading, such as overground walking² and stair walking²⁹, is needed to determine predictor variables of other common functional tasks. Also, the $R^2_{Adj} = 0.30$ for the selected regression model indicates that other factors account for WBA at this time point after TKA. Future studies should consider other candidate variables such as rehabilitation method, other compensatory movement patterns, proprioception, and hip strength. Finally, it is important to consider prediction of WBA at time points beyond 1 month post-TKA.

Summary

Habitual asymmetrical movement patterns, quadriceps strength asymmetry, and hamstrings strength asymmetry are predictors of WBA during the rehabilitation phase following unilateral TKA. In addition, all of these predictors are potentially modifiable through

targeted physical interventions. Future work should examine clinical feasibility of assessing WBA using economical, commercially available force measurement devices (e.g., Nintendo Wii® Balance Board or bathroom scales). In addition, targeting habitual movement patterns with innovative methods of biofeedback and achieving symmetry of strength early after TKA should be examined as ways to augment TKA rehabilitation for optimal functional recovery.

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References

- Christiansen CL, Bade MJ, Judd D, Stevens-Lapsley JE. Weight-bearing asymmetry during sit to stand transitions related to impairment and functional mobility after total knee arthroplasty. *Arch Phys Med Rehabil.* 2011; 92:1624–1629. [PubMed: 21839986]
- Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res.* Sep; 2005 23(5):1083–1090. [PubMed: 16140191]
- Farquhar SJ, Kaufman KR, Snyder-Mackler L. Sit-to-stand 3 months after unilateral total knee arthroplasty: comparison of self-selected and constrained conditions. *Gait Posture.* Aug; 2009 30(2): 187–191. [PubMed: 19473843]
- Farquhar SJ, Reisman DS, Snyder-Mackler L. Persistence of altered movement patterns during a sit-to-stand task 1 year following unilateral total knee arthroplasty. *Phys Ther.* May; 2008 88(5):567–579. [PubMed: 18292217]
- Harato K, Nagura T, Matsumoto H, Otani T, Toyama Y, Suda Y. Extension limitation in standing affects weight-bearing asymmetry after unilateral total knee arthroplasty. *J Arthroplasty.* Feb; 2010 25(2):225–229. [PubMed: 19264442]
- Boonstra MC, Schwing PJ, De Waal Malefijt MC, Verdonchot N. Sit-to-stand movement as a performance-based measure for patients with total knee arthroplasty. *Phys Ther.* Feb; 2010 90(2): 149–156. [PubMed: 20007664]
- Boonstra MC, De Waal Malefijt MC, Verdonchot N. How to quantify knee function after total knee arthroplasty? *Knee.* Oct; 2008 15(5):390–395. [PubMed: 18620863]
- Stevens JE, Mizner RL, Snyder-Mackler L. Quadriceps strength and volitional activation before and after total knee arthroplasty for osteoarthritis. *J Orthop Res.* Sep; 2003 21(5):775–779. [PubMed: 12919862]
- Hurwitz DE, Ryals AR, Block JA, Sharma L, Schnitzer TJ, Andriacchi TP. Knee pain and joint loading in subjects with osteoarthritis of the knee. *J Orthop Res.* Jul; 2000 18(4):572–579. [PubMed: 11052493]
- Christiansen CL, Stevens-Lapsley JE. Weight-bearing asymmetry in relation to measures of impairment and functional mobility for people with knee osteoarthritis. *Arch Phys Med Rehabil.* Oct; 2010 91(10):1524–1528. [PubMed: 20875509]
- O'Connor MI. Implant Survival, Knee Function, and Pain Relief After TKA: Are There Differences Between Men and Women? *Clin Orthop Relat Res.* Jan 26.2011
- Singh JA, O'Byrne M, Harmsen S, Lewallen D. Predictors of moderate-severe functional limitation after primary Total Knee Arthroplasty (TKA): 4701 TKAs at 2-years and 2935 TKAs at 5-years. *Osteoarthritis Cartilage.* Apr; 2010 18(4):515–521. [PubMed: 20060950]
- Santaguida PL, Hawker GA, Hudak PL, et al. Patient characteristics affecting the prognosis of total hip and knee joint arthroplasty: a systematic review. *Can J Surg.* Dec; 2008 51(6):428–436. [PubMed: 19057730]
- Stevens-Lapsley JE, Balter JE, Wolfe P, Eckhoff DG, Kohrt WM. Early neuromuscular electrical stimulation to improve quadriceps muscle strength after total knee arthroplasty: a randomized controlled trial. *Phys Ther.* Feb; 2012 92(2):210–226. [PubMed: 22095207]

15. Whitney SL, Wrisley DM, Marchetti GF, Gee MA, Redfern MS, Furman JM. Clinical measurement of sit-to-stand performance in people with balance disorders: validity of data for the Five-Times-Sit-to-Stand Test. *Phys Ther.* Oct; 2005 85(10):1034–1045. [PubMed: 16180952]
16. Mizner RL, Stevens JE, Snyder-Mackler L. Voluntary activation and decreased force production of the quadriceps femoris muscle after total knee arthroplasty. *Phys Ther.* Apr; 2003 83(4):359–365. [PubMed: 12665406]
17. Stevens-Lapsley JE, Balter JE, Kohrt WM, Eckhoff DG. Quadriceps and hamstrings muscle dysfunction after total knee arthroplasty. *Clin Orthop Relat Res.* Sep; 2010 468(9):2460–2468. [PubMed: 20087703]
18. Wang H, Simpson KJ, Ferrara MS, Chamnongkitch S, Kinsey T, Mahoney OM. Biomechanical differences exhibited during sit-to-stand between total knee arthroplasty designs of varying radii. *J Arthroplasty.* Dec; 2006 21(8):1193–1199. [PubMed: 17162181]
19. Mintken PE, Carpenter KJ, Eckhoff D, Kohrt WM, Stevens JE. Early neuromuscular electrical stimulation to optimize quadriceps muscle function following total knee arthroplasty: a case report. *J Orthop Sports Phys Ther.* Jul; 2007 37(7):364–371. [PubMed: 17710905]
20. Arborelius UP, Wretenberg P, Lindberg F. The effects of armrests and high seat heights on lower-limb joint load and muscular activity during sitting and rising. *Ergonomics.* Nov; 1992 35(11):1377–1391. [PubMed: 1425567]
21. Houck J, Kneiss J, Bukata SV, Puzas JE. Analysis of vertical ground reaction force variables during a Sit to Stand task in participants recovering from a hip fracture. *Clin Biomech (Bristol, Avon).* Jun; 2006 21(5):470–476.
22. McClelland J, Zeni J, Haley RM, Snyder-Mackler L. Functional and biomechanical outcomes after using biofeedback for retraining symmetrical movement patterns after total knee arthroplasty: a case report. *J Orthop Sports Phys Ther.* Feb; 2012 42(2):135–144. [PubMed: 22333656]
23. White SC, Lifeso RM. Altering asymmetric limb loading after hip arthroplasty using real-time dynamic feedback when walking. *Arch Phys Med Rehabil.* Oct; 2005 86(10):1958–1963. [PubMed: 16213238]
24. Isakov E. Gait rehabilitation: a new biofeedback device for monitoring and enhancing weight-bearing over the affected lower limb. *Eura Medicophys.* Mar; 2007 43(1):21–26. [PubMed: 17021589]
25. Fitzgerald GK, Piva SR, Irrgang JJ, Bouzubar F, Starz TW. Quadriceps activation failure as a moderator of the relationship between quadriceps strength and physical function in individuals with knee osteoarthritis. *Arthritis Rheum.* Feb 15; 2004 51(1):40–48. [PubMed: 14872454]
26. Rat AC, Guillemin F, Osnowycz G, et al. Total hip or knee replacement for osteoarthritis: mid- and long-term quality of life. *Arthritis Care Res (Hoboken).* Jan 15; 2010 62(1):54–62. [PubMed: 20191491]
27. Singh JA, O'Byrne MM, Harmsen WS, Lewallen DG. Predictors of moderate-severe functional limitation 2 and 5 years after revision total knee arthroplasty. *J Arthroplasty.* Oct; 2010 25(7):1091–1095. 1095 e1091–1094. [PubMed: 20888546]
28. Silva M, Shepherd EF, Jackson WO, Pratt JA, McClung CD, Schmalzried TP. Knee strength after total knee arthroplasty. *J Arthroplasty.* Aug; 2003 18(5):605–611. [PubMed: 12934213]
29. Stacoff A, Kramers-de Quervain IA, Luder G, List R, Stussi E. Ground reaction forces on stairs. Part II: knee implant patients versus normals. *Gait Posture.* Jun; 2007 26(1):48–58. [PubMed: 16979893]

Table 1

Participant Characteristics Included as Candidate Regressor Variables.

Variable	Mean (Standard Deviation)	Correlation with WBR (p-value)
Surgical Limb Quadriceps Strength (Nm/kg)	0.80 (0.33)	0.30 (0.02)
Surgical Limb Hamstring Strength (Nm/kg)	0.51 (0.23)	0.32 (0.01)
Non-Surgical Limb Quadriceps Strength (Nm/kg)	1.64 (0.43)	−0.05 (0.72)
Non-Surgical Limb Hamstring Strength (Nm/kg)	0.86 (0.28)	0.04 (0.75)
Quadriceps Ratio	0.49 (0.20)	0.43 (<0.001)
Hamstrings Ratio	0.60 (0.23)	0.36 (0.001)
Quadriceps Activation (%)	75.4 (19.2)	0.04 (0.80)
Surgical Limb Pain Rating	2.8 (2.0)	−0.08 (0.55)
Knee Extension (°)	96.5 (12.8)	0.08 (0.55)
Knee Flexion (°)	5.2 (5.2)	0.23 (0.09)
Age (years)	65.1 (8.6)	0.22 (0.09)
Sex (% male)	44%	0.07 (0.52)
Body Mass Index (kg/m ²)	28.9 (4.8)	0.04 (0.77)
Preoperative Weight-bearing Ratio	0.86 (0.15)	0.25 (0.05)
Arm Use (% of participants utilizing arms)	83%	−0.11 (0.31)

Correlations for continuous variables are Pearson correlations. Correlations for categorical variables are Kendall's Tau correlations.

Abbreviations: WBR; weight-bearing ratio 1 month after total knee arthroplasty.

Table 2

Testing Order for Candidate Regressor Variables at 1-Month Post-Operative Time Point

Order of Testing (Sequential)	
1	Height & Weight Measures
2	Active Knee Flexion/Extension Range of Motion Measures
3	Five-Times Sit-to-Stand Test *
4	Isometric Hamstrings Strength Testing
5	Isometric Quadriceps Strength and Activation Testing

* Knee pain reported by subject immediately following Five Times Sit-to-Stand test. Vertical ground reaction force measures obtained during the Five Times Sit-to-Stand test.

Table 3

Models Identified as Best Predictors of Weight-bearing Asymmetry 1 Month after Total Knee Arthroplasty

Model	Adjusted R-Square	Number of Variables
WBR ₀ + Age + Hamstrings Ratio + Quadriceps Ratio	0.3024	4
WBR ₀ + Hamstrings Ratio + Quadriceps Ratio	0.2978	3
WBR ₀ + Age + Hamstrings Ratio + Quadriceps Ratio + Surgical Limb Hamstrings Strength	0.2927	5
WBR ₀ + Age + Knee Flexion + Hamstrings Ratio + Quadriceps Ratio	0.2910	5
WBR ₀ + Age + Surgical Limb Hamstrings Strength + Quadriceps Ratio	0.2903	4
WBR ₀ + Age + Surgical Limb Quadriceps Strength + Hamstrings Ratio + Quadriceps Ratio	0.2889	5
WBR ₀ + Knee Flexion + Hamstrings Ratio + Quadriceps Ratio	0.2877	4
WBR ₀ + Surgical Limb Hamstrings Strength + Hamstrings Ratio + Quadriceps Ratio	0.2874	4
WBR ₀ + Age + Surgical Limb Hamstrings Strength + Surgical Limb Quadriceps Strength + Quadriceps Ratio	0.2857	5
WBR ₀ + Surgical Limb Quadriceps Strength + Hamstrings Ratio + Quadriceps Ratio	0.2845	4

Abbreviations: WBR₀: preoperative weight-bearing ratio.