Published in final edited form as:
Knee. 2014 March ; 21(2): 382–386. doi:10.1016/j.knee.2013.10.003.

Preliminary Investigation of Rate of Torque Development Deficits Following Total Knee Arthroplasty

Joshua D. Winters, PhD, CSCS[1], **Cory L. Christiansen, PT, PhD**[1], and **Jennifer E. Stevens-Lapsley, PT, PhD**[1]

[1]Physical Therapy Program, Department of Physical Medicine and Rehabilitation, University of Colorado

Abstract

Background—To assess changes in maximal strength and rate of torque development (RTD) following TKA, and examine the relationships between these measures and physical function.

Methods—Thirty-five TKA patients and 23 controls completed isometric knee extensor torque testing preoperatively, 1, and 6 months after surgery. Maximal strength was calculated as the peak torque during a maximal voluntary isometric contraction (MVIC) of the knee extensor muscles, peak RTD (RTD_{peak}) was calculated as the maximum value from the 1st derivative of the isometric knee extension torque data, $RTD_{25\%}$ and RTD $_{50\%}$ were calculated as the change in force over the change in time from force onset to 25% and 50% MVIC. Physical function was measured using a timed-up-and-go (TUG) and stair climbing test (SCT).

Results—RTD was significantly lower in the TKA group, at all-time points, compared to the Controls. MVIC and RTD significantly decreased 1-month following surgery ($p=0.000$ for all measures). RTD_{peak} measures added to linear regressions with strength improved the prediction of TUG scores ($p=0.006$) and the SCT scores ($p=0.015$) 1-month post-surgery. Adding $RTD_{50\%}$ to the regression model, following MVIC, improved predicting both TUG ($p=0.033$) and SCT ($p=0.024$). At 6-months, the addition of $RTD_{25\%}$ to the regression model, following MVIC, improved the prediction of TUG ($p=0.037$) and SCT ($p=0.036$).

Conclusion—Following TKA, physical function is influenced by both the maximal strength and the rate of torque development of the knee extensors, and the prediction of function is improved with the addition of RTD compared to that of maximal strength alone.

Keywords

Total knee arthroplasty; rate of force development; physical function; strength

Introduction

Knee OA is the leading cause of disability among older adults [1] often resulting in total knee arthroplasty (TKA). TKA is one of the most common elective surgical procedures

Corresponding Author: Joshua D. Winters, Post-doctoral fellow, UCD Physical Therapy Program, Mail Stop C244, 13121 East 17th Avenue, Aurora, CO 80045, Office: 303-724-9590, Fax: 303-724-9016, joshua.winters@ucdenver.edu.

Conflict of Interest Statement: The authors of this manuscript have no conflicts of interest to declare.

performed in older adults with over 600,000 performed each year; costing approximately $9 billion/year.[2] Evaluating the effectiveness of TKA surgery is often based upon patient-centered outcome measures, such as pain and physical function following surgery.[3] These outcomes are reliant not only upon surgery-related factors such as surgery technique and surgeon experience/skill, but also by rapidly regaining functional independence through an active physical rehabilitation process.[3] Current rehabilitation efforts focus on improving surgical outcomes with an emphasis on strengthening the knee extensors. This rehabilitation approach often results in significant functional improvement, but is often not sufficient to restore performance to that of healthy older adults.[4] Deficits in both strength and physical function exist prior to TKA and become significantly worse 1 month after surgery, often returning to preoperative levels 6 months following surgery.[5] Yet, while physical function returns to preoperative levels following TKA, function rarely returns to levels of healthy older adults. Deficits persist in tasks such as rising to standing and climbing stairs.[4]

While knee extensor strength is a key component, the speed of a muscle contraction, also has an important influence on physical function. Many aspects of physical function are dependent not only on strength, but also the speed with which force is developed (e.g. crossing a street or climbing stairs quickly). Studies are beginning to demonstrate the link between rapid force generation and functional task performance capabilities. [6-8] As such, older adults with mobility limitations have reduced ability to produce muscle force rapidly compared to healthy adults of similar age.[8] People with hip OA exhibit deficits in rapid knee extensor force generation that are larger than deficits in maximum knee extensor strength. [9] Three months following TKA, significant deficits in the rapid development of knee extensor force have been reported. [10] In addition, asymmetries in rapid knee extensor force generation between surgical and nonsurgical legs correlate to self-reported measures of function more strongly than the knee extensor strength asymmetries. [11] Identifying the inability to rapidly generate force, or torque, as a key factor associated with physical function would have important implications for rehabilitation strategies designed to optimize functional recovery following TKA.

Long term functional deficits persist following TKA [4, 12] and indicate that current rehabilitation practices are not sufficient in restoring function to levels similar to that of healthy older adults. The importance of rapid torque generation in function and disability has prompted the development of exercise programs with a focus on improving the ability to rapidly generate torque in older adults [6], yet following TKA, muscle strengthening is still commonly recommended without emphasis on the rate of torque development (RTD). Impaired rate of torque development of the knee extensors is a modifiable risk factor for diminished functional recovery following surgery that could be addressed with appropriate rehabilitation. Therefore, the purpose of this study was to assess maximal knee extensor strength and rate of torque development preoperatively, 1, and 6 months following TKA and 1) examine changes in maximal knee extensor strength and RTD following TKA, and compared to that of healthy older adults, 2) examine the correlation between knee extensor RTD and muscle activation deficits following TKA, and 3) determine if knee extensor RTD contributes to a timed-up-and-go (TUG) and stair climbing time (SCT) beyond that of knee extensor strength alone.

Methods

Subjects

Patients following TKA were retrospectively identified from 2 previous studies. [13, 14] Both studies were approved by the Colorado Multiple Institutional Review Board and informed consents were obtained from all subjects prior to participating in either of the 2 studies. Patients with TKA from the control groups for each trial were included in the TKA group for this secondary analysis focused on rate of torque development. All patients had a primary unilateral TKA secondary to knee osteoarthritis and participated in a standardized rehabilitation programs following surgery as previously described. [14] Exclusion criteria were similar, but not identical for both studies; [13, 14] both studies previously sought to recruit a patient population with unilateral OA, with minor differences in age and BMI targets. Exclusion criteria included uncontrolled hypertension, uncontrolled diabetes, significant neurologic impairments, contralateral knee OA (as defined by pain greater than 4/10 with activity), or other unstable lower-extremity orthopedic conditions. Patients were included in this study if they were between 45 and 85 years of age, had a body mass index > 40 kg/m^2, and underwent a tri-compartmental, cemented TKA with a medial parapatellar surgical approach. Rate of torque development was obtained from all control group participants who were able to perform a rapid maximal isometric contraction of the quadriceps. Subjects that could not produce a rapid maximal contraction, experienced technical difficulties during the data collection, or did not have a stable resting baseline prior to force initiation were excluded from this analysis. In addition, a cohort of healthy adults was recruited from the community and informed consent was obtained from each participant. The healthy control group subjects had no history of hip or knee osteoarthritis or joint replacement and were of similar age to the TKA subjects.

Knee extensor strength, rate of force development, and activation

Maximal strength was calculated as the peak torque measured during a maximal voluntary isometric contraction (MVIC) of the knee extensor muscles, rate of torque development (RTD), and activation of the knee extensors were assessed at the preoperative, 1-month and 6-month post-surgery testing sessions. A HUMAC NORM (CSMi, Stoughton, Massachusetts) electromechanical dynamometer was used to measure knee extensor muscle torque. Data were collected with a Biopac Data Acquisition System (BIOPAC Systems Inc, Goleta, California) and AcqKnowledge software, version 3.8.2 (BIOPAC Systems Inc). Subjects were positioned in an electromechanical dynamometer with 60 degrees of knee flexion. Subjects were asked to perform a maximal voluntary isometric contraction (MVIC) of the knee extensors using both visual and verbal feedback up to 3 times unless the first 2 attempts were within 5% of each other. The trial with the steepest linear rise in force from rest was then used for data analysis. Peak RTD (RTD_{peak}) was calculated for the surgical limb as the maximum value from the 1st derivative of the isometric knee extension torque data. RTD was also calculated as the change in force over the change in time from force onset to 25% MVIC ($RTD_{25\%}$) and 50% MVIC ($RTD_{50\%}$). [15] The torque onset was calculated as the point above 1.25 N (~2% of the average MVIC for the lowest testing point, which was 1 month post-surgery).

Activation was assessed using methods described in previous research. [16] Briefly, a two pulse (doublet) with a 10ms interpulse interval, supramaximal electrical stimulus was delivered to the muscle during a maximal voluntary isometric contraction (MVIC) of the quadriceps and again to the muscle at rest. In the absence of central activation deficits, no increase in muscle force is measured when the stimulus is delivered. Central activation of the knee extensors was quantified using the ratio of the force produced with resting and superimposed stimuli as previously described. [14]

Measures of Physical Function

The timed-up-and-go (TUG) measures the time it takes to rise from a chair, walk 3 meters, turn around and return to a seated position in the chair. [17] Subjects began seated with their feet on the floor and began the test upon the investigator's command. Subjects were permitted to use the arms of the chair for support during rising and sitting if needed. The faster of two trials was used for analysis. The TUG has excellent test-retest reliability and is commonly used to measure functional ability in older adults. [17] Stair climbing time (SCT) evaluates an individual's ability to ascend and descend a set of twelve steps. The steps were 18 cm high with a depth of 28 cm. Subjects were asked to ascend, turn around, and then descend the steps as quickly as possible in a safe manner. The handrail was available for use if needed. The faster of two trials recorded on a stopwatch to the nearest one hundredth of a second was used. A similar SCT was shown to have excellent test-retest reliability after TKA. [18-20]

Statistical Analysis

All statistical analyses were performed using IBM SPSS statistics for Windows, version 21 (IBM corp, Armonk, NY). Independent samples t-tests were used to asses differences between the TKA patients and control subjects in MVIC and RTD preoperatively, 1, and 6 months following TKA. Linear mixed models were used to analyze within subject differences for the repeated measures variables of MVIC, RTD_{peak}, $RTD_{25\%}$, and $RTD_{50\%}$ for the TKA group. Linear mixed models were chosen for this analysis to avoid the listwise deletion of patients from the entire analysis who did not have complete data sets. Post-hoc pairwise comparisons were performed using Bonferroni corrections to protect against a Type I statistical error. In the TKA group, hierarchical linear regressions were used to examine whether RTD provided a significant additional contribution to the explanation of the variability in TUG and SCT after accounting for the influence of MVIC. In hierarchical regression, variable(s) that are known to explain the variance in the dependent measure are added to the model first, in this case strength. [21] When additional variables are added to the model, the change in r^2 (Δr^2) is reported. If the Δr^2 is significant, then that variable is said to explain a unique portion of the variability in the dependent variable, after having accounted for the previous variable(s) entered in the model. Pearson correlation coefficients were used to investigate the MVIC and RTD relationships with activation, TUG, and SCT at each time point in the TKA group. Tolerance and variance inflation factor statistics were used to examine collinearity between MVIC and RTD measures during the regression analyses. For all tests, statistical significance was set at $p=0.05$. Bonferroni corrections were used to adjust the p-values from the multiple pairwise comparisons.

Results

Between and within group differences in RTD and MVIC

Thirty-five patients with TKA (19 females and 16 males; 63.6 ± 7.9 years of age) and 23 healthy controls (11 females and 12 males 65.6 ± 9.4 years of age) were included in the analysis. Independent samples t-tests revealed significant differences between the TKA and Control groups in both MVIC and RTD measures at all-time points (Figure 1). Linear mixed models showed a significant influence of time on MVIC in the TKA group ($p<0.001$). Bonferoni post-hoc tests revealed that MVIC significantly decreased 1-month following surgery ($p<0.001$), but at 6 months, was similar to preoperative levels. RTD_{peak}, $RTD_{25\%}$, and $RTD_{50\%}$ were also significantly influenced by time in the TKA group [($p<0.001$, $p<0.001$, $p<0.001$, respectively), (Figure 1)]. Bonnferroni post hoc tests revealed similar patterns as that of MVIC, with significant RTD decreases 1-month following surgery ($p<0.001$) returning to preoperative levels 6-months post-surgery (Figure 1).

RTD and MVIC correlations with function

Significant correlations were found between 1) MVIC and functional performance (TUG and SCT) and 2) all RTD variables and functional performance at each of the 3 assessment time intervals (Table 1). Activation correlated with MVIC and all RTD measures prior to surgery and 1-month post-operatively with the exception of $RTD_{50\%}$. Six months following surgery, activation did not correlate with MVIC or any of the RTD measures (Table 1).

Hierarchical regressions predicting function using MVIC and RTD

Hierarchical linear regressions (Figure 2), with strength entered into the model first followed by RTD_{pk} showed significant improvements in the prediction of TUG scores ($\Delta r^2 = 0.15$, p=0.006) and the SCT scores ($\Delta r^2 = 0.12$, p=0.015) 1-month post-surgery. Adding $RTD_{50\%}$ to the regression model following MVIC also significantly improved the prediction of both TUG scores ($\Delta r^2 = 0.10$, p=0.033) and the SCT scores ($\Delta r^2 = 0.097$, p=0.024) 1-month post-surgery. Though MVIC significantly correlated with both RTD_{peak} and $RTD_{50\%}$ (r=0.549, p=0.001 and r=0.527, p<0.0001) collinearity statistics were within an acceptable range to safely assume collinearity did not significantly influence either regression model (Tolerance=.699, .606 and VIF=1.431, 1.646 respectively).[21]

At 6-months following TKA, hierarchical linear regressions with strength entered into the model first followed by RTD_{peak} did not significantly improve the prediction of TUG scores ($\Delta r^2 = 0.067$, p=0.093) and the SCT scores ($\Delta r^2 = 0.074$, p=0.085). However, $RTD_{25\%}$ added to the regression model, following MVIC, did significantly improve the prediction of both TUG scores ($\Delta r^2 = 0.101$, p=0.037) and the SCT scores ($\Delta r^2 = 0.107$, p=0.036) 6-months after TKA. (Figure 2) At 6-months after TKA, MVIC significantly correlated with both RTD_{peak} and $RTD_{25\%}$ (r=0.595, p<0.001 and r=0.641, p<0.001) but collinearity statistics were within an acceptable range to safely assume collinearity did not significantly influence either regression model (Tolerance=.646, .590 and VIF=1.549, 1.696 respectively).[21]

Discussion

This investigation sought to examine deficits in the rate of knee extensor torque production following TKA. Results revealed significant changes in both maximal strength and the rate of torque development of the knee extensorss following TKA that significantly correlated with functional performance levels. Though both MVIC and RTD returned to preoperative values 6-months following surgery, they remained significantly lower than that of healthy controls (Figure 1). Activation levels significantly correlated to both MVIC and RTD preoperatively and 1-month post-surgery but these correlations became non-significant 6-months post-surgery. MVIC and RTD measures significantly correlated to physical performance measures (SCT and TUG). RTD significantly improved predicting physical function, beyond that of MVIC alone, 1-month and 6-months following surgery. These findings suggest that not only are substantial deficits in maximal strength of the quadriceps present after TKA, but significant deficits in quadriceps ability to rapidly generate torque also exist. Furthermore, these deficits in rapid torque development significantly contribute to functional performance capabilities beyond the contributions of maximal strength alone.

Deficits in both maximal strength and rate of torque development (RTD_{peak}, $RTD_{25\%}$, and $RTD_{50\%}$) of the knee extensors were found for the involved limb 1-month post-surgery and returned to preoperative levels 6-months following TKA. (Figure 1) Similar trends in maximal knee extensor strength deficits have been previously reported in patients who have undergone TKA. [5] [4] Though both maximal strength and rate of torque development values returned to preoperative values 6-months following surgery, they remain significantly lower than that of healthy controls. Patients undergoing TKA often have functional deficits prior to surgery; therefore, restoring function to that of previous, impaired preoperative levels should not be considered a successful outcome.

Altered neuromuscular activation has been implicated in muscle weakness following TKA with activation deficits of 17% from preoperative levels.[22] Both maximal strength and rate of torque development deficits reported 1-month after TKA in this study correlated with the subject's ability to maximally activate the knee extensors, but this relationship diminished over time (Table 1). One possible explanation for this is that activation deficits resolve by 6 months. [14, 23] Rapid torque generation is influenced by neural mechanisms (rate coding and recruitment strategies) [24] as well as muscle characteristics such as fiber type composition and muscle-tendon stiffness. [25, 26] It is possible that neural rate coding deficits, decreased initial firing rates, and or muscle characteristic changes, not assessed during the doublet interpolation assessment of quadriceps activation, exist and significantly influence deficits in the ability to rapidly generate torque following surgery. Further examination is needed to determine the specific neural and muscular mechanisms associated with deficits in the rate of torque development following surgery and their association with persisting long term functional performance deficits associated with TKA.

The ability of patients to rapidly generate torque was significantly associated with measures of physical function prior to and following surgery. Both MVIC and RTD measures significantly correlated to SCT and TUG preoperatively, 1 and 6 months following surgery. Similar deficits in functional performance and maximal strength have been previously reported in following TKA. [10] It is well understood and widely accepted that maximal strength significantly influences physical function following TKA. The observation that, at 6-months after surgery, RTD measures had stronger correlations with SCT and TUG than maximal strength further emphasize the significant role rapid torque generation has in successful functional recovery following surgery.

Rapid torque generation appears to have a strong relationship with physical functional performance measures independent of maximal strength. The regression model predicting TUG and SCT scores 1-month post-surgery with maximum strength was significantly improved with the addition of rate of torque development (RTD_{peak} or $RTD_{50\%}$). Though, RTD_{peak} did not improve the prediction of TUG and SCT 6 months following surgery, $RTD_{25\%}$ significantly improved the prediction of both TUG and SCT scores beyond that of strength alone. These results demonstrate the importance of the ability to rapidly generate torque during basic physical function such as stair climbing, not only immediately following surgery, but when functional recovery plateaus months after surgery. Current rehabilitative programs, focusing on knee extensor strength, return patients to preoperative functional levels, but rarely to levels comparable to healthy age-matched individuals. Therefore, incorporating strategies to promote rapid force generation along with strength might further improve physical function beyond that of functional levels prior to surgery.

Patient's ability to rapidly generate torque through relatively lower levels of torque production (from 25%-50% MVIC) significantly correlated to TUG and SCT measures independent of maximal strength 1 and 6 months following surgery. Though the RTD measures that significantly improved predicting function were different at 1-month ($RTD_{50\%}$) than at 6-months post-surgery ($RTD_{25\%}$) they both represent rapid torque generation during lower levels of torque production, during time intervals that are more consistent with those required for functional activities. In fact, the time needed to reach maximal strength, approximately 300ms [24], is much longer than the time required to perform many functional activities or respond to a perturbation in an attempt to prevent a fall. With patients following TKA being at a greater risk of falling, improving RTD may need to be an important focus of rehabilitation.

There were a few limitations to this study. Subjects for this study were chosen retrospectively from previous studies focusing on different types of rehabilitation interventions. Yet, a strength of this data set is that patients with TKA were all control subjects from previous studies, receiving standard rehabilitation following unilateral TKA. Lastly, further analysis is needed to 1) verify the role of RTD during function with a larger sample of patients following TKA, 2) examine surgical and nonsurgical lower extremity

RTD asymmetries within this group and 3) determine if relationships between these possible limb asymmetries influence function.

In conclusion, physical fucntion following TKA is influenced by not only the *maximal* torque generating capacity of the muscle but also by the ability to *rapidly* generate torque. It has been previously reported and is well understood that increased strength of the knee extensors is associated with improved functional recovery following TKA, and rehabilitation programs that emphasize strengthening of the knee extensors results in better functional performance than the standard of care.[20] But physical function does not return to levels of that of healthy adults, therefore, it is likely that strength is not the only aspect of muscle function involved. Following TKA, significant deficits in rate of torque development exist and rate of torque development significantly improves predicting function compared to maximal strength alone for up to 6 months following surgery. These results suggest the importance of designing rehabilitative interventions that encompass all aspects of muscle function and are aimed at improving neural and muscle characteristics associated with rapid torque generation as well as maximal strength for patients following TKA.

Acknowledgments

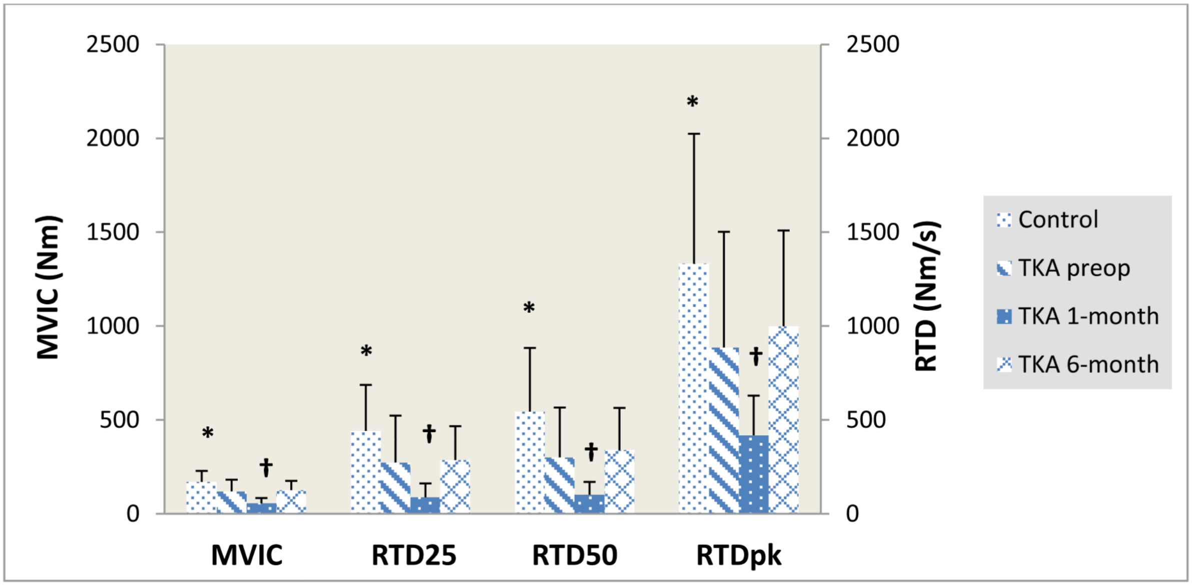
Support for this study was provided by the National Institutes of Health (R01-HD065900; and K23-AG029978), the Foundation for Physical Therapy and the Foundation for Physical Medicine & Rehabilitation. Sponsors had no role in the study design; in the collection, analysis and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication.

Grant Support: NIH RO1-HD065900

References

1. CDC. Prevalence and Most Common Causes of Disability Among Adults: United States, 2005. MMWR Weekly. 2009:421–426.
2. Cram P, et al. Total knee arthroplasty volume, utilization, and outcomes among Medicare beneficiaries, 1991-2010. JAMA. 2012; 308(12):1227–36. [PubMed: 23011713]
3. Jones CA, et al. Total joint arthroplasties: current concepts of patient outcomes after surgery. Rheum Dis Clin North Am. 2007; 33(1):71–86. [PubMed: 17367693]
4. Bade MJ, Kohrt WM, Stevens-Lapsley JE. Outcomes before and after total knee arthroplasty compared to healthy adults. J Orthop Sports Phys Ther. 2010; 40(9):559–67. [PubMed: 20710093]
5. Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. J Orthop Sports Phys Ther. 2005; 35(7):424–36. [PubMed: 16108583]
6. Orr R, et al. Power training improves balance in healthy older adults. J Gerontol A Biol Sci Med Sci. 2006; 61(1):78–85. [PubMed: 16456197]
7. Perry MC, et al. Strength, power output and symmetry of leg muscles: effect of age and history of falling. Eur J Appl Physiol. 2007; 100(5):553–61. [PubMed: 16847676]
8. Puthoff ML, Nielsen DH. Relationships among impairments in lower-extremity strength and power, functional limitations, and disability in older adults. Phys Ther. 2007; 87(10):1334–47. [PubMed: 17684086]
9. Suetta C, et al. Muscle size, neuromuscular activation, and rapid force characteristics in elderly men and women: effects of unilateral long-term disuse due to hip-osteoarthritis. J Appl Physiol. 2007; 102(3):942–8. [PubMed: 17122381]
10. Vahtrik D, et al. Quadriceps femoris muscle function prior and after total knee arthroplasty in women with knee osteoarthritis. Knee Surg Sports Traumatol Arthrosc. 2012; 20(10):2017–25. [PubMed: 22139408]
11. Maffiuletti NA, et al. Asymmetry in quadriceps rate of force development as a functional outcome measure in TKA. Clin Orthop Relat Res. 2010; 468(1):191–8. [PubMed: 19597897]

12. Walsh M, et al. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. Phys Ther. 1998; 78(3):248–58. [PubMed: 9520970]
13. Dayton MR, et al. Minimally Invasive Total Knee Arthroplasty: Surgical Implications for Recovery. J Knee Surg. 2012
14. Stevens-Lapsley JE, et al. Early neuromuscular electrical stimulation to improve quadriceps muscle strength after total knee arthroplasty: a randomized controlled trial. Phys Ther. 2012; 92(2):210–26. [PubMed: 22095207]
15. Angelozzi M, et al. Rate of force development as an adjunctive outcome measure for return-to-sport decisions after anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2012; 42(9):772–80. [PubMed: 22814219]
16. Stevens-Lapsley JE, et al. Relationship between intensity of quadriceps muscle neuromuscular electrical stimulation and strength recovery after total knee arthroplasty. Phys Ther. 2012; 92(9): 1187–96. [PubMed: 22652985]
17. Podsiadlo D, Richardson S. The timed “Up & Go” a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc. 1991; 39(2):142–8. [PubMed: 1991946]
18. Rejeski WJ, et al. Assessing performance-related disability in patients with knee osteoarthritis. Osteoarthritis Cartilage. 1995; 3(3):157–67. [PubMed: 8581745]
19. 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. 2005; 23(5):1083–90. [PubMed: 16140191]
20. Petterson SC, et al. Improved function from progressive strengthening interventions after total knee arthroplasty: a randomized clinical trial with an imbedded prospective cohort. Arthritis Rheum. 2009; 61(2):174–83. [PubMed: 19177542]
21. Field, AP. Discovering statistics using SPSS : (and sex, drugs and rock ‘n’ roll). 3rd. Los Angeles: SAGE Publications; 2009. p. xxxii821
22. Stevens JE, Mizner RL, Snyder-Mackler L. Quadriceps strength and volitional activation before and after total knee arthroplasty for osteoarthritis. J Orthop Res. 2003; 21(5):775–9. [PubMed: 12919862]
23. Meier WA, et al. The long-term contribution of muscle activation and muscle size to quadriceps weakness following total knee arthroplasty. J Geriatr Phys Ther. 2009; 32(2):79–82. [PubMed: 20039587]
24. Aagaard P, et al. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol. 2002; 93(4):1318–26. [PubMed: 12235031]
25. Parmiggiani F, Stein RB. Nonlinear summation of contractions in cat muscles. II. Later facilitation and stiffness changes. J Gen Physiol. 1981; 78(3):295–311. [PubMed: 7328404]
26. Andersen LL, et al. Early and late rate of force development: differential adaptive responses to resistance training? Scand J Med Sci Sports. 2010; 20(1):e162–9. [PubMed: 19793220]



* Represents significant differences between Control subjects and TKA patients at preop, 1-month and 6-months post -surgery

† Represents significant deficits for patients with TKA at 1-month post-surgery compared to preop and 6- months

Figure 1. MVIC and RTD Measures at each Assessment Time Period

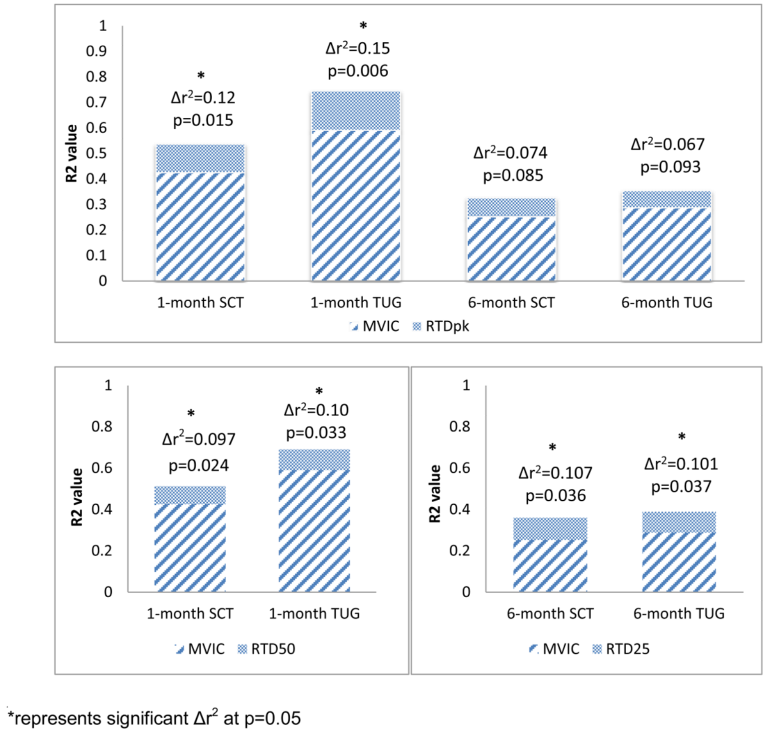


Figure 2. Hierarchical Regression analysis of Function entering MVIC followed by RTD Measures

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table 1
MVIC & RTD Correlations with Functional Performance

Variable	Max Torque	RTD25	RTD50	RTDpk
Preoperative				
TUG	r=-0.516, p=0 .002*	r=-0.440, p=0 .009*	r=-0.443, p=0 .009*	r=-0.460, p=0 .006*
SCT	r=-0.490, p=0 .004*	r=-0.397, p=0 .022*	r=-0.408, p=0 .018*	r=-0.439, p=0. 011*
Activation	r=0.632, p<0.0001*	r=0.522, p=0 .002*	r=0.582, p<0.0001*	r=0.557, p=0 .001*
1-month post-surgery				
TUG	r=-0.591, p<0.0001*	r=-0.416, p=0 .020*	r=-0.616 p<0.0001*	r=-0.652, p<0.0001*
SCT	r=-0.652, p<0.0001*	r=-0.488, p=0 .005*	r=-0.651, p<0.0001*	r=-0.638, p<0.0001*
Activation	r=0.450, p=0 .014*	r=0.371, p=0 .047*	r=0.348, p=0 .065	r=0.388, p=0 .038*
6-month post-surgery				
TUG	r=-0.536, p=0 .002*	r=-0.588, p=0 .000*	r=-0.526, p=0 .002*	r=-0.528, p=0 .002*
SCT	r=-0.502, p=0 .003*	r=-0.573, p=0 .001*	r=-0.539, p=0 .001*	r=-0.518, p=0 .002*
Activation	r=0.353, p=0 .061	r=0.311, p=0 .101	r=0.366, p=0 .051	r=0.311, p=0 .101

*represents significance at p<0.05