Published in final edited form as:

Clin Biomech (Bristol, Avon). 2015 January ; 30(1): 78–85. doi:10.1016/j.clinbiomech.2014.11.001.

RELATIONSHIP BETWEEN BIOMECHANICAL ASYMMETRIES DURING A STEP UP AND OVER TASK AND STAIR CLIMBING AFTER TOTAL KNEE ARTHROPLASTY

Federico Pozzi, PT, MA¹, Lynn Snyder-Mackler, PT, ScD¹, and Joseph Zeni Jr., MSPT, PhD¹

¹Department of Physical Therapy, University of Delaware, Newark, DE, USA

Abstract

Background—Patients six months after total knee arthroplasty demonstrate movement asymmetries and functional deficits, which may be related to poor functional performance. The aims of this study were to 1) compare biomechanical variables between subjects 6 months after total knee arthroplasty and an age-matched healthy control group during a step up and over task and 2) determine the relationship between quadriceps strength, movement patterns and stair climbing performance.

Methods—Twenty patients 6 months following unilateral total knee arthroplasty and twenty healthy controls were enrolled. Participants completed questionnaires, isometric quadriceps strength testing and performance based tests to quantify functional performance. Motion analysis was performed during a step up and over task. Functional and biomechanical variables were analyzed using a 2×2 ANOVA. The symmetry ratios (operated/non-operated limb *100) for biomechanical variables were analyzed using independent t-tests. Pearson correlations were performed to determine the relationships between biomechanical variables, strength and stair climbing performance.

Findings—In the TKA group, subjects had lower peak moments, power and sagittal plane excursion in the operated knee compared to the contralateral knee ($p < .05$), while the hip on the operated side had greater power generation ($p = .014$). Compared to the control group, all symmetry ratios were significantly lower in the surgical group ($p < .05$). Stair climbing time was correlated with quadriceps strength of the operated limb ($R = -0.762$, $p < 0.001$).

Interpretation—Individuals 6 months after total knee arthroplasty had worse performance with respect to biomechanics, quadriceps strength, and performance-based tests. Biomechanical asymmetries after TKA reduce the demand on the operated knee and increase reliance on the contralateral limb and ipsilateral hip.

© 2014 Elsevier Ltd. All rights reserved.

Please address all correspondence to: Joseph Zeni Jr., Department of Physical Therapy, University of Delaware, 540 S College Avenue, Suite 210Z, Newark, DE 19713, Phone: (302) 831-4263, jzenijr@udel.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

Osteoarthritis is characterized by joint pain, stiffness and functional impairments that affect walking, stair climbing and other activities of daily living (Felson et al. 2000). Osteoarthritis most commonly affects the knee joint (Felson et al. 2000) and currently total knee arthroplasty (TKA) is the most common and effective surgical procedure to manage the pain and symptoms associated with the disease (Jacobs et al. 2008). Before TKA, patients walk and climb stairs with asymmetrical movement patterns that reduce reliance on the affected joints, most likely a reflection of the pain and weakness in the symptomatic knee joint (Zeni & Higginson 2009; Zeni & Higginson 2011; Mandeville et al. 2007). Although pain is largely resolved after TKA (Loughead et al. 2008), unilateral strength deficits and movement asymmetries persist, even several years after TKA (Walsh et al. 1998; Zeni & Snyder-Mackler 2010; Alnahdi et al. 2011).

After TKA, movement abnormalities may affect the integrity of both the operated and non-operated lower extremity joints. These individuals continue to have less joint excursion and higher dynamic stiffness in the operated knee (McGinnis et al. 2013), greater load on the non-operated knee (Alnahdi et al. 2011) and rely on the hip to maintain support of the body during dynamic activities (Yoshida et al. 2008; Mandeville et al. 2007). The movement asymmetries that overload the uninvolved limb and ipsilateral hip correspond to the pattern of osteoarthritis progression in other lower extremity joints. Following a primary TKA, 35% of patients undergo a secondary joint arthroplasty to replace the contralateral knee (92%) or the contralateral hip (8%) (Shakoor et al. 2002). Although the biomechanical overloading patterns follow the pattern of OA progression, it should be noted that no longitudinal study has evaluated this mechanism of cartilage wear after the initial TKA.

While over ground walking is commonly used to identify these movement abnormalities, individuals perform a diverse range of functional activities on a daily basis, including stair and curb ascent and descent. The external knee flexor moment, which is countered by the quadriceps to avoid the collapse of the body, is 2.3 times greater during stair ascent when compared with over ground walking (Mandeville et al. 2007). In-vivo analyses of joint compression forces after TKA revealed that stair ascent and descent increase compression forces by 60% compared to over ground walking (D'Lima et al. 2011). These findings suggest that stair ascent and descent are more muscular demanding tasks than walking over ground. Stair ascent and descent is particularly challenging for individuals after TKA (Zeni & Snyder-Mackler 2010; Boutron et al. 2003), which may be a direct result of movement abnormalities that are exacerbated by these more demanding tasks. Therefore, biomechanical analyses that evaluate more demanding dynamic tasks are needed because they may better discriminate between patients' persistent movement abnormalities and underlying impairments and normal patterns of control individuals without joint pathologies.

During a step up and over task, individuals are required to step onto a box with one limb (stepping limb), traverse across the box while clearing the toe and foot of the trailing limb, and land with the contralateral limb (landing limb). This task mimics the functional demands (upward propulsion and downward energy absorption) of stair climbing and curb negotiation and has been used to evaluate outcomes after other knee joint surgeries (Rudolph & Snyder-

Mackler 2004; Rudolph et al. 1998; Lin et al. 2010). The purpose of this study was twofold. First, we compared kinematic and kinetic variables between patients 6 months after TKA and age-matched control subjects without joint pathology during the step up and over task. Second, we evaluated the relationship between quadriceps strength in the operated limb, biomechanical patterns during the step up and over task, and stair climbing performance.

We hypothesized that patients in the TKA group would demonstrate interlimb movement asymmetries and would present with altered knee and hip joints loads compared to the control group. We further hypothesized that quadriceps weakness and lower joint moments in the operated knee during the step up and over task would be related to worse performance on a stair climbing task.

Methods

Participants

Twenty patients following unilateral TKA and twenty healthy controls were enrolled in the study. The study was approved by the Human Subjects Review Board and each participant signed an informed consent before starting any component of the study. Patients in the TKA group were recruited 6 months after the surgery as most of the patients have completed the prescribed course of post-operative rehabilitation at this time point. Patients between the age of 50 and 85 years were recruited from a local group of orthopaedic surgeons, through advertisements in the local newspaper, and flyers on the university campus and at the local senior and rehabilitation centers. No participants were receiving routine orthopaedic care for the operated limb at this time. Participants were excluded if they had: 1) surgery in the lower extremities (other than the unilateral TKA for the TKA group); 2) knee pain greater than 4 out of 10 on a verbal analog scale in the non-operated knee (TKA group) or either knee (control group); 3) neuromuscular, cardiovascular, and/or musculoskeletal impairments that limited physical function; 4) uncontrolled blood pressure; 5) reported altered sensation (tingling or numbness) in their feet; or 6) body mass index greater than 50. Subjects participated in two days of testing that were scheduled at least 24 hours apart, but within 7 days of each other. The first day consisted of functional testing and the second day consisted of biomechanical testing.

Procedures

Functional Testing—All participants completed a battery of questionnaires and clinical tests to quantify the functional status of each group. Participants completed the Knee Outcome Survey - Activity of Daily Living (KOS-ADL) scale, which includes 14 questions about the participant's ability to perform activities of daily living. The total score is calculated as a percentage, in which higher scores indicate better functional ability. This questionnaire is a valid and responsive measure for patients with knee pathology (Marx et al. 2001; Irrgang et al. 1998). This scale was calculated for each leg, separately. Participants also performed three performance-based tests: the Timed Up and Go (TUG), Stair Climbing Test (SCT) and Six Minute Walk (6MW). For the TUG, participants stood up from a chair without using the armrests, walked as fast as possible for a distance of 3m, turned around, and returned back to sit in the original chair. Time started on the investigator's command

and stopped when the participants were fully seated in the chair (Piva et al. 2004). For the SCT, participants ascended and descended a set of 12 steps (15cm rise, 20cm run). Participants were instructed to perform the test “as fast as possible while still remaining safe”. If needed, participants were allowed to use one hand-rail for balance, but participants were not allowed to skip steps. The use of handrail and the pattern of stair ascent and descent (step over step or step-to patterns) were recorded. Time started on the investigator’s command and stopped when the participants touched the ground with both feet after the last step (Kennedy et al. 2005; Nightingale et al. 2014). For the 6MW, participants were asked to walk as far as they could for 6 minutes along a 115 m squared hallway. Participants were informed when they reached the second, fourth and fifth minutes. Running was not permitted. Participants were allowed to rest, if needed, but time was not stopped during rest (Kennedy et al. 2005). These performance-based tests are recommended for inclusion in clinical studies of patients with knee OA (Dobson et al. 2013).

Maximal voluntary isometric strength for the quadriceps muscle was measured using an electromechanical dynamometer (Kin-Com, Chattex Inc., Chattanooga, TN, USA) (Mizner et al. 2005). Participants were secured to the dynamometer with the knee positioned at 75° of flexion. Two submaximal contractions (50% and 75%) and one maximal contraction (100%) were completed to familiarize participants with the protocol and to warm-up. After one minute rest, three maximal contractions were performed with one minute of rest between contractions to avoid fatigue. Pain was assessed during isometric strength testing using a 0 to 10 scale where 0 represented no pain and 10 was the worse pain imaginable. Force data were recorded in Newton using a force transducer located at the distal anterior tibia two centimeters proximal to the lateral malleolus. Data were collected at 200Hz using custom Labview software (National Instrument, Austin, TX, USA). The lever arm of the resistance (distance between axis of rotation and transducer) was not collected for all patients; therefore, torque data were not calculated to avoid excessive missing data. We believe that the differences between groups for the lever arm distance would be negligible considering the similarity in height between groups. Data were acquired from each knee and were normalized to body mass (Kg) for the analysis.

Biomechanical Testing—The following anatomical measure were taken using a caliper: 1) pelvis depth, from anterior superior iliac spine to posterior superior iliac spine; 2) knee width, from medial to lateral femoral condyle; 3) ankle width, from medial to lateral malleolus; and 4) foot width, from the 1st to the 5th head of the metatarsal bone. Retro-reflective markers were placed bilaterally on the iliac crest, greater trochanter, lateral femoral condyle, lateral malleolus, head of the 5th metatarsal, and two markers on the heel. Four rigid thermoplastic shells with four markers were used to track the movement of the thigh and shank; one thermoplastic shell with three markers was used to track the pelvis. An 8-camera three-dimensional motion capture system (Vicon, Oxford Metrics, London, UK) was used to track marker position at 120Hz. The capture volume was 1.2m wide, 1.5m long, and 2.3m high. Two force plates (Bertec Corp., Worthington, OH, USA) were used to collect force data at 1080Hz.

Motion analysis was performed as participants stepped up and over a wooden step (31.5 cm length, 43.5 cm width, and 20.5 cm height) that was screwed into one force plate via a flat

metal footing positioned on each side of the step (Rudolph et al. 1998; Rudolph & Snyder-Mackler 2004; Lin et al. 2010). The height of the point of contact of the force plate was then adjusted in the data acquisition software to account for the height of the step. Participants started the motion by standing 5 cm behind the wooden step with their feet shoulder width apart. Participants were instructed to step onto the box with one limb (stepping limb), traverse over the step to clear the swinging limb, land on the force plate in front of the wooden step with the contralateral limb (landing limb), and keep walking (Figure 1). The landing limb did not come to rest on the top of the box. Both limbs were tested and five trials using each limb as the stepping and landing limb were collected.

Prior to testing, the step up and over task was described and demonstrated to each participant. Participants were then asked if they felt they could safely perform the activity. If the answer was no, participants were not allowed to perform the test. If the answer was yes, they were allowed to perform two practice trials. During the practice, the investigator stood close to the participant to assess safety and provide support if needed. After practice, participants were asked again whether they felt confident performing the activity without close supervision. If the answer was “no” or if participants required support from the investigator during the test, they were not allowed to perform the test. Participants were also excluded from the test if the investigator deemed the activity unsafe (i.e., participant lost his or her balance or was not able to perform the task as described by the investigator). This decision was based on the clinical judgment of the graduate student who was leading the data collection session and had a clinical background in physical therapy.

Visual3D software (C-Motion Inc., Germantown, MD, USA) was used for kinematic and inverse dynamic analyses. A standing calibration trial was taken to identify joint centers and create the segment coordinate systems. During the calibration, participants were positioned with the medial/lateral axis of the knee, ankle, and foot parallel to the horizontal axis of the lab coordinate system (X). To define the knee joint center, a virtual medial marker was created based on the position of the real marker placed on the lateral femur condyle. The virtual marker was offset on the X lab coordinate system direction based on the joint width, which was measured with a caliper. The same procedure was employed to define a virtual marker on the medial malleolus and head of the 1st metatarsal bone. Real and virtual markers were then used to determine joint centers and create the segment coordinate system. Marker trajectories were low-pass filtered at 6Hz. Force data were filtered at 40Hz using a second-order phase corrected Butterworth filter. Joint angles for the ankle, knee, and hip joints were calculated using Euler X-Y-Z sequence corresponding to sagittal, frontal, and transverse rotations sequence. Kinematic and kinetic data were calculated for both limbs. Joint moments and power were normalized by body mass. All moments are reported as external moments.

The data of the stance phase for the stepping and landing limb were time normalized to 100% of stance for each limb. The time series curves for the stepping and landing limb were visually inspected to check for consistency during landing. After an analysis of the knee power curve (Appendix A/B), the task was divided into functional intervals. The stepping portion of the task was divided in two intervals (Figure 1): 1) from initial contact on the box to 60% of stance, the time at which the knee of the stepping limb generated energy to propel

the center of mass up onto the step (propulsive phase); and 2) from 60% of the stance phase to toe-off from the box, the time at which the knee of the stepping limb absorbed energy during the descent of the center of mass (lowering phase). For the landing limb, only one phase was evaluated; this was the interval between initial contact and 25% of stance and was considered the weight acceptance phase (Figure 1). During this interval, the landing limb provides a stable support for the level transition and contributes to absorbing the energy generated during the descent of the center of mass.

The execution speed of the step up and over task was measured by calculating the first derivative of the trajectory of a marker placed on the pelvis shell. For each limb, speed was averaged during the interval between initial contact of the stepping limb and toe-off of the landing limb. Biomechanical variables included peak sagittal knee moment and peak knee power, which were calculated at each interval for the stepping (propulsive and lowering phases) and landing limbs (weight acceptance phase). Peak hip power was calculated for the stepping limb during the propulsive and lowering phases. Sagittal knee angle was calculated at initial contact of the landing limb and knee flexion excursion, peak ground reaction force, and loading rate (peak ground reaction force/time to peak) were calculated during weight acceptance. Knee excursion was calculated as knee angle at initial contact of weight acceptance subtracted from the peak knee flexion angle during weight acceptance. All variables were calculated in each trial and the means were used for data analysis.

Data Analysis

In the control group, one of the limbs was randomly assigned as the surgical limb using a coin flip. Age, height, weight, BMI and scores from the performance-based tests were compared between groups using independent sample t-tests. A preliminary analysis revealed the absence of significant limb*group interaction or limb main effect for speed. Therefore, speed was averaged across limbs and compared between groups using an independent sample t-test. Quadriceps strength, KOS-ADL scores and biomechanical variables from each limb were compared between limbs and groups using individual 2×2 ANOVAs for each variable with one repeated measure (limb). A significant interaction effect in the ANOVA indicated that limb symmetry was different between groups. Follow-up paired and independent t-tests were used to determine interlimb and group differences, respectively.

Mean differences between groups for the operated and non-operated limbs were calculated as (Control - TKA), where positive values indicate higher values in the control group and negative values indicated higher values in the TKA group. Percent differences between groups were calculated as (Control - TKA)/(Control), where positive values indicate higher values in the control group and negative values indicated higher values in the TKA group.

The symmetry ratio was calculated as percentage where the operated limb was divided by the non-operated limb. This symmetry ratio was calculated for any kinetic variables of the stepping limbs that were significantly different between limbs. Values less than 100 indicate that the operated limb had lower values, while values greater than 100 indicate that the non-operated limb had higher values. Values of 100 indicate perfect symmetry. Symmetry ratios were compared between TKA and control groups using independent sample t-tests. This metric becomes extremely variable when values approach zero. During the landing phase,

several of the biomechanical variables approached zero. For this reason, the symmetry ratio was not calculated for biomechanical variables during the landing phase.

In the TKA group, bivariate correlations were performed to determine the relationship between SCT, strength and biomechanical variables obtained during the propulsive and lowering phases of the step up and over test. All analyses were performed using SPSS (IBM, v.20). Significance level was set at 0.05.

Results

Participant Characteristics

Data from one participant in the control group was not usable due to missing tracking markers. Therefore, 20 participants in the TKA group and 19 participants in the control group were used in the analysis. There were no differences between groups for age and height, but the TKA group was 16% heavier ($P = 0.039$) and had a BMI that was 15% greater than the control group ($P = 0.008$) (Table 1). The leg randomization in the control group produced higher number of right surgical limb (13 vs. 7) compared to the TKA group ($P = 0.036$). Participants in the control group executed the step up and over significantly faster compared to the TKA group (mean difference 0.09 m/s, $P = 0.019$).

Clinical tests

Individuals in the TKA group took 2.04 seconds (33%) longer to complete the TUG ($P < 0.001$) and 3.94 seconds (41%) longer to complete the SCT ($P < 0.001$) compared to the control group. All participants in both groups performed the SCT with a step-over-step pattern. Four participants in the TKA group and three participants in the control group required the use of a handrail to perform the SCT. Participants in the TKA group also walked 107.5 m (16%) less during the 6MW ($P < 0.001$) when compared to the control group (Table 1).

Significant limb*group interactions were found for KOS-ADL ($P = 0.028$), and quadriceps strength ($P < 0.001$). In the TKA group, KOS-ADL was 15% greater ($P = 0.018$) in the non-operated limb compared to the operated limb (Table 2). There was no difference between limbs for the KOS-ADL in the control group ($P = 0.777$). Moreover, KOS-ADL scores in the operated limb and non-operated limb were 19% and 8% lower in the TKA group compared to the control group ($P = 0.002$ and $P = 0.026$, Table 3). Quadriceps strength was 18% higher in the non-operated limb compared to the operated limb in the TKA group ($P = 0.007$). There was a small, but significant difference in quadriceps strength between limbs in the control group ($P = 0.02$). The operated limb of the TKA group was significantly weaker than the operated limb of the control group (30.6% weaker, $P = 0.001$), but there was no difference between groups in the quadriceps strength on the non-operated limb ($P = 0.182$). No subjects in both TKA and control groups reported pain during quadriceps strength testing.

Motion Analysis

The time series curves for hip and knee biomechanics of the stepping and landing limbs are reported in Appendix A and B. On the stepping limb, significant limb*group interactions were found for peak sagittal knee moment and power during the propulsive phase ($P < .001$ for both) and lowering phase ($P < .001$ and $P = 0.003$, respectively). Significant limb*group interactions were also found for peak hip power during the propulsive phase ($P = 0.029$) and the lowering phase ($P = 0.048$). On the landing limb during the weight acceptance phase, significant limb*group interactions were found for peak vertical GRF ($P = 0.027$), sagittal knee angle at initial contact ($P = 0.037$), sagittal knee excursion ($P < 0.001$), and peak sagittal knee power ($P = 0.002$). Follow-up paired t-tests revealed that all of these biomechanical variables were significantly different between limbs in the TKA group, but there were no differences between limbs in the control group (Table 2).

When comparing values for the operated and non-operated limbs between groups, the TKA group had significantly lower peak sagittal knee moments and peak knee power during all phases of the step up and over task compared to the control group for the operated limb (Table 3). During the lowering phase, the peak power absorption at the hip joint was 35% greater in the operated limb of the TKA group compared to the hip of the control group ($P = 0.019$). Lastly, the operated limb of the TKA group had 38% less knee excursion during weight acceptance compared to the control group ($P < 0.001$). The largest differences between groups for the operated limb were seen during the landing phase, where the control group had peak knee moments that were 42.6% greater and peak knee power absorption that was 58.1% greater than the TKA group (Table 3).

When comparing symmetry ratios for the stepping limb during the propulsive and lowering phases between the TKA and control groups, all variables were significantly different with the exception of peak hip power during the lowering phase (Figure 2). For the TKA group, all symmetry ratios were less than 100 (operated limb was less than the non-operated limb), with the exception of peak hip power during the propulsive phase, which was 123.9% (SD 37.8%) in the TKA group.

For the TKA group, quadriceps strength was highly and negatively correlated with SCT times ($r = -0.762$, $P < 0.001$), suggesting that persons with greater strength in the operated side took less time to complete the SCT (Table 4). There were no significant relationships between biomechanical variables and SCT or between biomechanical variables and quadriceps strength, with the exception of peak sagittal knee moment during the lowering phase and quadriceps strength ($r = 0.551$, $P = 0.015$). Participants with greater quadriceps strength on operated limb had greater knee moment on the operated side during the lowering phase of the stepping task.

Discussion

We hypothesized that: 1) patients in the TKA group would demonstrate movement asymmetries and abnormal knee and hip joints loads compared to the control group during the step up and over task and 2) quadriceps strength deficits and abnormal biomechanics of the operated leg during the step up and over task would be related to poor functional

performance as measured by the SCT. The first hypothesis was supported by our findings. Six months after TKA, patients completed the step up and over test with significant kinematic and kinetic asymmetries, as knee moments and powers in their operated limb were significantly lower than those of their non-operated limb. Moreover, the hip joint on the operated side produced more power during the propulsive phase. Knee moments and powers in their operated limb were also significantly lower compared to healthy, age-matched individuals without knee pathology. Our second hypothesis was partially supported by our findings. Strength in the operated limb was highly correlated to both stair climbing time and the magnitude of the knee moment during the lowering phase of the stepping task. Albeit not significant, quadriceps strength was also moderately related to knee power generation and absorption during the propulsive and lowering phase, respectively. However, no biomechanical variables from the step up-and-over task were significantly related to stair climbing time.

Although all patients were able to perform the step up and over without external aids or supervision, patients after TKA had smaller moments and lower power absorption and generation on their operated knee compared to their non-operated limb during all phases of the task. Furthermore, the values of the operated knee were significantly lower when compared to the knee of the control group. These findings are similar to what have been previously observed during stair ascent and descent (Mandeville et al. 2007; Berti et al. 2006; McClelland et al. 2014); however, the magnitude of the difference between TKA and control groups was larger in the current study. The higher magnitude differences measured during the step up and over task may be caused by several factors. First the step used for the step up and over task is higher than a standard step used in a staircase. Second, participants completed the step up and over task with an average speed of 0.86m/s (TKA group) and 0.95m/s (control group), which are faster speeds compared to what have been previously measured during stair ascent where speed ranged from 0.28 and 0.52 m/s in similar post-TKA populations and between 0.39 and 0.71 m/s in older adults without knee pathology (Standifird et al. 2014). Lastly, the knee of the stepping limb does not reach extension during the step up and over task (maximum extension was approximately 30 degree of flexion), which in turn increases the external knee flexor moment throughout the propulsive and lowering phases. As a result, the step up and over task may represent a more demanding biomechanical activity compared to stair climbing.

We anticipated that reduced operated knee moment and power of the stepping limb during the propulsive and lowering phase of the step up-and-over task would be related to worse functional performance as measured by SCT. Although patients in the TKA group took longer to complete both the step up and over task and the SCT, there were no significant relationships between operated knee moments or knee power of the stepping limb and SCT times. Although not related to SCT, the TKA group had higher power generation at the hip joint on the operated side during the propulsive portion of the task. The use of proximal joints to complete a step up task is consistent with previous results in similar post-TKA populations (Byrne et al. 2002; Mandeville et al. 2007) and in patients after ACL reconstruction (Rudolph & Snyder-Mackler 2004) and may represent a compensatory strategy to complete a challenging anti-gravity task. Zeni & Snyder-Mackler (2010) reported that the strength of the non-operated leg predicts SCT performance at both one and two

years after TKA. Therefore, it is also possible that the non-operated limb influenced the performance during the step up and over task and SCT. It is also important to note that the step up and over task may be more challenging or more novel than stair climbing. Differences in physical or muscular demand may account for different substitution or compensatory patterns between each task. Lastly, participants performed the step up and over at their self-selected speed, while SCT was performed as fast and safe as possible. Lack of task specificity may have also affected the relationship between biomechanical variables and SCT.

Despite the potential to compensate with hip muscles during the movement and functional testing, we did find a strong relationship between quadriceps strength and SCT, with weaker participants taking longer to complete the task. This is consistent with previous studies that found that quadriceps strength was one of the strongest predictors of functional ability after TKA, including SCT (Mizner & Snyder-Mackler 2005). Furthermore, quadriceps strength was related to peak sagittal knee moment of the stepping limb during the lowering phase of the step up-and-over task. This eccentric, lowering motion is often difficult for individuals after TKA and is the most common phase in which falls occur (Templer et al. 1985). This is the phase of stair negotiation that creates the largest external knee flexion moment (Andriacchi et al. 1980) and where the most knee power is absorbed (Riener et al. 2002). The ability to complete this task is related to quadriceps strength (Nyland et al. 2007), as it counteracts the external moments that act to flex the knee and prevent the lower extremity from collapsing during weight bearing. Therefore, it is not surprising that individuals with greater quadriceps strength complete this portion of the task with greater knee flexion moments. Stronger individuals may be able to generate larger internal muscle moments to meet the biomechanical demands of larger knee external flexion moments.

Although patients after TKA had greater hip power generation during the propulsive phase, less quadriceps strength was not related to less knee moment or less knee power on the operated side during this phase of the activity. Factors other than quadriceps strength may be responsible for this shift in the kinetic contribution from the joints in the operated limb. Prior to TKA, patients adopt compensatory strategies in the presence of pain and weakness. These changes are characterized by reduction of range of motion (Zeni & Higginson 2009), external forces (Zeni & Higginson 2009), and joint moments in the affected knee joint during walking and stair climbing (Kaufman et al. 2001). Furthermore, individuals with knee pain have greater contribution from the hip joint to maintain support of the body during gait (Zeni & Higginson 2011), rising from a chair (Pai et al. 1994) and stair climbing (Mandeville et al. 2007). Although pain diminish after TKA and muscle strength is improved, increased reliance on the non-operated limb may arise as a result of learned motor behaviors that will not be corrected by merely eliminating the predisposing impairments, in this case pain. This asymmetrical movement patterns may also bode poorly on the integrity of the cartilage of the non-operated knee joint. Several studies (McMahon & Block 2003; Shakoor et al. 2002; Shao et al. 2013; Sayeed et al. 2011; Smith et al. 2013) demonstrated that contralateral knee is the most common joint to be replaced after a primary TKA, and ultimately, one in two patients undergoing TKA is at risk of undergoing contralateral TKA within 10 years from the first surgery (Sayeed et al. 2011).

Stair climbing represents a challenging functional activity for individuals after TKA. Approximately 57% of patients required the use of a handrail to perform a similar SCT two years after the surgery (Zeni & Snyder-Mackler 2010). However, only 20% of patient included in the TKA group of the current study used the handrail during the SCT and all were also able to perform the step up and over task without aid or close supervision. Therefore, patients in the current study may represent a high functioning cohort of patients six months after TKA and the caution must be taken when generalizing these results to the general population of patients after TKA. However, even in this potentially high functioning cohort, there were substantial differences between limbs and we would expect these differences to be even greater in patients with greater levels of impairment. Several methodological limitations exist. We did not screen the control group for presence of radiographic OA, although we did exclude subjects if they reported any joint pain. The randomization process also produced a higher number of operated right legs in the control group, but given the similarity in biomechanics between limbs of the control group, this is unlikely to affect the results. Quadriceps strength was different between limbs in the control group, but the difference was less than 0.75 N/Kg, which is likely attributed to normal variability between limbs. Our research questions also include multiple post-hoc comparisons. *P*-values were not adjusted for multiple comparisons; however, the differences between limbs and groups were systematic and do not appear to be associated with random error.

In conclusion, patients 6 months after TKA complete the step up and over task with biomechanical asymmetries that reduce the demand on the operated knee and increase reliance on the contralateral limb and ipsilateral hip. When compared to age-matched individuals without knee pathology, patients after TKA had abnormal movement patterns during the step up and over task, considerable impairments in quadriceps strength, worse performance-based tests results, and lower self-reported questionnaire scores.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

Funding for this study was provided by the National Institutes of Health K12 HD055931 and the University of Delaware Research Foundation. We would also like to acknowledge the Research Core in the Delaware Rehabilitation Institute for screening and scheduling all subjects for this study.

References

- Alnahdi AH, Zeni Ja, Snyder-Mackler L. Gait after unilateral total knee arthroplasty: frontal plane analysis. *Journal of Orthopaedic Research*. 2011; 29(5):647–652. [PubMed: 21437943]
- Andriacchi TP, et al. A study of lower-limb mechanics during stair-climbing. *The Journal of bone and joint surgery. American volume*. 1980; 62(5):749–757. [PubMed: 7391098]
- Berti L, et al. Clinical and biomechanical assessment of patella resurfacing in total knee arthroplasty. *Clinical biomechanics (Bristol, Avon)*. 2006; 21(6):610–616.
- Boutron I, et al. Disability in adults with hip and knee arthroplasty: a French national community based survey. *Annals of the rheumatic diseases*. 2003; 62(8):748–754. [PubMed: 12860730]

- Byrne JM, Gage WH, Prentice SD. Bilateral lower limb strategies used during a step-up task in individuals who have undergone unilateral total knee arthroplasty. *Clinical Biomechanics*. 2002; 17(8):580–585. [PubMed: 12243717]
- D’Lima DD, et al. The 2011 ABJS Nicolas Andry Award: “Lab”-in-a-knee: in vivo knee forces, kinematics, and contact analysis. *Clinical orthopaedics and related research*. 2011; 469(10):2953–2970. [PubMed: 21598121]
- Dobson F, et al. OARSI recommended performance-based tests to assess physical function in people diagnosed with hip or knee osteoarthritis. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society*. 2013; 21(8):1042–1052.
- Felson DT, et al. Osteoarthritis: new insights. Part 1: the disease and its risk factors. *Annals of Internal Medicine*. 2000; 133(8):635–646. [PubMed: 11033593]
- Irrgang JJ, et al. Development of a patient-reported measure of function of the knee. *The Journal of bone and joint surgery. American volume*. 1998; 80(8):1132–1145. [PubMed: 9730122]
- Jacobs JJ, et al. The Burden of Musculoskeletal Diseases in the United States. *Bone and Joint Decade*. 2008:1–9.
- Kaufman KR, et al. Gait characteristics of patients with knee osteoarthritis. *Journal of Biomechanics*. 2001; 34(7):907–915. [PubMed: 11410174]
- Kennedy DM, et al. Assessing stability and change of four performance measures: a longitudinal study evaluating outcome following total hip and knee arthroplasty. *BMC musculoskeletal disorders*. 2005; 6(1):3. [PubMed: 15679884]
- Lin H-C, et al. Alterations of kinetic characteristics in step up and over test in patients with anterior cruciate ligament deficiency. *Journal of sports science & medicine*. 2010; 9(3):472–479. [PubMed: 24149643]
- Loughead JM, et al. Outcome following knee arthroplasty beyond 15 years. *The Knee*. 2008; 15(2): 85–90. [PubMed: 18249124]
- Mandeville D, Osternig LR, Chou L-S. The effect of total knee replacement on dynamic support of the body during walking and stair ascent. *Clinical Biomechanics*. 2007; 22(7):787–794. [PubMed: 17532102]
- Marx RG, et al. Reliability, validity, and responsiveness of four knee outcome scales for athletic patients. *The Journal of bone and joint surgery. American volume*. 2001; 83-A(10):1459–1469. [PubMed: 11679594]
- McClelland JA, et al. Patterns in the knee flexion-extension moment profile during stair ascent and descent in patients with total knee arthroplasty. *Journal of biomechanics*. 2014; 47(8):1816–1821. [PubMed: 24746020]
- McGinnis K, et al. Dynamic joint stiffness and co-contraction in subjects after total knee arthroplasty. *Clinical Biomechanics*. 2013; 28(2):205–210. [PubMed: 23219062]
- McMahon M, Block JA. The risk of contralateral total knee arthroplasty after knee replacement for osteoarthritis. *The Journal of rheumatology*. 2003; 30(8):1822–1824. [PubMed: 12913941]
- Mizner R, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *Journal of orthopaedic and sports physical therapy*. 2005; 35(7):424–436. [PubMed: 16108583]
- Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *Journal of Orthopaedic Research*. 2005; 23(5): 1083–1090. [PubMed: 16140191]
- Nightingale EJ, Pourkazemi F, Hiller CE. Systematic review of timed stair tests. *Journal of rehabilitation research and development*. 2014; 51(3):335–350. [PubMed: 25019658]
- Nyland J, et al. Self-reported chair-rise ability relates to stair-climbing readiness of total knee arthroplasty patients: A pilot study. *Journal of Rehabilitation Research and Development*. 2007; 44(5):751–760. [PubMed: 17943686]
- Pai YC, et al. Alteration in multijoint dynamics in patients with bilateral knee osteoarthritis. *Arthritis and rheumatism*. 1994; 37(9):1297–1304. [PubMed: 7945492]
- Piva SR, et al. Get up and go test in patients with knee osteoarthritis. *Archives of Physical Medicine and Rehabilitation*. 2004; 85(2):284–289. [PubMed: 14966715]

- Riener R, Rabuffetti M, Frigo C. Stair ascent and descent at different inclinations. *Gait & posture*. 2002; 15(1):32–44. [PubMed: 11809579]
- Rudolph KS, et al. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *Journal of electromyography and kinesiology*. 1998; 8(6):349–362. [PubMed: 9840891]
- Rudolph KS, Snyder-Mackler L. Effect of dynamic stability on a step task in ACL deficient individuals. *Journal of electromyography and kinesiology*. 2004; 14(5):565–575. [PubMed: 15301775]
- Sayed SA, et al. The risk of subsequent joint arthroplasty after primary unilateral total knee arthroplasty, a 10-year study. *The Journal of arthroplasty*. 2011; 26(6):842–846. [PubMed: 20884167]
- Shakoor N, et al. Nonrandom evolution of end-stage osteoarthritis of the lower limbs. *Arthritis and rheumatism*. 2002; 46(12):3185–3189. [PubMed: 12483722]
- Shao Y, et al. The fate of the remaining knee(s) or hip(s) in osteoarthritic patients undergoing a primary TKA or THA. *The Journal of arthroplasty*. 2013; 28(10):1842–1845. [PubMed: 24238572]
- Smith HK, et al. The effect of pain after total knee arthroplasty on the contralateral, nonreplaced knee. *The Journal of bone and joint surgery. American volume*. 2013; 95(4):315–322. [PubMed: 23426765]
- Standifird TW, Cates HE, Zhang S. Stair Ambulation Biomechanics Following Total Knee Arthroplasty: A Systematic Review. *The Journal of arthroplasty*. 2014
- Templer J, Archea J, Chen HH. Study of factors associated with risk of work-related stairway falls. *Journal of Safety Research*. 1985; 16(4):183–196.
- Walsh M, et al. Physical impairments and functional limitations: a comparison of individuals 1 year after total knee arthroplasty with control subjects. *Physical therapy*. 1998; 78(3):248–258. [PubMed: 9520970]
- Yoshida Y, et al. Examining outcomes from total knee arthroplasty and the relationship between quadriceps strength and knee function over time. *Clinical Biomechanics*. 2008; 23(3):320–328. [PubMed: 18060669]
- Zeni J, Higginson J. Knee osteoarthritis affects the distribution of joint moments during gait. *Knee*. 2011; 18(3):156–159. [PubMed: 20510618]
- Zeni J, Snyder-Mackler L. Early postoperative measures predict 1- and 2-year outcomes after unilateral total knee arthroplasty: importance of contralateral limb strength. *Physical therapy*. 2010; 90(1):43–54. [PubMed: 19959653]
- Zeni JA, Higginson JS. Differences in gait parameters between healthy subjects and persons with moderate and severe knee osteoarthritis: a result of altered walking speed? *Clinical Biomechanics*. 2009; 24(4):372–378. [PubMed: 19285768]
- Zeni JA, Snyder-Mackler L. Preoperative predictors of persistent impairments during stair ascent and descent after total knee arthroplasty. *The Journal of bone and joint surgery. American volume*. 2010; 92(5):1130–1136. [PubMed: 20439658]

Highlights

- Patients after TKA reduce the demand on the operated knee during a stepping task
- Compensations include increased effort of contralateral knee and ipsilateral hip
- Stronger quadriceps strength is related to faster stair climbing after TKA
- Stronger knee extensor muscles may be needed for more sagittal plane mechanics

Figure 1.

Representative subject performing the step up and over task. Subjects started behind the wooden box and stepped up and over the box on the investigator's command. The limb on the box was referred to as the stepping limb and the limb that landed on the anterior side of the box was referred to as the landing limb. The propulsive phase started when the stepping limb contacted the wooden box and ended at 60% of the stance phase. At this point, the lowering phase started and lasted until toe-off of the stepping limb from the box. The weight acceptance phase started at initial contact of the landing limb on the ground and ended at 25% of the stance phase for this limb.

Figure 2.

Symmetry ratio (operated divided by the non-operated side) for peak sagittal knee moment and peak knee and hip powers during the propulsive and lowering phases in the stepping limb. Error bars represent standard deviation.

Table 1

Subject characteristics

	TKA Group		Control Group		P-value
	Mean	SD	Mean	SD	
Age, years	69.8	6.2	68.53	7.39	0.564
Height, m	1.68	0.7	1.68	0.9	0.873
Mass, kg	85.96	17.39	74.23	16.75	0.039
BMI, kg*m ⁻²	30.12	4.96	26.08	3.87	0.008
Sex, male/female	9/11		10/9		0.633
Surgical limb, right/left	7/13		13/6		0.036
Step up and over speed, m/s	0.86	0.14	0.95	0.14	0.019
Time Up and Go, s	8.15	1.26	6.11	1.08	<0.001
Stair Climbing Test, s	13.57	2.73	9.63	1.64	<0.001
Six Minute Walk, m	545.24	72.88	652.69	79.55	<0.001

Abbreviation: BMI, body mass index.

Table 2
Biomechanical and unilateral functional metrics compared between limbs. Data are presented as mean (SD).

	TKA Group		Control Group	
	Operated Limb	Non-Op limb	Operated Limb	Non-Op limb
Unilateral Clinical Metrics				
KOS-ADLS, %	82.8 (19.5) *	90.5 (14.1)	98.7 (2.7)	98.4 (3.5)
Quadriceps Strength, N/Kg	6.21 (2.40) *	7.33 (2.21)	8.95 (2.37) *	8.20 (2.34)
Stepping Limb Propulsive Phase				
Peak Sagittal Knee Moment, Nm/Kg	0.66 (0.21) *	0.92 (0.25)	1.06 (0.20)	1.00 (0.24)
Peak Knee Power (generation), W/Kg	1.05 (0.46) *	1.51 (0.51)	1.83 (0.44)	1.75 (0.44)
Peak Hip Power (generation), W/Kg	1.34 (0.46) *	1.14 (0.41)	1.34 (0.49)	1.36 (0.42)
Stepping Limb Lowering Phase				
Peak Sagittal Knee Moment, Nm/Kg	0.94 (0.20) *	1.14 (0.29)	1.16 (0.24)	1.10 (0.20)
Peak Knee Power (absorption), W/Kg	2.69 (0.57) *	3.27 (0.61)	3.99 (0.79)	4.06 (0.78)
Peak Hip Power (absorption), W/Kg	0.64 (0.45) *	0.82 (0.58)	0.99 (0.44)	0.95 (0.44)
Landing Limb Weight Acceptance				
Peak Sagittal Knee Moment, Nm/Kg	0.58 (0.26)	0.72 (0.42)	1.01 (0.41)	0.96 (0.39)
Peak Knee Power (absorption), W/Kg	1.05 (0.81) *	1.88 (1.42)	2.51 (1.39)	2.19 (1.35)
Peak Vertical GRF, N/Kg	1.77 (0.16) *	1.90 (0.24)	1.90 (0.27)	1.87 (0.28)
Loading Rate, N/Kg*s	18.17 (5.60)	20.69 (6.15)	21.05 (6.61)	21.34 (7.78)
Knee flexion excursion, °	12.89 (4.92) *	17.79 (6.41)	20.87 (4.15)	19.82 (4.61)
Knee angle at initial contact, °	10.55 (4.7) *	7.48 (4.38)	9.27 (3.64)	9.08 (4.53)

* Paired sample t-test comparing operated limb vs. non-operated limb.

* Indicates significant difference between limbs

Table 3

Mean and percent differences between groups for the operated and non-operated limbs.

	OPERATED LIMB				NON-OPERATED LIMB			
	Mean Difference [#] Control-TKA group	Percent Difference [#] (Control-TKA)/Control	95% Confidence interval of the difference	P-value [†]	Mean Difference [#] Control-TKA group	Percent Difference [#] (Control-TKA)/Control	95% Confidence interval of the difference	P-value [†]
Unilateral Clinical Metrics								
KOS-ADLS, %	15.9*	19.2%	0.06 – 25.2	0.002	7.90*	8.0%	0.01 – 0.14	0.026
Quadriceps Strength, N/BMI	2.74*	30.6%	1.16 – 4.30	0.001	1.00	10.6%	-0.48 – 2.47	0.182
Stepping Limb Propulsive Phase								
Peak Sagittal Knee Moment, Nm/Kg	0.39*	37.7%	0.26 – 0.52	<0.001	0.08	8.0%	-0.08 – 0.23	0.319
Peak Knee Power (generation), W/Kg	0.78*	52.6%	0.48 – 1.07	<0.001	0.24	13.7%	-0.06 – 0.55	0.124
Peak Hip Power (generation), W/Kg	0	0.1%	-0.30 – 0.30	0.992	0.22	16.1%	-0.49 – 0.49	0.106
Stepping Limb Lowering Phase								
Peak Sagittal Knee Moment, Nm/Kg	0.22*	18.9%	0.07 – 0.37	0.003	-0.04	-3.7%	-0.20 – 0.11	0.604
Peak Knee Power (absorption), W/Kg	1.31*	32.6%	0.86 – 1.75	<0.001	0.78*	19.4%	0.32 – 1.23	0.001
Peak Hip Power (absorption), W/Kg	0.35*	35.4%	0.06 – 0.64	0.019	0.13	13.7%	-0.21 – 0.46	0.454
Landing Limb Weight Acceptance								
Peak Sagittal Knee Moment, Nm/Kg	0.44*	42.6%	0.21 – 0.66	<0.001	0.24	25.0%	-0.02 – 0.50	0.074
Peak Knee Power (absorption), W/Kg	1.89*	58.1%	0.72 – 2.19	<0.001	0.30	14.1%	-0.59 – 1.20	0.307
Peak Vertical GRF, N/Kg	0.13	6.8%	-0.01 – 0.27	0.071	-0.04	-1.6%	-0.20 – 0.12	0.647
Loading Rate, N/Kg*s	2.88	13.7%	-1.07 – 6.83	0.148	0.66	3.0%	-3.88 – 5.19	0.771
Knee flexion excursion, °	7.98*	38.2%	5.01 – 10.94	<0.001	2.03	10.2%	-1.61 – 5.67	0.090
Knee angle at initial contact, °	-1.28	-13.8%	-1.47 – 4.02	0.353	1.60	17.6%	-4.48 – 1.29	0.270

[#] Positive values indicate higher values in the control group; negative values indicate higher values in the TKA group

[†] Independent sample t-test comparing limbs between control and TKA groups.

* Indicates significant difference between group

Table 4

Pearson correlation coefficients for biomechanical, strength and stair climbing time in the TKA group

	SCT, s	Quadriceps Strength
Quadriceps Strength, N/Kg	-0.762 [*]	--
Stepping Limb Propulsive Phase		
Peak Sagittal Knee Moment, Nm/Kg	-0.022	0.176
Peak Knee Power (generation), W/Kg	-0.151	0.339
Peak Hip Power (generation), W/Kg	-0.107	0.236
Stepping Limb Lowering Phase		
Peak Sagittal Knee Moment, Nm/Kg	-0.302	0.551 [†]
Peak Knee Power (absorption), W/Kg	0.333	-0.366
Peak Hip Power (absorption), W/Kg	0.294	-0.082

^{*} $P < 0.001$;

[†] $P = 0.015$