Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty

Ryan L. Mizner, Lynn Snyder-Mackler *

Department of Physical Therapy, University of Delaware, 301 McKinly Laboratory, Newark, DE 19716, United States

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Abstract

Purpose: Total knee arthroplasty (TKA) successfully reduces pain, but has not achieved comparable improvements in function. We hypothesized that quadriceps strength affects performance by altering loading and movement patterns during functional tasks.

Methods: Fourteen subjects with isolated, unilateral TKA were tested three months after surgery. Quadriceps strength was assessed isometrically and kinematics, kinetics, and EMG were collected during level walking and sit-to-stand (STS). Function was assessed using the timed up and go test (TUG), stair climbing test (SCT), and the 6 min walk test (6MW).

Results: Functional performance was significantly related to the quadriceps strength of both legs, but was more strongly related to the uninvolved strength (involved rho = -0.43 with TUG; -0.65 with SCT; 0.64 with 6MW) (uninvolved rho = -0.63 with TUG; -0.68 with SCT; 0.77 with 6MW). During STS, subjects shifted weight away from the operated limb (p < 0.01). Quadriceps muscle activity and the extension moments at the knee and hip were smaller in the involved compared to the uninvolved (p < 0.05). The amount of asymmetry in knee excursion during weight acceptance in gait, the asymmetry in weight bearing from sit-to-stand, and the uninvolved hip extension moment during STS were related to the amount of asymmetry in quadriceps strength (rho > 0.56, p < 0.05).

Conclusions: Quadriceps weakness in patients with TKA has a substantial impact on the movement patterns and performance of the knee during functionally important tasks.

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Keywords: Total knee replacement; Muscle; Compensation; Strength; Function

Introduction

Total knee arthroplasty (TKA) is one of the most common knee surgeries performed in the United States with an incidence (300,000 per year) greater than twice the incidence of anterior cruciate ligament reconstruction [1]. TKA reliably reduces knee pain [10,16], but has not been shown to lead to comparable improvements in functional performance. Reductions of about 20% in walking speed and 50% in stair climbing speed compared to age-matched groups without knee pathology have been reported a year after surgery [32].

Patients with TKA exhibit qualitative and quantitative deficits in functional tasks. Shortened stride length and limited knee excursion during weight acceptance is a common finding after TKA [3,4,6,7,11,17,33]. Patients with TKA rise from a chair more slowly than control groups and use higher hip and knee moments in the uninvolved leg compared to the involved leg to stand [31]. The involved knee and hip joints also perform proportionally less work than the uninvolved while negotiating a curb [5]. Even patients considered to be fully rehabilitated with excellent self-assessment scores have smaller sagittal plane knee ranges of motion, angular
velocities, and maximum knee moments in the operated limb during loaded knee extension than control subjects during stair climbing and chair transfers [14,33].

The cause of persistent disability and aberrant movement patterns in individuals who have undergone TKA is unclear, but quadriceps weakness is a likely contributor. Quadriceps weakness is a common and persistent impairment after TKA and has been correlated with poor functional performance in older adults [8,23]. Weakness is often pronounced even years after knee replacement surgery with deficits ranging from 30% to 40% when compared to age-matched comparison groups [3,11,20,25,32]. Impaired quadriceps strength would appear to be a prime factor to consider when examining disability after TKA.

The impact of strength on function and movement patterns has gone unexamined in patients with TKA. Several investigations have suggested that movement strategies used during functional tasks are due to quadriceps weakness, but they stop short of measuring this impairment [5,14,31]. To date, only three studies have included quadriceps strength assessment in conjunction with a motion analysis assessment for patients with TKA [4,29,33], but they did not report the relationship between quadriceps weakness and altered movement patterns.

The purpose of this investigation was to determine the relationship between quadriceps weakness and function after TKA when patients are discharged from outpatient rehabilitation. We hypothesized that (1) quadriceps muscle strength (peak torque) will show a (high) positive correlation with functional outcomes measures, (2) knee flexion at heel strike in gait would be higher and knee excursion during weight acceptance would be less in the involved leg compared to the uninvolved, (3) knee moments will be lower in the involved compared to the uninvolved leg during the weight acceptance phase of gait and sit-to-stand (STS) and hip moments will be lower in the involved lower extremity compared to the uninvolved during sit-to-stand, and (4) the amount of symmetry between legs in quadriceps strength will be strongly and positively correlated with the amount of symmetry in knee flexion during weight acceptance in gait, symmetry in vertical ground reaction force in standing, and the distribution of lower extremity extension moments in standing.

Methods

Subjects

The study included fourteen subjects (9 men, 5 women) who had undergone TKA for osteoarthritis three months prior to testing (Table 1). Patients were referred by a group of local orthopedic surgeons who performed tricompartmental, cemented total knee arthroplasty with a medial parapatellar surgical approach. Subjects were excluded from the study if they had uncontrolled blood pressure, diabetes mellitus, neoplasms, neurological disorders, or a body mass index (weight in kg/(height in m)²) of greater than 40 (morbidly obese). In addition, subjects were excluded if they required an assistive device to walk or if they could not stand from a chair independently without the use of arm rests. The uninvolved leg was required to be asymptomatic and the operated leg could have no more than a 5° flexion contracture and an active flexion range of motion greater than 100°.

All subjects underwent three days of inpatient physical therapy followed by two to three weeks of home physical therapy visits. Subjects received six weeks (2-3 times/week, mean = 17 visits) of outpatient physical therapy. Physical therapy included interventions designed to control pain and swelling, and improve knee range of motion, muscle strength and functional ability [19]. Motion analysis testing

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<td>Quadriceps index (QI)</td>
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BMI = body mass index, ROM = range of motion, NMVIC = normalized maximal voluntary isometric contraction. Quadriceps Index (QI) = peak torque of involved quadriceps/peak torque of uninvolved quadriceps, N = newtons, m = meters, deg = degrees, s = seconds. Gait speed refers to the speed during the motion analysis collection.
was performed within a week of strength testing. The Human Subjects Review Board of the University of Delaware approved the study and all subjects gave written informed consent.

**Functional testing**

Measures of functional performance included the timed up and go (TUG) test, a stair climbing test (SCT), and the 6-min walk (6MW) test. The TUG measures the time it takes a patient to rise from an armless chair (seat height of 46 cm), walk 3 m, turn and return to sitting in the same chair [28]. Subjects were asked to walk as quickly as they felt safe and comfortable. The subject was allowed to use the arms of the chair to stand up and sit down. The SCT measures the time it takes a subject to ascend and descend a flight of twelve, seven inch high steps with a depth of eleven inches. Subjects were asked to complete the test as quickly as they felt safe and comfortable and one handrail was allowed if required. For both the TUG and SCT, one practice test was performed and the average of two subsequent tests was used for analysis. For the 6MW test, subjects were asked to cover as much distance as possible in 6 min while walking laps 516 ft long in a 10 ft wide tiled hallway. Feedback on the time remaining for the test was given at two, four and five minutes into the 6 min test. Assistive devices were not used to complete all tests and all subjects used a foot over foot technique to go up and down the stairs.

**Quadriiceps strength testing**

Maximal voluntary isometric contraction (MVIC) of the quadriceps femoris was assessed with a burst superimposition technique [30]. In brief, subjects were seated in an electromechanical dynamometer (Kin-Com 500 H, Kin Com, Chattanooga Corporation, Harrison, Tennessee) with the hip flexed to 90° and the knee flexed to 75°. Subjects performed two submaximal contractions and one maximal isometric contraction of 2-3 s in duration to familiarize the patient with the testing method.

After 5 min of rest, subjects were instructed to maximally contract the quadriceps for a contraction lasting approximately 3 s. Verbal encouragement and visual output of their force was used to provide feedback to help facilitate the highest force possible. Approximately 2 s into the contraction, the stimulator (Grass S8800 stimulator with a Grass model SIU8T stimulus isolation unit, Grass Instruments, Braintree, Massachusetts), delivered a supramaximal electrical stimulus to the quadriceps muscle. If maximum volitional force output was achieved and no augmentation of force was observed due to the stimulation (i.e. optimal recruitment) then the testing session was concluded for that leg. If augmentation was present during the application of the electrical stimulus, the test was repeated. Five minutes of rest was provided between test contractions. A maximum of three trials were recorded. The highest volitional torque achieved during the three attempts was used for analysis. Burst superimposition testing was performed on uninvolved limb first and then the operated leg. The burst superimposition technique has been shown to be highly reliable in subjects without knee pathology, with repeated testing that demonstrated an intraclass correlation coefficient of 0.98 [27].

**Pain measurement**

A numeric rating scale was used to quantify knee pain during the MVIC and the motion analysis collection. Subjects were asked to verbally rate knee pain during the contraction on a scale from zero to ten where zero represented no pain and ten represented the worst pain imaginable. Numeric rating scales were appropriate for repetitive knee pain assessments in this study as they can be completed quickly and easily and have demonstrated good reliability in arthritic populations [9].

**Motion analysis**

Motion analysis testing of walking and a sit-to-stand (STS) task was performed using a three dimensional, six camera motion analysis system (VICON 512, MCam cameras, Workstation 512 with software version 3.7 build 074, Oxford Metrics, London, England). Two force plates (Bertec Corp, Worthington, OH) were positioned in the floor to capture two successive steps during walking and to assess the ground reaction forces for each leg during sit-to-stand transfers. Force plate data were acquired at 1080 Hz and kinematic data were sampled at 120 Hz. Retro reflective anatomical markers (25 mm in diameter) were placed bilaterally on the head of the fifth metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter, iliac crest, acromioclavicular joints, and centrally on the 7th cervical vertebrae. Rigid, thermoplastic shells with four markers affixed to their surfaces were attached bilaterally to the lower leg and thigh using elastic wraps (SuperWrap™, Fabricaom, Inc. Exton, PA) to minimize movement artifact. Another four-marker shell used to track the trunk was affixed to the skin midline at approximately the level of the 8th thoracic vertebrae through the use of double sided tape. A shell with a triad of markers was placed over the sacrum to track the motion of the pelvis. Two markers were placed on the heel counter of the shoe and with the marker on the 5th metatarsal provide a triad of markers to track the three dimensional movement of the foot. Each body segment was assumed to be rigid.

A standing calibration was performed prior to the walking trials and the sit-to-stand trials to identify joint centers with respect to each segment coordinate system. Prior to STS collections, subjects were positioned in the center of the calibrated volume and had warm-up trials on one leg in a backless chair with their trunk oriented vertically. The height of the chair was set to the height of the subject’s knee joint line. The subjects were asked to hold the arms across the chest to standardize arm position and prevent the upper extremities from blocking markers during the collection. The subject was positioned on the chair so that the feet were shoulder width apart and a long-arm goniometer was placed under the back to allow for consistent reproduction for each trial. The subjects stood from the chair at a self-selected pace. One practice trial was used to confirm understanding of verbal instructions and the mean of five trials were used for analysis.

Upon the completion of the STS collections, the subjects practiced walking trials until they walked at a consistent self-selected walking pace. Gait trials were continuously collected until the subject had 10 trials with only one foot on each force plate and speed was maintained within 5% of practice speed.

**Electromyography**

Electromyography (EMG) was recorded at 1080 Hz with a 16-channel system (Motion Lab Systems, Baton Rouge, LA) interfaced with the VICON 512 (Vicon, Oxford Metrics, London, UK) for simultaneous recording. Active surface electrodes were taped over the mid-muscle belly of the vastus lateralis, biceps femoris, the anterior tibialis, the medial head of the gastrocnemius, the soleus. Elastic bands (SuperWrap™, Fabricaom, Inc., Exton, PA) were wrapped over the electrodes to minimize movement on the skin. The subject was positioned on a padded plinth in order to isometrically test the quadriceps, hamstrings, gastrocnemius, anterior tibialis [15] for verification of electrode placement and for normalization. Maximal soleus activity was tested in a seated position with the knees flexed.

**Data management and analysis**

The torque produced during strength assessment was normalized to body mass index. A quadriceps index (QI) was determined to give a relative measure of strength and as a measure of symmetry in quadriceps force production between limbs (quadriceps index (QI) = involved torque/uninvolved torque × 100%).

Marker trajectories from the motion analysis collection were low pass filtered at 6 Hz and force plate data was low passed filtered at 40 Hz [2] with a recursive fourth order Butterworth digital filter. Sagittal plane hip, knee and ankle joint angles were calculated using rigid body analysis (Visual3D, Version 2.94, C-Motion, Inc., Notre Dame, MD). Joint kinetics were calculated using inverse dynamics, and are expressed as net internal moments normalized to body mass and height. In walking, each trial’s stance time was normalized to 100% of weight acceptance defined as the time from heel strike to peak knee flexion. In STS, each trial’s standing time was normalized from the
start of standing (defined as the initiation of hip flexion) to the end of stand (defined as when hip angular velocity reached zero). Trials within a testing session were averaged to obtain a mean for each subject.

The signal for the EMG data was pre-amplified at the skin and then band pass filtered from 20 to 1000 Hz with mechanical filters prior to sampling at 1080 Hz. Visual 3D software was used to digitally filter the signals with a low pass filter at 20 Hz. Following full wave rectification, a linear envelope of the signal was created using a phase corrected filter with a low pass cutoff frequency of 20 Hz. This linear envelope was normalized to the maximum signal obtained during the MVIC trials or during dynamic contractions during the walking or STS trials. The integral of the quadriceps activity during the loading response during walking and during sit-to-stand was used for analysis.

Nonparametric tests were used for analysis to reduce the threat of outliers inaccurately skewing the findings of the investigation. Differences in means between limbs in strength, peak joint moments, peak flexion angles, peak vertical ground reaction force during STS, and normalized, integrated EMG activity were analyzed with Wilcoxon Sign Rank tests. Spearman Correlation Coefficients were used to analyze the strength of relationships between the factors of interest in this study. The first specific relationship of interest was between peak quadriceps torque during strength testing and functional performance during the TUG, SCT, and 6MW. The relationship between normalized, integrated quadriceps muscle activity and peak knee flexion during weight acceptance and the ratio of the involved over the uninvolved vertical ground reaction force during standing was also analyzed. Finally, the relationship between the degree of symmetry in quadriceps strength (i.e. quadriceps index) and the symmetry between limbs in knee excursion in weight acceptance and vertical ground reaction force during STS was analyzed. An alpha level of 0.05 was chosen for significance.

Results

The involved quadriceps muscles were weaker (65%) than the uninvolved (p < 0.01) (Table 1). Two subjects had mild knee pain during quadriceps strength assessment (1/10 and 2/10). One subject reported mild discomfort (2/10) on the lateral aspect of the involved knee during STS trials. Quadriceps strength in the involved leg correlated negatively with the time to complete the SCT (rho = -0.65, p < 0.01), positively with the distance traveled on the 6MW (rho = 0.64, p < 0.01), but it did not significantly correlate with the time to complete the TUG (rho = -0.43, p = 0.12). Quadriceps strength in the uninvolved leg was correlated negatively with the time to complete the SCT (rho = -0.68, p < 0.01), positively with the distance traveled on the 6MW (rho = 0.77, p < 0.01), and had a significant negative correlation with the time to complete the TUG (rho = -0.63, p = 0.02). Functional performance in all tests was more strongly correlated to the uninvolved quadriceps strength than the involved quadriceps strength for all tests.

During walking, there was no significant difference in the knee flexion angle at heel strike between legs (p = 0.10) (Fig. 1). The average peak knee flexion angle during weight acceptance was significantly lower in the involved limb than the uninvolved leg (p = 0.02) (Fig. 1). Correspondingly, knee excursion during weight acceptance was also significantly lower in the involved limb (p < 0.01) (Fig. 1). Despite less knee flexion in gait, the peak knee extension moment for the involved knee was not different from the extension moment in the uninvolved knee (p = 0.43) (Fig. 1). There were no significant differences in the normalized EMG integrals between the quadriceps muscles (p = 0.67) (Fig. 1). The ratio of the involved leg's knee excursion over the uninvolved leg's knee excursion in weight acceptance was correlated to the QI (r = 0.70, p < 0.01) (Fig. 2).

For the STS assessment, there were no significant differences in the peak flexion angles of the hip (involved =
96 ± 9.3°, uninvolved = 96 ± 8.1° (p = 0.64), knee (involved = 83 ± 5.4°, uninvolved = 85 ± 4.3°) (p = 0.11), or ankle joints (involved = 11 ± 3.3°, uninvolved = 13 ± 4.0°) (p = 0.06) between legs. The average peak vertical ground reaction forces were lower (14% less than uninvolved) in the involved leg (514 ± 81 N) compared to the uninvolved (599 ± 89 N) (p < 0.01). All subjects, except the subject with the highest peak involved quadriceps muscle torque, had a lower peak vertical ground reaction force in the involved leg compared to the uninvolved. The ratio of the involved over the uninvolved vertical ground reaction force was correlated with quadriceps index (r = 0.56, p = 0.04).

The involved leg’s average peak hip (p < 0.01) and knee moments (p < 0.01) were significantly lower than the uninvolved leg while the peak ankle moments were not significantly different between legs (p = 0.98) (Fig. 3). The vastus lateralis (p < 0.01) had significantly smaller integrals of EMG activity in the involved leg compared to the uninvolved during STS (Fig. 4). The remaining muscles did not have significantly different integrals between limbs (p > 0.17) (Fig. 4). The peak knee torque of the involved quadriceps correlated with the peak involved knee moment (r = 0.60, p < 0.02) during STS. The QI correlated negatively with the involved hip moment (r = −0.61, p = 0.02) (Fig. 5); the more symmetrical subjects were in quadriceps strength the more symmetrical they were in the distribution of moments between hips.

Discussion

The hypotheses that quadriceps strength correlates to functional performance with altered loading and movement patterns in weight bearing activities were supported by the data. At three months after surgery, patients with TKA exhibited pronounced weakness in the involved quadriceps muscles typical of the patient population. Functional performance was significantly related to the quadriceps strength of both legs, but was more strongly related to the uninvolved quadriceps strength. Asymmetry in quadriceps strength was correlated to asymmetry in knee excursion during the weight acceptance phase of gait. Subject's had lower normalized quadriceps EMG activity as well as smaller extension moments at the knee and hip during STS.
Those individuals with weaker quadriceps used the uninvolved limb as a compensation to complete the function tasks. Compensations were particularly evident in the bilateral support task of STS. Increasing the involved leg’s strength should improve loading symmetry between limbs with a corresponding improvement in the functional performance of patients with TKA. Reliance on the uninvolved leg to compensate for the involved leg during functional tasks could help to explain the persistent quadriceps weakness present in this population. Not only did the involved leg have lower peak torque production during strength assessment, but the subjects performed the STS task with relatively lower levels of quadriceps muscle recruitment. Less loading and lower muscle activity in the involved leg may be limiting the stress to the involved limb’s musculature to the point that the quadriceps are not stressed enough to provide a stimulus for strength gain [21].

The movement pattern used during STS has potential ramifications for exercise prescription for patients with.
TKA. An exercise prescription that stresses bilateral activities (e.g. leg press) may not provide an overload for inducing gains in strength. Any exercise that uses both legs provides an opportunity for the uninvolved limb to compensate for weakness in the involved limb. Incorporating unilateral exercises (e.g. seated knee extension) in a strengthening program after TKA may enhance quadriceps strength gains in this population as it isolates the limb and prevents potential compensations for weakness.

Depending on the uninvolved limb to accomplish functional tasks may have considerable long-term consequences. Shakoor and colleagues found in patients who undergo unilateral knee replacement, the contralateral knee joint was the most common second joint to undergo replacement [24]. In patients with osteoarthritis for whom the second joint replacement was the hip, the contralateral side was more than twice as likely to be replaced as the ipsilateral side. In contrast, the evolution of subsequent hip joint replacement in patients with rheumatoid arthritis was random and no laterality was observed. The authors remarked that absence of such laterality in patients with rheumatoid arthritis suggests that osteoarthritis progression may be mediated by extrinsic factors such as altered joint loading. The unequal distribution in loading related to involved quadriceps weakness in this study may help explain the nonrandom nature of subsequent hip and knee joint replacements after primary unilateral TKA. The impact of quadriceps weakness on the wear of the prosthesis and progression of osteoarthritis in the uninvolved lower extremity merits further investigation.

While our inclusion criteria were selective, virtually all other studies of kinetics and kinematics of walking, rising from a chair and stair climbing have demonstrated similar movement patterns as we are reporting despite widely varying inclusion and exclusion criteria [4,11,14,26,29,31,33]. While it is unclear from the present study how the movement patterns and relationships described in this investigation may change over time, other studies suggest our findings are quite robust. A cross-sectional study examining a control population, people with knee OA awaiting TKA surgery, and people after TKA would suggest that compensations during sit-to-stand were present prior to surgery [31]. Prospective studies also suggest that movement patterns after TKA are influenced by preoperative patterns [26]. Patients with TKA continue to make significant improvements in quadriceps strength after three month assessments [20,22]. The differences between limbs in this investigation may lessen as quadriceps strength between limbs becomes more symmetrical, but the influence of weakness on movement patterns would remain as patients have exhibited significant differences in quadriceps strength between limbs even years after surgery [12].

Knee pain is another factor common to patients with knee osteoarthritis that can influence joint loading and movement patterns of the knee [13]. Preoperative knee pain could have contributed to habitual movement patterns that persist after knee replacement. The small (2/10) knee pain in only one subject during the testing, however, suggests that knee pain did not affect performance in this sample at three months after TKA. While pain reduction after TKA has been shown to relate to improved walking performance [18], simply eliminating pain and providing good range of motion, as in this study, was not sufficient to restore normal symmetrical knee and hip kinetics and kinematics.

Quadriceps weakness is a significant impairment that plays an important role in functional outcomes after TKA. Subjects with TKA adopted a strategy of movement which allows the uninvolved limb to compensate for involved quadriceps weakness during functional tasks as opposed to a potential alternate strategy of increasing the recruitment of the involved quadriceps. Quadriceps strength influenced lower extremity loading in a way that could alter the wear of the prosthesis and progression of osteoarthritis in the major weight-bearing joints of the lower extremity. Better outcomes in the involved quadriceps strength may result in a more balanced distribution of load between limbs.

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References


